education sciences

Article

A Case Study of a Secondary Biology Teacher's Pedagogical Reasoning and Action with Augmented Reality Technology †

Hsiao-Ping Hsu [1,*], Yin Hong Cheah [2] and Joan E. Hughes [3]

1 School of STEM Education, Innovation and Global Studies, Institute of Education, Dublin City University, Dublin D09AW21, Ireland
2 Department of Curriculum and Instruction, The University of Idaho, Moscow, ID 83844, USA; yhcheah@uidaho.edu
3 Department of Curriculum and Instruction, The University of Texas at Austin, Austin, TX 78712, USA; joanh@austin.utexas.edu
* Correspondence: hsiao-ping.hsu@dcu.ie

† This manuscript represents a conceptual expansion of the paper entitled "From Beginner to Expert: A Teacher's Reflective Practice of Applying Augmented Reality", which was previously presented at the 2019 International Society for Technology in Education (ISTE) Conference in Philadelphia.

Abstract: While recognizing the vital role of teachers in augmented reality (AR) integration, a noticeable literature gap exists regarding how science educators address challenges related to technology, pedagogy, and content during AR instructional design and implementation. Conducted in a secondary school in Taiwan, this study addressed this gap by conducting a qualitative single-case analysis of a science teacher's integration of AR technology into her biology lessons. The teacher's pedagogical reasoning and action processes were observed and analyzed over 10 weeks, with a focus on micro-level exploration across two iterations of pedagogical analysis, design, implementation, reflection, and revision. The primary data collection includes teacher interviews, supplemented by teacher reflective notes, lesson plans, teaching materials, researcher observations and field notes taken during the weekly, one-hour teacher learning community meetings, and the AR-integrated lessons, student assessment results, and feedback. The study was informed by both the Technology Integration Planning model and the Technological Pedagogical Content Knowledge framework. Data analysis techniques involved deductive coding and thematic analysis. The findings reveal the teacher's developmental proficiency in AR, a reimagined depiction of AR-enhanced instructional content, a shift from didactic-based to inquiry-based teaching approaches, and an intertwined development of technological pedagogical knowledge, technological content knowledge, and pedagogical content knowledge. This study provides valuable insights into how the educator became a pedagogical designer, overcame individual and contextual challenges, and leveraged reflective strategies to enhance biology lessons using AR technology, emphasizing technology's potential to enrich pedagogy in science education.

Keywords: augmented reality; education with VR/AR/MR; pedagogical reasoning and action; professional development; teacher learning; technology integration; Technological Pedagogical Content Knowledge; science education

check for updates

Citation: Hsu, H.-P.; Cheah, Y.H.; Hughes, J.E. A Case Study of a Secondary Biology Teacher's Pedagogical Reasoning and Action with Augmented Reality Technology. *Educ. Sci.* **2023**, *13*, 1080. https://doi.org/10.3390/educsci13111080

Academic Editor: Han Reichgelt

Received: 18 August 2023
Revised: 20 October 2023
Accepted: 21 October 2023
Published: 26 October 2023

1. Introduction

Digital tools in science classrooms are becoming increasingly prevalent [1–3]. Augmented reality is a novel technology that has the potential to merge the real and virtual worlds. This fusion might empower educators to demystify complex topics, making them more comprehensible and enhancing classroom interactivity [4–6]. Numerous studies have started shedding light on the teaching benefits of augmented reality in controlled experimental conditions [7–9]. Scholars also suggest that using augmented reality in the realm of science education can bolster student enthusiasm, engagement, and overall learning performance [10–12]. However, the regular use of augmented reality in standard classrooms is still in its nascent phase [13–16]. Although several studies have examined secondary students' application of augmented reality in learning science [17–20], only a limited number have delved into how secondary science teachers acquaint themselves with, strategize, and integrate augmented reality into their pedagogy [9,21,22], particularly when scrutinizing its specifics. Given that educators play a pivotal role in deciding the nature, method, and rationale behind technological adoption in their classes [23–25] and given the budding potential of augmented reality in science education [7,26,27], it is imperative to thoroughly understand the pedagogical strategies, rationales, and hands-on experiences of science teachers. Overall, a noticeable gap in the literature concerns the pedagogical necessities and strategies of science educators in embedding augmented reality into regular school programs. As a response to this, our investigation embarked on a single-case study centered on a science educator's journey of formulating and executing augmented reality-integrated lessons. We aimed to unearth (a) this teacher's step-by-step pedagogical analysis, design, implementation, reflection, and revision and (b) this teacher's use and development of their Technological Pedagogical Content Knowledge [28] amidst this journey.

2. Literature Review

Given the nature of biology in understanding the natural world and the living organisms within it, augmented reality (AR) has been viewed as a promising technology to visualize micro and abstract concepts in life science education [29]. Extant research documented that integration of AR technology could lead to a better understanding of difficult and abstract concepts in biology [30,31]. In a systematic review, Chen and colleagues [32] found that AR is often integrated to simulate scientific phenomena or visually present abstract concepts that support the assimilation of content or declarative knowledge. Among the 22 studies reviewed, 12 articles applied AR in biology covering topics across botany, zoology, biodiversity, and biotechnology. However, only three studies focused on designing inquiry-based AR lessons that promote students' analytical and problem-solving skills when learning scientific phenomena.

Recent shifts in educational policies and their execution [33–35] underscore the pivot from viewing science as mere "knowledge" to embracing it as an *activity*. Science, as an activity, encourages students to participate in inquiries akin to those of scientists and engineers. With the swift progression in science and technology, there is a pressing call for educators to explore in-depth knowledge, adopt learner-focused teaching methods, and hone apt technological competencies. This combination can pave the way for students to immerse actively in learning, collaboratively forge knowledge, and apply this knowledge to address real-world challenges [36]. In the context of technology-driven learning, Howland, et al. [37] posited that educators ought to frame scenarios where students *learn with* technology, allowing them to use these tools hands-on, tailored to their contextual learning requirements. This contrasts with just *learning from* technology, where educators primarily leverage technology for knowledge dissemination and memorization.

2.1. Prior Studies on Science Teachers' Integration of Augmented Reality

Integrating technology into teaching comes with a range of obstacles for educators. These can be categorized as first-order external barriers, such as infrastructural issues related to technology, and second-order internal barriers, which encompass individual beliefs about the utilization of technology [38]. When integrating AR into the curriculum, the primary concerns teachers express include the perception of inadequate technological backing, a lack of confidence in their own tech skills [16,39,40], and skepticism about AR's role in everyday educational processes [41]. These concerns align with Ertmer's distinction between first- and second-order hurdles. For instance, in a study by Dunleavy, et al. [42], which spanned multiple qualitative case studies across two high schools, the benefits and drawbacks of AR simulations were explored. Participating science educators conveyed that their most daunting tasks revolved around addressing hardware and software glitches inherent to AR. Alkhattabi's research [43], based on a survey involving 200 teachers, concluded that primary educators in Saudi Arabia identified a dearth of ICT infrastructure, human support, or technology expertise as the prime roadblocks to adopting AR.

Incorporating AR in teaching is not just a technical challenge; it also presents pedagogical hurdles [44]. For example, AR-focused instructional approaches may advocate for student-centric methods of teaching [22,45,46]. This can pose difficulties for educators accustomed to more direct, teacher-led instruction [9,47]. There are other notable challenges associated with AR: students getting easily distracted [40,48,49], AR's incompatibility with large-group teaching [50], and the substantial amount of instructional time it can consume [25,51,52]. Moreover, educators often resist adopting pre-set AR-integrated lessons that do not offer them the flexibility to tailor or modify the content as they see fit [9]. We know even less about the teachers who take on the intricacies of designing applicable AR content tailored to specific subjects. Moreover, Perifanou et al. [22] emphasize the crucial role that teachers play in the successful melding of technology into education, stressing the need to view AR integration through the lens of educators.

Tsai and Chai [53] argue that fostering teachers' design thinking skills and dispositions could be a more important area to develop for enabling meaningful AR integration than tackling first- and second-order barriers [38]. Teachers, as designers, could be supported to creatively overcome the abovementioned barriers by reorganizing or creating learning materials and instructional activities, in response to different learning contexts or varying groups of learners, which will always exist. The argument suggests that creating lessons enriched with technology in specific subjects is crucial but demanding [54,55]. Indeed, there is a noticeable gap in the existing literature, which does not adequately delve into how science (biology) educators navigate the challenges tied to technology, pedagogy, and content creation as pedagogical designers of AR-focused instruction.

2.2. Developing Teachers as Pedagogical Designers

Incorporating technology in science education necessitates teachers leverage their Technological Pedagogical Content Knowledge (TPACK) to inform their teaching methodologies within the framework of their syllabus requirements. TPACK is an anchored knowledge type that integrates three crucial components: content knowledge, pedagogical knowledge, and technological knowledge tailored for technology-enabled teaching methods [28]. As teachers immerse themselves in designing, deploying, and introspecting on technology's role in their lesson plans and broader curriculum, they call up, engage, and apply TPACK. This journey encompasses both declarative knowledge (i.e., teachers' understanding of technology-integrated teaching) and procedural knowledge (i.e., the aptitude to materialize this understanding into tangible teaching practices).

Previous research investigating science teachers' TPACK has primarily illustrated their TPACK progression through engagement in targeted group-based initiatives, including singular interventions, professional growth events, teacher training programs, and teacher-focused learning communities [56–62]. However, these investigations have not delved into the nuances of how an individual educator utilizes their TPACK during real-time lesson planning in daily classroom settings [63,64], offering a deeper perspective. This discrepancy underscores a gap between educators' theoretical knowledge and its practical application during everyday teaching. To gain a holistic grasp of science educators' in situ pedagogical choices, it is crucial to undertake granular studies on their routine lesson formulation, the rationale behind such plans, and their execution strategies using technology. An additional goal is to discern how teachers' TPACK is used or changes across cycles of pedagogical analysis, design, implementation, reflection, and revision.

Numerous experts advocate for viewing teachers as designers, suggesting that this perspective can enhance technology-integrated teaching and, in turn, generate superior learning avenues for students (e.g., [65]). Delving deeper, Brown [66] posited that a teacher's capacity for pedagogical design—their prowess in employing knowledge, convictions, and objectives to drive fruitful curricular choices—critically steers the formation and application of lessons that harness technology. This design aptitude bears conceptual parallels with a teacher's pedagogical reasoning and action (PR&A), a notion first delineated by Shulman [67]. Shulman painted a picture of a cyclical mechanism wherein educators ardently grasp, modify, and convey the teaching material, instructing responsively, gauging both student progress and their teaching approach, introspecting on the unfolded instruction, and culminating in novel understandings or expert revelations. Foundational to this journey are the teacher's core professional competencies, such as Pedagogical Content Knowledge (PCK) [63] and TPACK, both vital to the intricate processes of pedagogical reasoning and subsequent activities [68,69]. Building on this, Loveless underscores that pedagogical concepts and understanding are not merely attributes of individuals but evolve socially. They manifest "through distributed cognition, design, interaction, integration, context, complexity, dialogue, conversation, concepts, and relationships" (p. 304).

In their study, Ekanayake and Wishart [70] delved into the ways science educators incorporated mobile phones in their teaching environment. They used Shulman's six-fold PR&A processes as a foundational blueprint, streamlining them into three main stages: preparation, execution, and introspection. However, they remained open to the possibility of uncovering new processes and knowledge domains. True to their approach, they pinpointed several technology-centric elements intertwined with PR&A. These included aspects like verifying tech resources' accessibility, evaluating mobile-phone-centric educational tools, accounting for technology's time demands, insights into students' tech utilization patterns, potential technology-induced diversions, the educator's tech proficiency, and the gamut of reasons or added benefits from tech integration. Ekanayake and Wishart [70] breathed life into what Loveless [69] termed as "pedagogy in action" (p. 312), striving to decode the instructional strategies tied to mobile phone usage in science academia, particularly set against the backdrop of Sri Lanka.

While ample studies have been focused on the effects of AR and explored teachers' perspectives on using AR in education (e.g., [71,72]), investigating teachers' involvement in designing and implementing AR-based instruction remains scarce, especially in the K-12 biology context. Given the significance of actively involving students in "doing" biology with AR rather than passively consuming knowledge through AR representations, it is imperative that we shift our research focus toward understanding how teachers navigate the realms of lesson design, implementation, and reflective practices.

To unpack the biology teacher's PR&A in this research, we adopted the Technology Integration Planning (TIP) model [73], which is organized around the three core stages: pedagogical assessment, design and teaching, and evaluation and revision (as illustrated in Table 1). TIP recognizes the intrinsic, socially embedded learning journey of an educator's pedagogical reasoning and action. This journey consists of (a) a cognitive emphasis on teachers' prevailing knowledge (explicitly referencing TPACK), perceptions, and inclinations, and (b) external social drivers. These external factors encompass the significance of resources and the contributions of students, parents, and the broader school community, all playing a role as an educator crafts fresh insights and/or teaching methods. This learning and design path may involve collaborative exchanges, a point underscored by Loveless [69]. Moreover, the stages encapsulated within TIP also incorporate the technology-focused considerations spotlighted by Ekanayake and Wishart [70]. Table 1 offers a concise representation of the phases and corresponding steps inherent in the TIP model.

Table 1. The Technology Integration Planning Model (TIP) [73].

The Technology Integration Planning Model	
Phase 1: Lead from Enduring Problems of Practice	Step 1: Identify problems of practice (PoPs). Step 2: Assess technological resources of students, families, teachers, the school, and the community. Step 3: Identify technological possibilities and select an integration strategy.
Phase 2: Design and Teach the Technology Integration Lesson	Step 4: Decide on learning objectives and assessments. Step 5: Assess the relative advantage: RATify the planned lesson. Step 6: Prepare the learning environment and teach the lesson.
Phase 3: Evaluate, Revise, and Share	Step 7: Evaluate lesson results and impact. Step 8: Make revisions based on results. Step 9: Share lessons, revisions, and outcomes with other peer teachers.

Consequently, we embraced the TIP as a foundational framework to decipher the pedagogical reasoning and pivotal decisions our focal teacher made concerning the infusion of technology (i.e., AR) into her classroom instruction over 10 weeks. We aimed to track this science educator's step-by-step pedagogical and contextual analysis, design, implementation, reflection, and revision as they engaged in lesson designs with AR. Simultaneously, we discerned how their TPACK was used or changed during this design process.

2.3. Research Questions

Our research was guided by two questions:

(1) How does a teacher engage in pedagogical and contextual analysis, design, implementation, reflection, and revision of a biology lesson that incorporates augmented reality technology?

(2) How does a biology teacher call upon, use, or develop their Technological Pedagogical Content Knowledge as they engage in lesson design of a biology lesson that incorporates augmented reality technology?

3. Methodology

The project's objective was to study how teachers incorporated AR into secondary school curricula and pedagogy. To gain a detailed understanding of one teacher's planning, implementation, and reflection process, a qualitative single-case study approach [74] was employed. This method was also utilized by Scott [75] to delve into a teacher's technology-enhanced teaching process, including experimentation and adaptation, as well as to examine the complexities of teacher development and pedagogical change. Therefore, this approach seemed apt and was chosen to investigate a teacher's in situ pedagogical reasoning and action, as represented through the TIP model (see Table 1).

3.1. Context and Participants

This study was situated within an AR project introduced in 2016 in a secondary school in a large urban city in Taiwan. The secondary school, with a student population of around 1200 from working- and middle-class families, received 30 cutting-edge smartphones from the local government for individual student use. The school administrators established a teacher learning community (TLC) to promote mobile learning in the school, spearheaded by a computer science teacher pseudonymously referred to as David. Teachers were invited to voluntarily participate in the TLC. Concurrently, David was in charge of the Student AR Creation Club, one of the many after-school groups. This club focused on exploring how AR technology can be applied in everyday life. Additionally, it assisted teachers in incorporating AR tools into their lesson plans when needed. The TLC's objective was to have the involved teachers utilize mobile learning technologies, like AR, in at least two lessons within a single semester.

The participant in this single-case study was Jenny (a pseudonym), a biology teacher with eight years of experience teaching secondary students. Jenny dedicated five years to the creation and guidance of biology-related field trips. Despite having no prior experience with AR, Jenny joined the TLC in the spring semester of 2017. Her goal was to design AR-driven teaching approaches for her formal curriculum over a 10-week period (from February to April) and to communicate her advancements and challenges with the TLC. Jenny used the Aurasma platform, which was later renamed HP Reveal, to implement her AR-based teaching activities. Aurasma produces an Aura, an AR responsive trigger that manifests texts, visuals, videos, or animations. This reaction is elicited when users direct their devices towards an item previously programmed with an AR activation point.

The first author offered his expertise in curriculum design to the TLC and joined their weekly meetings to observe how teachers incorporated AR technology into their teaching practices. During this endeavor, the case focus was Jenny. Over the semester, she developed two AR-integrated lessons for her biology course. The first lesson catered to a class of 25 students, while the second lesson was designed for her five classes, encompassing 112 students. Students were allocated to classes based on random assignment as mandated by the Ministry of Education of Taiwan. As a member of the TLC, Jenny reflected on her teaching with her colleagues and conducted open-ended surveys and biology content tests to assess her students' learning outcomes and adjust her AR-based teaching approaches.

3.2. Data Sources

A single-case study design [74] was selected to consider the teacher, Jenny, as a critical case of pedagogical reasoning and action in relation to designing instruction with AR. In particular, the case of Jenny offered a granular view into how an experienced science teacher reasoned about and took action to use AR to teach biology. The case tests the explanatory power of theories of pedagogical design built into the TIP model [73] and TPACK [28]. The primary data included teacher interviews, supplemented with reflective notes, teaching materials, lesson plans, observation field notes, a teacher-administered biology content test, and an open-ended student survey after each lesson (see Table 2). The use of multiple sources of data allowed for triangulation and increased the validity and credibility of the study [76].

Table 2. Data sources.

Data	Description	Collection Timeframe
Teacher interviews (12)	Jenny was interviewed 12 times. The progress interview questions were derived to align with the research objectives to understand Jenny's pedagogical reasoning, decisions, and actions in relation to her weekly lesson design activities. The post interview was designed to document her progress, achievements, and challenges in relation to the lesson implementation. The semi-structured interview protocols are available in Appendix A.	Weeks 1–10: One progress interview per week conducted after each TLC meeting. Interviews lasted between 30 and 40 min. Week 6 & 10: One post-lesson interview after each AR-enhanced lesson. Interviews lasted 45 min.
Reflective notes (2)	Jenny composed reflective notes after teaching the two lessons. During these lessons, she jotted keywords and thoughts and later elaborated her notes after the school day ended. The first note was four typed pages, while the second note was two pages. These reflective notes conveyed Jenny's perspectives on her experiences with instructional analysis, design, implementation, and revision. Consequently, they enabled the researchers to delve further into these aspects during the two post AR-enhanced lesson interviews.	Week 5 and 9: Reflective notes were written after Jenny taught the lessons.

Table 2. *Cont.*

Data	Description	Collection Timeframe
Teaching materials and lesson plans	The researchers collected Jenny's teaching materials, including the lesson plan for each of the two lessons, AR Auras, AR triggers, and student handouts.	Week 4 and 8: Teaching materials and lesson plans were gathered prior to Jenny's two AR-enhanced lessons.
Observation field notes (12)	The first author actively participated in the weekly TLC one-hour meetings and observed both of Jenny's lessons that integrated AR. Detailed field notes were taken, which documented Jenny's interactions with fellow TLC members, particularly in terms of sharing her progress, challenges, and the advice provided by others. Additionally, separate field notes were taken during the lesson observations, focusing on how Jenny executed her planned lessons and capturing the students' learning experiences and their responses to her teaching.	Weeks 1–10: TLC weekly meeting field notes. Week 5 and 9: Lesson observation field notes.
Biology content test (2)	The content test comprised ten multiple choice questions about the local plants' characteristics and edibility, with each question worth ten points	Week 5 and 9: Test after Jenny taught the lessons.
Open-ended survey (2)	The survey queried students' experiences learning when using or not using AR in the field trip and their suggestions for improving AR-enhanced learning experience.	Week 5 and 9: Survey after Jenny taught the lessons.

3.3. Data Analysis

The data analysis involved a deductive coding approach using pre-determined, literature-based codes [77] generated from the TIP model and TPACK framework, which were used to track Jenny's pedagogical reasoning, lesson design decisions, and knowledge (i.e., TPACK) use during her AR technology integration processes. Utilizing the codes derived from the TIP model and TPACK framework, we meticulously coded the interviews, teaching materials, and field notes. We calculated descriptive statistics for the two biology tests. We used open coding and thematic analysis for the student survey to identify students' views on the AR-based learning experience. Through a comprehensive analysis of the coded data, we generated three interpretive memos. The first two memos were narrative representations of Jenny's pedagogical reasoning and action leading up to Lesson 1 and Lesson 2, respectively, which align with the TIP model [73]. The third memo was a comparison matrix of Jenny's TPACK engagement during Lesson 1 and 2 designs. We then performed a member check with Jenny in order to achieve credibility. A confirmability audit was conducted by a second coder to monitor the first coder's interpretations to secure trustworthiness.

4. Results

The results present a granular, step-by-step view of Jenny's two lesson design experiences. We present two narratives (Sections 4.1 and 4.2) of Jenny's pedagogical and contextual analysis, design, implementation, reflection, and revision that represent each of the two biology lessons she designed and taught using AR technology. The third Section 4.3 shares how Jenny utilized and developed her TPACK through these two lessons.

4.1. Lesson One: The First Iteration of Jenny's Pedagogy in Action

4.1.1. Phase 1

Initially, Jenny was not guided by a content-related challenge or problem of practice. Rather, she was assigned to design an AR-enhanced biology lesson as part of a government-sponsored school project to weave AR into the teaching and learning of different subject areas. Even though Jenny was not familiar with the educational uses of AR (TPK or TCK), she felt that students would be instinctively attracted to AR due to its resemblance to popular AR applications like Pokémon GO (TK). She believed that her students, being digital natives, would know how to use AR without difficulty. This was a motivation/engagement-based rationale for using AR. To support her teaching practice, Jenny assessed the technological resources available to her. To facilitate students' learning, Jenny's school equipped them with 30 smartphones and provided WiFi and portable 4G routers for internet access both on and off campus. David, the computer science teacher and head of the TLC, suggested Aurasma as the ideal AR technology due to its user-friendly interface, coding-free features, and capacity to create AR content without requiring specialized training. Jenny chose David's tutorial sessions over the local education authority's professional development workshops to learn about Aurasma. She appreciated David's effort to translate the Aurasma tutorial from English to Chinese, allowing her to learn independently. In comparison, the Aurasma workshops, offered by the local education authority, were standalone events, which made it difficult to get ongoing support. Moreover, Jenny found these workshops lacking, as they only touched on the technical basics of AR and did not delve into its pedagogical applications in teaching biology.

She also struggled to find AR content that was specific to her needs as she was teaching local ecological knowledge. This meant that she had to create her own content, which was challenging as she was still learning about AR herself. David suggested that she collaborate with students in his AR Creation Club to help her overcome her technological barriers. Together, they were able to create an Aura and Jenny felt more confident in developing AR-enhanced teaching methods. She decided to focus on teaching about local plants and their edibility using AR. In sum, Jenny's design process was different from the TIP model as she started with the goal of integrating AR into education rather than beginning with an instructional problem of practice.

4.1.2. Phase 2

Jenny's aim for her first AR-based biology lesson was to educate her students on local plants by highlighting their features and whether they were edible. In the past, this was achieved through a field trip where students would attend a lecture and jot down details from a physical handout describing the plants. However, this method was challenging for students, primarily due to their limited pre-existing knowledge about the local flora and the sheer volume of information they had to absorb. Moreover, teaching in an outdoor environment posed management challenges, especially with students who were not as engaged in the learning process.

To better engage her students and improve learning outcomes, Jenny decided to incorporate AR technology into the field trip. By using digital image triggers, students could scan and learn about the plants in a more interactive and fun way. Jenny found that AR technology was eye-catching and motivated her students to read the instructional content while listening to her lecture. The scan-and-read action was similar to the game-like environment of Pokémon GO, which made it more enjoyable for students. Although the medium of instruction changed, the curricular content remained the same as her previous teaching approach. She believed that by digitizing the original content from the paper handout onto Aura, students would benefit from the convenience of being able to browse the augmented information while looking at a real plant. This would enhance students' motivation to learn and increase their engagement. Furthermore, students can avoid the hassle of constantly shifting their attention between the plant and the written information. Jenny utilized a biology knowledge test that she had previously used to teach the topic. Additionally, she issued a student survey to gather their perspectives and experiences on AR-based learning. Jenny got ready for the AR field trip by inviting members of the AR Creation Club to the park. Together, they installed six image triggers and rehearsed her teaching to ensure that all the triggers were functioning correctly.

During the class field trip, Jenny observed an initial surge of enthusiasm among students, evident in their keenness to scan and comprehend the AR-enhanced content. This enthusiastic reception of AR as an educational tool underscores its potential to engage learners in novel ways. Nevertheless, as the instruction evolved, there was a discernible shift in students' engagement patterns. An increasing number of students began to divert their attention from the AR interfaces, choosing instead to focus solely on Jenny's verbal lecture.

Jenny followed all the steps in Phase 2 of the TIP model, testing her AR integration approach in a real-world setting before implementing her lesson. She believed that using AR could enhance student engagement by making handouts more visually appealing. However, during the lesson, she noticed that students started ignoring the AR elements and only paid attention to her oral instruction. This indicates that although AR may initially capture students' attention, maintaining their interest requires a balance between technology, teaching methods, and content.

4.1.3. Phase 3

After conducting a thorough post-instruction analysis of her AR-based teaching approach, Jenny identified several obstacles. She particularly highlighted the issue that each site only had one image trigger, which caused the augmented information to disappear when students moved away. The physical space was also limited, and the image trigger size should have been made larger to accommodate all students. Furthermore, students with limited English proficiency struggled to utilize Aurasma due to its English-only interface, despite having received prior instruction. Additionally, the wireless 4G routers could not handle all the students simultaneously, and the internet speed was unreliable, especially when accessing the augmented video streaming content on Aurasma.

Jenny highlighted a concerning observation regarding the average content test score of 46.8. These results, she found, were noticeably lower than those of previous cohorts who had participated in a traditional paper-based field trip. She posited that a significant factor contributing to this decline was the disruptions introduced by the application of AR technology. Due to these disruptions, students were confined to merely listening to the lecture, devoid of the information that paper handouts usually provide. This absence of tangible reference material made it challenging for them to effectively consolidate their learning. Moreover, student feedback gathered through the survey accentuated this concern. A considerable number of respondents expressed dissatisfaction with the AR experience. They found the process of scanning the AR triggers not just tedious, but also a source of distraction from the main content of the lecture. This sentiment was further echoed by a prevailing preference among students for traditional paper-based handouts, which they felt offered a more straightforward and less disruptive learning experience.

In response to these challenges, Jenny shared her experiences and struggles with her colleagues at a regular TLC meeting. She received feedback and decided to adjust her teaching methods and strategies to better incorporate AR technology. In line with the TIP model, she spent time contemplating improvements to boost the observed outcomes. The TLC played a crucial role in supporting these changes.

4.2. Lesson Two: The Second Iteration of Jenny's Pedagogy in Action

4.2.1. Phase 1

Jenny received valuable input from members of the TLC, which helped her address the technical and pedagogical problems she faced with her PoPs. These included issues with image triggers, Aurasma's English interface, outdoor wireless internet quality, and various pedagogical concerns. Colleagues suggested that Jenny divide the students into smaller groups for field trips to reduce the image triggering issue. Grouping students with different levels of English proficiency could also provide peer support for learning within Aurasma's English interface. David recommended that students pre-scan all image triggers before leaving campus to reduce reliance on wireless internet in the field. Jenny found these suggestions to be helpful, as she had prior experience planning the first integrated lesson, which helped her to make sense of her colleagues' suggestions.

With the support of the TLC, Jenny was inspired to design a new AR lesson that actively facilitated students' learning experiences with science. She further collaborated with

Lisa (pseudonym), another member of the TLC, to design an interdisciplinary lesson that educated students on the biological attributes, edibility, and environmental determinants affecting the spread of local plants. She elaborated:

> I needed to teach students about the biology and edibility of local plants, while Lisa, a geography teacher, focused on spatial reasoning and environmental factors affecting plant distribution. Together, we co-designed a lesson to help students identify and assess the edibility of local wild plants.

In essence, with the TLC's support, Jenny overcame the technical and pedagogical challenges she encountered with her PoPs, prompting her to re-plan her approach to using AR in instructing students about plant biology. Utilizing the TIP model, Jenny took into account both technological and pedagogical elements of the revamped lesson plan, aided by her TLC.

4.2.2. Phase 2

In the initial iteration, merely replacing the paper handouts with AR-augmented information did not enhance the students' learning experiences or outcomes. Collaborative discussions with a researcher from the TLC guided Jenny in refining her approach to integrating AR into biology lessons. She shared, "The researcher introduced me to studies showcasing the use of AR in fostering inquiry-based learning, which helped enhance students' scientific reasoning and ecological understanding. This feedback provided me with a direction to adapt my teaching method."

Inspired by these insights, Jenny, alongside Lisa, curated an AR-driven, inquiry-based interdisciplinary lesson module termed *Plant Hunt*. In this simulation game, students utilized their spatial reasoning skills to locate plants and assessed their features to determine their edibility. Even though the instructional objectives in the biology segment remained unchanged from the previous iteration, the revamped lesson encouraged students to actively engage and learn biology in context. The teaching approach shifted from being instructor-led to student-centric. Furthermore, the students' role evolved from being mere passive learners to active participants in knowledge construction.

Students were grouped and assigned six problem-solving tasks scattered across different locations within a local ecological park. Their primary mission was to search for food sources for survival. Jenny's newly designed handout offered visuals illustrating the plants' characteristics and guidelines to determine their edibility. Unlike the first session where Jenny verbally conveyed this information, in the subsequent session, students assimilated the same content by practically applying on-site knowledge and discerning the local plants' features.

At each designated location, student groups were tasked with locating an AR image trigger. Upon scanning this trigger, they received information about a specific plant's biological attributes and its visual representation. Students then cross-referenced the data they gathered on-site with the illustrations and guidelines provided in their handouts to determine the plant's suitability for consumption. Once they ascertained whether the plant was edible or not, they received a clue that tested their spatial reasoning skills, guiding them to their next destination. An example of such a clue might direct students to a location bathed in sunlight, featuring a shrine to its northwest, and surrounded by Marabutan trees.

Apart from determining the edibility of plants, each group documented their journey and the paths they took to complete the assignments. After navigating through all six locations, the class reconvened. The teachers then reviewed the determined edibility of the six identified plants, tallied the number of plants that students correctly classified, assessed the strategies employed by the groups to tackle the tasks, and announced the number of groups that would have successfully survived based on their choices.

This time, Jenny and Lisa decided to modify the AR content in line with their revamped pedagogical approach. They did not want to solely rely on the students for technical assistance this time around. Their goal was to be hands-on in integrating technology seamlessly into the lesson, ensuring it complemented their teaching methods and enhanced the students' learning experience. As Jenny explained:

> If I had continued depending on my students, I would have frequently had to request them to handle tasks like XYZ. Any unforeseen issues would have meant waiting for them to make corrections. In the past, even though I didn't create an Aura entirely on my own, my students were thorough in explaining their procedures. This guidance, coupled with David's tutorial, equipped me with the necessary insights to construct an Aura by myself

In the second iteration, the biology exam previously administered was utilized. In addition, a survey was distributed to gather students' feedback and experiences related to their use of AR. To facilitate the field trip for this joint session, Jenny and Lisa requested schedule modifications from the school administration, enabling them to teach all their classes together, utilizing the latest AR teaching approach. To verify the effectiveness of this innovative instructional approach, they enlisted the participation of students from the AR Creation Club to test the *Plant Hunt* lesson and incorporated their feedback to make necessary adjustments.

During this stage of the TIP, Jenny retained the same scientific instructional goals and evaluation methods. However, there was a significant shift in the approach to technology integration. This was achieved through collaboration with another educator, which also influenced the structuring of the teaching environment. In the context of relative advantages, Jenny reimagined the use of AR technology, creating an inquiry-driven teaching environment. This setup was designed to assist students in acquiring on-the-spot biological knowledge, enabling them to address a real-world, location-specific challenge.

4.2.3. Phase 3

The content test for the second AR integrated lesson yielded an average score of 68.4. Students' feedback was overwhelmingly positive, expressing a keen interest in learning more about local plants, a desire to integrate AR across all subjects, and an appreciation for group collaboration. Comments included praises like, "Learning with AR was engaging," and "Group work exposed me to diverse viewpoints and reasoning." Jenny's records further depicted the depth of student involvement, especially during the "edible plant hunt" simulation. The grouping approach notably helped bypass the language restrictions of Aurasma, especially benefiting students less proficient in English. Their successful implementation resonated within the TLC, with plans to incorporate their lesson into the broader school curriculum.

However, Jenny believed there was scope for refining the AR experience. She envisioned utilizing pre-existing landmarks at the park as AR triggers, eliminating the need for prior setup and incurring cost savings. David's recommendation of shifting to location-based AR technology was also on her radar.

While the collaborative teaching approach yielded favorable outcomes, Jenny discerned potential challenges. A surge in co-teaching might burden administrative logistics, primarily in synchronizing two educators' schedules. She also projected the necessity for a Bring Your Own Device (BYOD) policy, given that the current 30 smartphones might fall short as AR-based teaching gained traction.

In line with the TIP model, Jenny and Lisa scrutinized the results of their lesson and enlightened their peers about their achievements. Jenny pinpointed areas needing enhancement, hinting at a potential future iteration of the integrated plan involving more school teachers.

4.3. Jenny's TPACK Development through Iterative Pedagogical Reasoning and Action

Jenny's lesson design processes involving pedagogical and contextual analysis, design, implementation, reflection, and revision across the two AR-integrated lessons called upon and enhanced her TPACK, as depicted in Table 3. As she navigated through the lessons, Jenny's teaching approach transitioned from a technology-focused paradigm to one that emphasized student-centered learning. This journey to design and teach an inquiry-based

AR approach in Lesson 2 developed her Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK), and PCK.

Table 3. Use and Development of TPACK Across Design of Lesson 1 and 2.

	AR Integrated Lesson One	AR Integrated Lesson Two
TK	Jenny had limited knowledge of Aurasma's technical affordances; she depended on student support to use AR.	Jenny became better acquainted with Aurasma and independently created AR.
CK	Jenny taught the biological characteristics of local plants.	
PK	Jenny used a directed, didactic, teacher-centered approach.	Jenny used a constructivist, student-centered approach.
TPK	Jenny applied AR to replace traditional paper-based medium (didactic pedagogy) with a goal of increasing students' motivation to engage in learning.	Jenny used AR to facilitate inquiry-based activities (constructivist pedagogy) with a goal of students developing and applying their knowledge to solve a challenge.
TCK	Jenny used AR's scan-and-read feature to make the handout content more attractive to increase student involvement and engagement with the biology content.	Jenny created a mashup of AR's scan-and-read feature and a newly designed paper-based handout to engage students in authentic knowledge application.
PCK	Jenny used didactic instruction to systematically teach students about plant characteristics.	Jenny used inquiry-based instruction, so students could apply knowledge about plant characteristics to solve the contextual problems.

In the first lesson, Jenny recognized her need to acquire AR technical abilities (TK). Faced with the intricate nuances of Aurasma and her time constraints, she heavily relied on students in the AR Creation Club for assistance in developing AR content. This digital augmentation focused on the information about local plant characteristics and edibility, originally presented on paper-based handouts (TCK). Throughout this lesson, Jenny stuck to her conventional, teacher-led teaching method (PCK). While lecturing, she employed AR to superimpose the traditional handout content onto actual plants, facilitating a direct comparison for students and enhancing their grasp of the subject (TCK, TPK). She noticed the captivating "scan-and-read" feature of AR heightened student engagement in understanding plant traits. However, merely transitioning from conventional paper resources to AR illustrations (TCK) did not translate to better academic outcomes. Despite introducing AR into her teaching, Jenny's pedagogical approach remained largely teacher-led. This inaugural attempt resulted in unenthusiastic student responses and modest academic achievements. In her second lesson, interactions with the TLC members and researchers shaped Jenny's AR teaching approach. Her advanced PCK was apparent as she adopted a socio-constructivist strategy, organizing students into groups to identify edible plants through a simulation activity.

In this iteration, the data on local plants and their suitability for consumption served as a foundational tool aiding students in their problem-solving endeavors. Ingeniously blending AR with a redesigned paper-based handout to establish TCK, Jenny empowered students with augmented details about a plant's features. Concurrently, the handout (CK) showcased the plant's illustrations and guidelines to determine its edibility. This method encouraged students to observe the plant and compare its augmented details directly with the handout's information. Coinciding with her pedagogical shift, Jenny's utilization of AR transitioned from merely presenting and absorbing information to facilitating problem-solving within a simulated context (TPK).

Jenny took a step forward in enhancing her technical knowledge (TK) by collaborating with Lisa, her co-teacher, to generate AR content, rather than relying solely on the AR Creation Club students. This progression in Jenny's TPACK paved the way for her to harness AR in fostering inquiry-driven tasks. She crafted a scenario where students were empowered to use their acquired knowledge in a context-sensitive manner, addressing relevant local challenges. As evident from the feedback on student surveys and the improved scores in content tests, this second lesson significantly boosted both learning results and student enthusiasm in contrast to the initial lesson.

5. Discussion and Conclusions

5.1. Systematic Approach to Lesson Integration with Augmented Reality

The TIP framework effectively outlined the stages of Jenny's pedagogical reasoning and action, illustrating how individual and community aspects, such as knowledge, resources, and directives, intertwined with the overall design process and progress. In Jenny's initial lesson, which was not as effective with the students, the driving force was an edict for integrating AR technology, akin to what Loveless [69] terms as "retooling." Keeping the same educational objectives, she crafted an AR-infused content representation to take the place of the traditional paper handout. She also mirrored her previous teacher-led approach to impart knowledge on plant attributes at an ecological location and saw AR as a tool to boost student interest in passive learning. However, the initial allure of AR technology was short-lived, especially when it could not cater to all students' technical accessibility needs. As a result, accessing AR content became an optional aspect of the learning journey and did not result in improved knowledge acquisition. Moreover, Jenny also encountered challenges in integrating AR, such as limited outdoor infrastructure, a deficit in technical expertise, and the absence of tailored content, as underscored by prior studies [16,39,40].

In her subsequent lesson redesign, Jenny pinpointed a content-focused problem of practice and leveraged it as an impetus to collaboratively design and execute a lesson plan with a geography colleague, infusing AR. She enriched her PCK by incorporating elements of inquiry-based science teaching, in line with current views of science as action [33–35], and reshaped the lesson, prompting students to employ on-site, AR-enhanced data (TCK) to drive their inquiry into identifying edible plants essential for sustenance and survival. This maturation in her TPACK spurred a lesson framework that revolutionized the way teaching, curriculum, and student learning were approached. Students actively channeled their biological insights and spatial analytical prowess to navigate content-driven challenges within a simulation game. AR technology served as an ally in the pedagogical paradigm, harmoniously complementing the freshly crafted handout. Jenny's teaching methodology metamorphosed, empowering students to harness interdisciplinary acumen and techniques to address real-world, situational challenges. The novelty of AR technology also doubled as an incentive, compelling students to engage with the learning activities, while student enthusiasm was buoyed by an active, inquiry pedagogy and supporting technology. By scanning AR triggers to gather hints, students were immersed in an inquiry-driven educational journey, with AR emerging as crucial. A novel teaming tactic saw students embarking on collaborative endeavors and mutual assistance, culminating in enhanced learning outcomes and heightened student contentment.

To summarize, for AR technology integration to be efficacious, it is paramount to meticulously assess its influence on pedagogical techniques, student learning trajectories, and educational objectives. Merely substituting traditional paper-driven information mediums with cutting-edge tech might fall short of expectations, similar to Jenny's first lesson design. We advocate for more investigative endeavors into the dynamics and variances when educators sculpt tech integrations centered around content-based problems of practice versus a technology-centric planning approach. This could be pivotal, given that many educational administrators embrace tech advancements without seeking educator feedback [78], often steering towards technology-centric educational reforms.

Jenny's progression in the second lesson redesign indicated a shift towards a content-focused problem of practice. Her collaboration with colleagues and the infusion of inquiry-based teaching methods led AR to be used more effectively, promoting deeper biological insights and spatial analytical abilities in students. Our study showed that merely integrating AR does not guarantee students' deep learning in the biology subject. The pedagogical approach plays a critical role, emphasizing a shift from didactic-based to inquiry-based teaching [79,80]. This is particularly important, given other cases where students exposed to AR did not show significant improvements in academic scores [81]. Previous research had also demonstrated cases where teachers had a positive perception of AR's effectiveness, yet student outcomes did not match expectations [82,83]. Our findings align with this, further underscoring the need for a strong pedagogical foundation in AR-integrated lessons.

In sum, a deep dive into Jenny's pedagogical design experiences not only unveiled these obstacles in a real-world context but also highlighted her progression in technological self-assurance and pedagogical adaptation through consistent pedagogical reasoning and action. Jenny's growth was bolstered by the supportive network of the TLC, underscoring the pivotal role of collaborative teacher initiatives in mastering and implementing AR technology [22,25]. As members of this TLC engage in dynamic technology-integrated pedagogy, their experiences can resonate with and shape the PR&A journeys of their peers. Our findings reinforce the notion that thriving professional evolution via teacher learning communities necessitates a substantial time investment. Moreover, it also unlocks avenues for learning and iterative feedback grounded in the unique cultural and contextual nuances of educational settings [69,84,85].

5.2. Evolution of TPACK through Iterative Pedagogical Reasoning and Action

Jenny's iterative pedagogical reasoning and action across two lesson designs illuminated the importance of evaluating TPACK in real-world classrooms. Despite Jenny's evident access and use of her TPACK, the lessons were not both successful, emphasizing the need to scrutinize both the evolution of TPACK and actual teaching practices. Our research builds upon the existing literature, reinforcing the notion that cyclical reflective practice, underpinned by consistent commitment and supportive communities, is crucial in fortifying teachers' TPACK [86,87] and its application in their teaching. Jenny adeptly leveraged available resources, including the TLC, David, the researcher, and her co-teacher Lisa, to introspect and restructure her lessons after facing setbacks in her initial lesson. This process was instrumental in deepening her grasp of TPACK, with a specific focus on her PCK. However, Jenny's experience underscores that merely possessing and applying TPACK does not invariably result in enhanced teaching or learning in specific content areas. While Jenny demonstrated TPACK application in both lessons (refer to Table 3), the inaugural lesson was not as fruitful for learning. Hence, we posit that simply identifying TPACK in isolation from its application might be inadequate. We advocate for a comprehensive examination of both the evolution of TPACK and the actual teaching in action to truly discern the impact of technology. This approach is gaining traction, evidenced by research where scholars have meticulously analyzed teachers' practical implementation of technology-supported methodologies [88–90].

Our study highlighted the crucial role of a teacher's TPACK in successful AR integration. While much of the prior research centered on the growth of TPACK through reflective practice [91,92], a limited number have zeroed in on the classroom level, especially those spanning multiple lesson design–implementation–reflection cycles. Consequently, this research augments existing scholarship by shedding light on the role of a science teacher's TPACK within hands-on pedagogy [69] (refer to Table 3).

5.3. Conclusions

This study can be regarded as one of the very few studies that addresses the lack of literature investigating a biology teacher's pedagogical reasoning and action, through a detailed, iterative approach encompassing pedagogical and contextual analysis, design, implementation, reflection, and revision of AR instruction alongside the teacher's evolving TPACK expertise. In this context, the teacher becomes a pedagogical and lesson designer [53]. Specifically, our findings underscore the notion that merely integrating AR does not ensure students' deep learning in biology if the teaching practice does not couple with a pedagogical shift from didactic-based to inquiry-based teaching approaches [79,80]. This could potentially explain cases in which many teachers have a positive perception of the effectiveness of integrating AR into biology teaching, yet the actual student learning outcomes may not align with their expectations [82,83]. For instance, a comparison study was conducted to examine the effects of AR activities in a ninth-grade biology course and found that there were no significant differences between the academic scores of the experimental group who studied three-dimensional biology content and videos on tablets using AR apps and the control group who studied the pictures and samples in textbooks [81].

Throughout the iterative pedagogical design experience, Jenny increasingly harnessed resources and leaned on her professional network to bolster her expertise and self-confidence in weaving AR into her teaching toolbox. This trajectory highlights her transition towards a more efficacious technology-integrated pedagogical approach. Jenny's narrative underscores the significance of iterative cycles in pedagogical enhancement through technology. The outcomes from each cycle offer a reflective foundation for cultivating fresh insights or "comprehensions" [67], which can be exchanged with peers and serve as a springboard for renewed endeavors. The TIP model champions this iterative philosophy, framing it as a routine model valuable for educators aiming to incorporate digital tools in their teaching practices [73]. While Jenny's experience offers a comprehensive and persistent snapshot of PR&A in action, we advocate for expanded research that delves into the characteristics, scope, and regularity of PR&A in the realm of technology integration. Such investigations should explore variations in PR&A dynamics across different educator profiles: from novices to seasoned educators, from isolated teachers to those embedded in learning collectives, from technology-savvy educators to those just dipping their toes in the digital world. A pertinent inquiry would also be the duration of engagement in the PR&A cycle: does it span mere hours, extend over a day, or span weeks of immersive learning?

This study has several limitations. First, we concentrated exclusively on the pedagogical reasoning and action and the related TPACK development of a single teacher, Jenny, in connection to lesson designs with AR. To gain a broader insight, it would be beneficial to study these processes with several teachers from the same TLC, particularly those with varied educational backgrounds or previous technological experiences. Second, the duration of our study was limited to 10 weeks. It is plausible that, given more time and increased familiarity with AR's potential, Jenny might have further refined her pedagogical strategies and use of the technology. Finally, our findings, though insightful, are primarily applicable to the specific educational setting we studied (i.e., a secondary school). To derive broader implications, it would be beneficial to examine the PR&A approach in varied teaching contexts, like elementary schools or higher education institutions. This would enable us to draw conclusions that can be applied or tailored to diverse educational scenarios.

Author Contributions: Conceptualization, H.-P.H., Y.H.C. and J.E.H.; methodology, H.-P.H. and Y.H.C. and J.E.H.; investigation, H.-P.H.; data curation, H.-P.H.; writing—original draft preparation, H.-P.H. and Y.H.C.; writing—review and editing H.-P.H. and Y.H.C. and J.E.H.; supervision, J.E.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of the University of Texas at Austin (protocol code 2016-10-0034 and date of approval: 10 February 2017).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data is available from the corresponding author and can be provided upon a reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Teacher Semi-Structured Interview Protocol

Weekly Progress Interview Questions:

- Can you provide an overview of the progress you made this week in terms of designing the AR-enhanced biology lesson?
- What specific achievements or successes did you experience this week?
- Did you make any updates to your lesson this week, including the use of AR technology, instructional content, or teaching methods? If yes, what updates did you make and for what reasons?
- What challenges did you encounter this week, and how do you plan to overcome them?
- How did your participation in the weekly teacher learning community impact your design of the AR-enhanced biology lesson?
- How are you preparing for next week's AR lesson? [*This set of questions was asked in Week 4 and 8 before teaching the AR lesson].
    - Do you believe the incorporation of AR technology will be advantageous for students? If so, what's your reasoning?
    - What challenges do you expect to encounter, and how do you plan to deal with them?
    - Did you seek support from others?

Post AR-enhanced Lesson Interview Questions:

- What specific achievements or successes have you experienced in implementing the biology lesson with AR this week? Are there any noteworthy moments or student reactions you'd like to share?
- What insights can you share about the impact of AR on your students' learning outcomes? Have you seen any improvements in their understanding of biology concepts or their overall engagement with the subject?
- What challenges did you encounter during this week of implementing the AR-enhanced lesson? How do you plan to overcome these challenges?
- How have your students responded to the AR learning activity this week? Have you received any feedback from them that has informed your approach or improvements?
- How did the feedback from the teacher learning community members influence your instructional approach as you progressed through the AR teaching experience? Can you provide examples of specific feedback-driven changes?
- What are the key lessons you've learned about using AR for biology instruction? Are there any best practices or strategies you would recommend to other educators considering similar approaches?

References

1. Anil, Ö.; Batdi, V. Use of augmented reality in science education: A mixed-methods research with the multi-complementary approach. *Educ. Inf. Technol.* **2023**, *28*, 5147–5185. [CrossRef]
2. Oliveira, A.; Feyzi Behnagh, R.; Ni, L.; Mohsinah, A.A.; Burgess, K.J.; Guo, L. Emerging technologies as pedagogical tools for teaching and learning science: A literature review. *Hum. Behav. Emerg. Technol.* **2019**, *1*, 149–160. [CrossRef]
3. Mikropoulos, T.A.; Iatraki, G. Digital technology supports science education for students with disabilities: A systematic review. *Educ. Inf. Technol.* **2023**, *28*, 3911–3935. [CrossRef]
4. Azuma, R.T. A survey of augmented reality. *Presence Teleoperators Virtual Environ.* **1997**, *6*, 355–385. [CrossRef]
5. Ewais, A.; Troyer, O.D. A Usability and Acceptance Evaluation of the Use of Augmented Reality for Learning Atoms and Molecules Reaction by Primary School Female Students in Palestine. *J. Educ. Comput. Res.* **2019**, *57*, 1643–1670. [CrossRef]
6. Klopfer, E.; Squire, K. Environmental Detectives—The development of an augmented reality platform for environmental simulations. *Educ. Technol. Res. Dev.* **2008**, *56*, 203–228. [CrossRef]
7. Demircioglu, T.; Karakus, M.; Ucar, S. The Impact of Augmented Reality-Based Argumentation Activities on Middle School Students' Academic Achievement and Motivation in Science Classes. *Educ. Q. Rev.* **2022**, *5*, 22–34. [CrossRef]
8. Yildirim, I.; Kapucu, M.S. The effect of augmented reality applications in science education on academic achievement and retention of 6th grade students. *J. Educ. Sci. Environ. Health* **2021**, *7*, 56–71. [CrossRef]
9. Wu, H.-K.; Lee, S.W.-Y.; Chang, H.-Y.; Liang, J.-C. Current status, opportunities and challenges of augmented reality in education. *Comput. Educ.* **2013**, *62*, 41–49. [CrossRef]
10. Kul, H.H.; Berbe, A. The Effects of Augmented Reality in a 7th-Grade Science Lesson on Students' Academic Achievement and Motivation. *J. Sci. Learn.* **2022**, *5*, 193–203. [CrossRef]

11. Fidan, M.; Tuncel, M. Integrating augmented reality into problem based learning: The effects on learning achievement and attitude in physics education. *Comput. Educ.* **2019**, *142*, 103635. [CrossRef]
12. Sirakaya, M.; Alsancak Sirakaya, D. Trends in Educational Augmented Reality Studies: A Systematic Review. *Malays. Online J. Educ. Technol.* **2018**, *6*, 60–74. [CrossRef]
13. Radu, I.; Joy, T.; Bott, I.; Bowman, Y.; Schneider, B. A Survey of Educational Augmented Reality in Academia and Practice: Effects on Cognition, Motivation, Collaboration, Pedagogy and Applications. In Proceedings of the 2022 8th International Conference of the Immersive Learning Research Network (iLRN), Vienna, Austria, 30 May–4 June 2022; pp. 1–8.
14. Al-Ansi, A.M.; Jaboob, M.; Garad, A.; Al-Ansi, A. Analyzing augmented reality (AR) and virtual reality (VR) recent development in education. *Soc. Sci. Humanit. Open* **2023**, *8*, 100532. [CrossRef]
15. Schutera, S.; Schnierle, M.; Wu, M.; Pertzel, T.; Seybold, J.; Bauer, P.; Teutscher, D.; Raedle, M.; Heß-Mohr, N.; Röck, S.; et al. On the Potential of Augmented Reality for Mathematics Teaching with the Application cleARmaths. *Educ. Sci.* **2021**, *11*, 368. [CrossRef]
16. Romano, M.; Díaz, P.; Aedo, I. Empowering teachers to create augmented reality experiences: The effects on the educational experience. *Interact. Learn. Environ.* **2023**, *31*, 1546–1563. [CrossRef]
17. Del Cerro Velázquez, F.; Morales Méndez, G. Application in Augmented Reality for Learning Mathematical Functions: A Study for the Development of Spatial Intelligence in Secondary Education Students. *Mathematics* **2021**, *9*, 369. [CrossRef]
18. Kapp, S.; Thees, M.; Strzys, M.P.; Beil, F.; Kuhn, J.; Amiraslanov, O.; Javaheri, H.; Lukowicz, P.; Lauer, F.; Rheinländer, C.; et al. Augmenting Kirchhoff's laws: Using augmented reality and smartglasses to enhance conceptual electrical experiments for high school students. *Phys. Teach.* **2019**, *57*, 52–53. [CrossRef]
19. Yoon, S.A.; Anderson, E.; Park, M.; Elinich, K.; Lin, J. How Augmented Reality, Textual, and Collaborative Scaffolds Work Synergistically to Improve Learning in a Science Museum. *Res. Sci. Technol. Educ.* **2018**, *36*, 261–281. [CrossRef]
20. Akçayır, M.; Akçayır, G. Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educ. Res. Rev.* **2017**, *20*, 1–11. [CrossRef]
21. Arici, F.; Yildirim, P.; Caliklar, Ş.; Yilmaz, R.M. Research trends in the use of augmented reality in science education: Content and bibliometric mapping analysis. *Comput. Educ.* **2019**, *142*, 103647. [CrossRef]
22. Perifanou, M.; Economides, A.A.; Nikou, S.A. Teachers' Views on Integrating Augmented Reality in Education: Needs, Opportunities, Challenges and Recommendations. *Future Internet* **2023**, *15*, 20. [CrossRef]
23. Larke, L.R. Agentic neglect: Teachers as gatekeepers of England's national computing curriculum. *Br. J. Educ. Technol.* **2019**, *50*, 1137–1150. [CrossRef]
24. Tondeur, J.; Braak, J.; Ertmer, P.; Ottenbreit-Leftwich, A. Understanding the relationship between teachers' pedagogical beliefs and technology use in education: A systematic review of qualitative evidence. *Educ. Technol. Res. Dev.* **2017**, *65*, 555–575. [CrossRef]
25. Tzima, S.; Styliaras, G.; Bassounas, A. Augmented Reality Applications in Education: Teachers Point of View. *Educ. Sci.* **2019**, *9*, 99. [CrossRef]
26. Ibáñez, M.-B.; Delgado-Kloos, C. Augmented reality for STEM learning: A systematic review. *Comput. Educ.* **2018**, *123*, 109–123. [CrossRef]
27. Arici, F.; Yilmaz, R.M.; Yilmaz, M. Affordances of augmented reality technology for science education: Views of secondary school students and science teachers. *Hum. Behav. Emerg. Technol.* **2021**, *3*, 1153–1171. [CrossRef]
28. Mishra, P.; Koehler, M.J. Technological pedagogical content knowledge: A framework for teacher knowledge. *Teach. Coll. Rec.* **2006**, *108*, 1017–1054. [CrossRef]
29. Saidin, N.F.; Halim, N.D.A.; Yahaya, N. A review of research on augmented reality in education: Advantages and applications. *Int. Educ. Stud.* **2015**, *8*, 1–8. [CrossRef]
30. Fuchsova, M.; Korenova, L. Visualisation in Basic Science and Engineering Education of Future Primary School Teachers in Human Biology Education Using Augmented Reality. *Eur. J. Contemp. Educ.* **2019**, *8*, 92–102. [CrossRef]
31. Kozcu Cakir, N.; Guven, G.; Celik, C. Integration of Mobile Augmented Reality (MAR) Applications into the 5E Learning Model in Biology Teaching. *Int. J. Technol. Educ.* **2021**, *4*, 93–112. [CrossRef]
32. Chen, J.; Zhou, Y.; Zhai, J. Incorporating AR/VR-assisted learning into informal science institutions: A systematic review. *Virtual Real.* **2023**, *27*, 1985–2001. [CrossRef]
33. National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; National Academies Press: Washington, DC, USA, 2012.
34. Next Generation Science Standards. The Next Generation Science Standards. Available online: http://www.nextgenscience.org/ (accessed on 18 October 2023).
35. Department of Education and Skills. *STEM Education Policy Statement 2017–2026*; Department of Education and Skills: Dublin, Ireland, 2017.
36. Mayer, R.E. Rote versus meaningful learning. *Theory Pract.* **2002**, *41*, 226–232. [CrossRef]
37. Howland, J.L.; Jonassen, D.; Marra, R.M. *Meaningful Learning with Technology*, 4th ed.; Allyn & Bacon: Boston, MA, USA, 2012.
38. Ertmer, P.A. Addressing first- and second-order barriers to change: Strategies for technology integration. *Educ. Technol. Res. Dev.* **1999**, *47*, 47–61. [CrossRef]
39. Ilona-Elefteryja, L.; Meletiou-Mavrotheris, M.; Katzis, K. Augmented Reality in Lower Secondary Education: A Teacher Professional Development Program in Cyprus and Greece. *Educ. Sci.* **2020**, *10*, 121. [CrossRef]

40. Çetin, H. A Systematic Review of Studies on Augmented Reality Based Applications in Primary Education. *Int. J. Educ. Lit. Stud.* **2022**, *10*, 110–121. [CrossRef]
41. Mei, B.; Yang, S. Chinese pre-service music teachers' perceptions of augmented reality-assisted musical instrument learning. *Front. Psychol.* **2021**, *12*, 609028. [CrossRef]
42. Dunleavy, M.; Dede, C.; Mitchell, R. Affordances and Limitations of Immersive Participatory Augmented Reality Simulations for Teaching and Learning. *J. Sci. Educ. Technol.* **2008**, *18*, 7–22. [CrossRef]
43. Alkhattabi, M. Augmented Reality as E-learning Tool in Primary Schools' Education: Barriers to Teachers' Adoption. *Int. J. Emerg. Technol. Learn.* **2017**, *12*, 91–100. [CrossRef]
44. Osuna, J.B.; Gutiérrez-Castillo, J.; Llorente-Cejudo, M.; Ortiz, R.V. Difficulties in the incorporation of augmented reality in university education: Visions from the experts. *J. New Approaches Educ. Res.* **2019**, *8*, 126–141. [CrossRef]
45. Chang, H.-Y.; Wu, H.-K.; Hsu, Y.-S. Integrating a mobile augmented reality activity to contextualize student learning of a socioscientific issue. *Br. J. Educ. Technol.* **2013**, *44*, E95–E99. [CrossRef]
46. Huang, T.-C.; Chen, C.-C.; Chou, Y.-W. Animating eco-education: To see, feel, and discover in an augmented reality-based experiential learning environment. *Comput. Educ.* **2016**, *96*, 72–82. [CrossRef]
47. Mundy, M.-A.; Hernandez, J. Perceptions of the effects of augmented reality in the classroom. *J. Instr. Pedagog.* **2019**, *22*, 1–15.
48. Chiang, T.H.C.; Yang, S.J.H.; Hwang, G.-J. Students' online interactive patterns in augmented reality-based inquiry activities. *Comput. Educ.* **2014**, *78*, 97–108. [CrossRef]
49. Alzahrani, N.M. Augmented reality: A systematic review of its benefits and challenges in e-learning contexts. *Appl. Sci.* **2020**, *10*, 5660. [CrossRef]
50. Yoon, S.A.; Elinich, K.; Wang, J.; Steinmeier, C.; Tucker, S. Using augmented reality and knowledge-building scaffolds to improve learning in a science museum. *Int. J. Comput. -Support. Collab. Learn.* **2012**, *7*, 519–541. [CrossRef]
51. Delello, J.A. Insights from pre-service teachers using science-based augmented reality. *J. Comput. Educ.* **2014**, *1*, 295–311. [CrossRef]
52. Buchner, J.; Zumbach, J. Augmented Reality in Teacher Education. A Frameowkr to Support Teachers' Technological Pedagogical Content Knowledge. *Ital. J. Educ. Technol.* **2020**, *28*, 106–120. [CrossRef]
53. Tsai, C.-C.; Chai, C.S. The" third"-order barrier for technology-integration instruction: Implications for teacher education. *Australas. J. Educ. Technol.* **2012**, *28*, 1057–1060. [CrossRef]
54. George, A.; Sanders, M. Evaluating the potential of teacher-designed technology-based tasks for meaningful learning: Identifying needs for professional development. *Educ. Inf. Technol.* **2017**, *22*, 2871–2895. [CrossRef]
55. Lee, C.B. Initial development of the Meaningful Learning with Technology Scale (MeLTS) for high-school students. *Interact. Learn. Environ.* **2018**, *26*, 163–174. [CrossRef]
56. Sun, J.; Ma, H.; Zeng, Y.; Han, D.; Jin, Y. Promoting the AI teaching competency of K-12 computer science teachers: A TPACK-based professional development approach. *Educ. Inf. Technol.* **2023**, *28*, 1509–1533. [CrossRef]
57. Luo, F.; Ijeluola, S.A.; Westerlund, J.; Walker, A.; Denham, A.; Walker, J.; Young, C. Supporting Elementary Teachers' Technological, Pedagogical, and Content Knowledge in Computational Thinking Integration. *J. Sci. Educ. Technol.* **2023**, *32*, 583–596. [CrossRef]
58. Chai, C.S.; Koh, J.H.L.; Chin-Chung, T. A review of technological pedagogical content knowledge. *J. Educ. Technol. Soc.* **2013**, *16*, 31–51.
59. Chittleborough, G. Learning How to Teach Chemistry with Technology: Pre-Service Teachers' Experiences with Integrating Technology into Their Learning and Teaching. *J. Sci. Teach. Educ.* **2014**, *25*, 373–393. [CrossRef]
60. Habowski, T.; Mouza, C. Pre-Service Teachers' Development of Technological Pedagogical Content Knowledge (TPACK) in the Context of a Secondary Science Teacher Education Program. *J. Technol. Teach. Educ.* **2014**, *22*, 471–495.
61. Maeng, J.L.; Mulvey, B.K.; Smetana, L.K.; Bell, R.L. Preservice Teachers' TPACK: Using Technology to Support Inquiry Instruction. *J. Sci. Educ. Technol.* **2013**, *22*, 838–857. [CrossRef]
62. Qasem, A.A.A.; Viswanathappa, G. Blended Learning Approach to Develop the Teachers' TPACK. *Contemp. Educ. Technol.* **2016**, *7*, 264–276. [CrossRef] [PubMed]
63. Cheah, Y.H.; Chai, C.S.; Toh, Y. Traversing the context of professional learning communities: Development and implementation of Technological Pedagogical Content Knowledge of a primary science teacher. *Res. Sci. Technol. Educ.* **2019**, *37*, 147–167. [CrossRef]
64. Aktaş, İ.; Özmen, H. Investigating the impact of TPACK development course on pre-service science teachers' performances. *Asia Pac. Educ. Rev.* **2020**, *21*, 667–682. [CrossRef]
65. Bennett, S.; Lockyer, L.; Agostinho, S. Towards sustainable technology-enhanced innovation in higher education: Advancing learning design by understanding and supporting teacher design practice. *Br. J. Educ. Technol.* **2018**, *49*, 1014–1026. [CrossRef]
66. Brown, M.W. The teacher-tool relationship: Theorizing the design and use of curriculum materials. In *Mathematics Teachers at work: Connecting Curriculum Materials and Classroom Instruction*; Remillard, J.T., Herbel-Eisenmann, B.A., Lloyd, G.M., Eds.; Routledge: New York, NY, USA; London, UK, 2009; pp. 37–56.
67. Shulman, L. Knowledge and teaching: Foundations of the new reform. *Harv. Educ. Rev.* **1987**, *57*, 1–23. [CrossRef]
68. Kozcu, J.; Phillips, M. If there's TPACK, is there technological pedagogical reasoning and action? In *Proceedings of the Society for Information Technology & Teacher Education International Conference*; Association for the Advancement of Computing in Education (AACE): Washington, DC, USA, 2018; pp. 2051–2061.
69. Loveless, A. Technology, pedagogy and education: Reflections on the accomplishment of what teachers know, do and believe in a digital age. *Technol. Pedagog. Educ.* **2011**, *20*, 301–316. [CrossRef]

70. Ekanayake, T.M.S.S.K.Y.; Wishart, J.M. Developing teachers' pedagogical practice in teaching science lessons with mobile phones. *Technol. Pedagog. Educ.* **2014**, *23*, 131–150. [CrossRef]
71. Şimşek, B.; Direkçi, B. The effects of augmented reality storybooks on student's reading comprehension. *Br. J. Educ. Technol.* **2023**, *54*, 754–772. [CrossRef]
72. Schmidthaler, E.; Anđic, B.; Schmollmüller, M.; Sabitzer, B.; Lavicza, Z. Mobile Augmented Reality in Biological Education: Perceptions of Austrian Secondary School Teachers. *J. Effic. Responsib. Educ. Sci.* **2023**, *16*, 113–127. [CrossRef]
73. Hughes, J.E.; Roblyer, M.D. *Integrating Educational Technology into Teaching: Transforming Learning Across Disciplines*, 9th ed.; Pearson: Boston, MA, USA, 2022.
74. Yin, R.K. *Case Study Research Design and Methods*, 4th ed.; Sage: London, UK, 2009.
75. Scott, K.M. Does a University Teacher Need to Change e-Learning Beliefs and Practices When Using a Social Networking Site? A Longitudinal Case Study. *Br. J. Educ. Technol.* **2013**, *44*, 571–580. [CrossRef]
76. Patton, M.Q. Enhancing the quality and credibility of qualitative analysis. *Health Serv. Res.* **1999**, *34*, 1189. [PubMed]
77. DeCuir-Gunby, J.T.; Marshall, P.L.; McCulloch, A.W. Developing and using a codebook for the analysis of interview data: An example from a professional development research project. *Field Methods* **2011**, *23*, 136–155. [CrossRef]
78. Bull, G.; Spector, J.M.; Persichitte, K. Preliminary recommendations regarding preparation of teachers and school leaders to use learning technologies. *Contemp. Issues Technol. Teach. Educ.* **2017**, *17*, 1–9.
79. Yang, K.-T.; Wang, T.-H.; Chiu, M.-H. How technology fosters learning: Inspiration from the "media debate". *Creat. Educ.* **2014**, *5*, 1086–1090. [CrossRef]
80. Becker, K. The clark-kozma debate in the 21-st century. In Proceedings of the CNIE Conference 2010, Heritage matters: Inspiring Tomorrow, Saint John, NB, Canada, 16–19 May 2010.
81. Erbas, C.; Demirer, V. The effects of augmented reality on students' academic achievement and motivation in a biology course. *J. Comput. Assist. Learn.* **2019**, *35*, 450–458. [CrossRef]
82. Yapici, I.Ü.; Karakoyun, F. Using augmented reality in biology teaching. *Malays. Online J. Educ. Technol.* **2021**, *9*, 40–51. [CrossRef]
83. Savela, N.; Oksanen, A.; Kaakinen, M.; Noreikis, M.; Xiao, Y. Does augmented reality affect sociability, entertainment, and learning? A field experiment. *Appl. Sci.* **2020**, *10*, 1392. [CrossRef]
84. Clarke, D.; Hollingsworth, H. Elaborating a model of teacher professional growth. *Teach. Teach. Educ.* **2002**, *18*, 947–967. [CrossRef]
85. Lawless, K.A.; Pellegrino, J.W. Professional development in integrating technology into teaching and learning: Knowns, unknowns, and ways to pursue better questions and answers. *Rev. Educ. Res.* **2007**, *77*, 575–614. [CrossRef]
86. Agyei, D.D.; Voogt, J. Developing technological pedagogical content knowledge in pre-service mathematics teachers through collaborative design. *Australas. J. Educ. Technol.* **2012**, *28*, 547–564. [CrossRef]
87. Baran, E.; Uygun, E. Putting technological, pedagogical, and content knowledge (TPACK) in action: An integrated TPACK-design-based learning (DBL) approach. *Australas. J. Educ. Technol.* **2016**, *32*, 47–63. [CrossRef]
88. Blanchard, M.R.; LePrevost, C.E.; Tolin, A.D.; Gutierrez, K.S. Investigating technology-enhanced teacher professional development in rural, high-poverty middle schools. *Educ. Res.* **2016**, *45*, 207–220. [CrossRef]
89. Kimmons, R.; Miller, B.G.; Amador, J.; Desjardins, C.D.; Hall, C. Technology integration coursework and finding meaning in pre-service teachers' reflective practice. *Educ. Technol. Res. Dev.* **2015**, *63*, 809–829. [CrossRef]
90. Voet, M.; De Wever, B. Towards a differentiated and domain-specific view of educational technology: An exploratory study of history teachers' technology use. *Br. J. Educ. Technol.* **2017**, *48*, 1402–1413. [CrossRef]
91. Harris, J.B.; Hofer, M.J. Technological Pedagogical Content Knowledge (TPACK) in Action: A Descriptive Study of Secondary Teachers' Curriculum-Based, Technology-Related Instructional Planning. *J. Res. Technol. Educ.* **2011**, *43*, 211–229. [CrossRef]
92. Lu, L. Cultivating Reflective Practitioners in Technology Preparation: Constructing TPACK through Reflection. *Educ. Sci.* **2014**, *4*, 13–35. [CrossRef]