

Article

Empowering Diverse Learners: Integrating Writing-to-Learn Strategies in a Middle School Science Classroom in the U.S.

So Lim Kim ^{1,*} and Deoksoon Kim ² 

¹ Department of Adolescence Education & TESOL, School of Education, State University of New York at New Paltz, New Paltz, NY 12561, USA

² Department of Teaching, Curriculum, and Society, Lynch School of Education and Human Development, Boston College, Chestnut Hill, MA 02467, USA; deoksoon.kim@bc.edu

* Correspondence: kims23@newpaltz.edu

Abstract: Science education has shifted towards emphasizing science literacy rather than simply memorizing facts. Studies have shown that incorporating writing in science education engages students in higher-order thinking, fosters critical reasoning skills, and deepens subject matter comprehension. However, writing can be particularly challenging for CLD (culturally and linguistically diverse) students due to content-specific vocabulary and distinctive grammatical patterns. This case study explores six CLD students' experiences with writing in a seventh-grade science classroom in the northeastern United States that used invention-based learning (IBL). By incorporating hands-on invention processes, IBL facilitates problem-solving and student-centered learning. The study shows how a writing-to-learn approach in science education can simultaneously support CLD students in developing a scientific understanding of abstract concepts and address the need for science literacy skills. The implications of this study suggest that teachers should integrate writing-to-learn strategies into their science instruction to promote deeper understanding and improve science literacy. By supporting students through productive struggles with writing and providing opportunities to practice scientific language, teachers can help students develop critical thinking skills and better comprehension of scientific concepts. In addition, by connecting hands-on experiences with writing tasks, educators can make science more accessible and engaging for students, particularly those from diverse linguistic and cultural backgrounds.

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1. Introduction

As technology advances, science education has evolved from an emphasis on memorizing facts to helping students develop science literacy [1,2]. This means cultivating students' abilities to solve problems and establish connections between scientific concepts and real-world scenarios, to meet the demands of contemporary society [3]. New curriculum standards and frameworks have emerged, aiming to empower teachers in promoting higher-order thinking and critical reasoning skills among all students [4–7]. Among various strategies used to reach these educational objectives, writing stands out as one particularly valuable tool [2,8,9]. Writing requires cognitive processes that significantly aids learners in constructing meaning [2,8,9]. When deliberately integrated into instruction, writing-to-learn is especially effective in enhancing students' understanding of science content [10–12]. Numerous studies have underscored the benefits writing has for engaging students in higher-order thinking, fostering critical reasoning skills, and deepening subject matter comprehension [10,11,13–15]. Through writing, students clarify their grasp of content, generate new ideas, and apply acquired knowledge to real-life contexts [11,15,16].

However, many students find writing challenging. This can be particularly true for culturally and linguistically diverse (CLD) students, whose linguistic and cultural

backgrounds are different from many of their peers and teachers [17,18]. CLD students who use more than one language at home or in the community may find it challenging to complete school-based writing tasks, which in the US are typically in English. Unlike oral language, proficiency with written language does not develop naturally through social interactions [19,20]. Furthermore, the language of science can be particularly challenging to understand due to content-specific vocabulary and distinctive grammatical patterns [1]. To make full use of writing in support of science learning, educators must appropriately and intentionally incorporate thoughtful writing instruction into science curriculum and instruction [1,21]. Such intentional instructional work is challenging but worth careful study as the field seeks increasingly effective ways to support CLD students [1].

This study explored CLD students' writing experiences in an invention-based learning (IBL) science classroom, to understand how students perceived writing as supportive of their science learning. IBL is a type of project-based learning pedagogy emphasizing collaboration and the invention process, as a means of building understanding [22]. IBL is inherently hands-on and oriented to problem solving, and it also aims to foster student interest [22–24]. Through IBL teachers facilitate learning engagements where students use scientific knowledge, practice thinking processes, design, invent, and come to understand for themselves how to apply science in the wider world [22–24]. As both IBL and writing are distinctive but effective pedagogical methods to engage students in learning and developing science literacy, teachers can use them together to meet the needs of diverse students by providing creative and supportive opportunities for them to apply knowledge in practice [22–25].

While there is much research demonstrating the effects of writing-to-learn in general science education, very little research has been carried out in invention-based learning environments in K-12 settings [22,23]. This study addresses this gap in the research by exploring what six CLD students in an IBL classroom wrote about their science-based learning, and what they said about their experiences with science writing. This study also explores the ways writing supported students' knowledge development and learning transfer. In an effort to understand how writing impacted students' science literacy development, the study posed the following questions:

- How do CLD students perceive and experience writing in an IBL program?
- In what observable ways does CLD students' scientific knowledge and application of that knowledge change through writing?

2. Literature Review

This paper builds on previous research [2,8–10,13,25] related to how writing serves learning by addressing (1) the particular language challenges of science, (2) writing-to-learn in science, (3) the concept of forward search in writing, and (4) knowledge transfer in writing.

2.1. Language of Science

According to research studies [26–28], many science teachers spend relatively little time on writing tasks and do not view teaching language and literacy as part of their responsibilities within science education. This troubling fact means many science teachers misunderstand the ways their subject area heavily relies on language and literacy to communicate and exchange science-based knowledge [1,29,30].

Moreover, the language of science uses distinct discourse patterns, which make science language and literacy development even more challenging and important for teachers to help students access [31]. The language of science can be impersonal and even authoritative in nature [1,21]. It relies on patterns of logical reasoning that differ significantly from students' daily dialogues. For example, instead of using conjunctions, such as 'because' and 'but', to directly connect ideas, science textbooks often use other words, such as 'cause', 'result', and 'occur', to imply relationships and connections [1]. Additionally, science

texts often use dense noun groups, making them even more challenging for students to comprehend [20,30–32].

Accordingly, many scholars emphasize the importance of language instruction and writing practices in science to support student comprehension and access to science content [1,8,15,23,31]. Brisk and Zhang-Wu [31] argue that students must be taught to use subject-specific academic language; students also need to see others use and rehearse using such language in their own literacy tasks. Such practices enhance students' ability to develop their comprehension alongside their science-based academic language [1,10,21,30,31].

2.2. *Writing-to-Learn in Science*

Writing-to-learn is a pedagogical practice designed to support students in developing subject-specific academic language [10,25]. Yet the process of writing-to-learn is also composed of challenging sub-skills that are important for students to experience [2]. Engaging in the writing process means that writers must reflect and elaborate on learned content, formulating ideas, analyzing, identifying, drafting, and revising [2,33]. Such practices demand much of writers and can significantly strengthen students' knowledge and understanding of academic subjects as they productively struggle with such tasks [1,2,34–36].

Although this process of “productive struggles” can be seen as time-consuming and somewhat counterproductive compared to simply answering questions on the learned concepts, the struggle to conceptualize understanding is a crucial element of deepening comprehension of the subject matter [37–39]. As students participate in such processes, they not only develop their language, but gain a deeper understanding of scientific concepts and strengthen their higher-order thinking skills [2,9,16,37–39].

Several key studies demonstrate how useful writing can be to helping students develop critical thinking skills [2,8,9,13], deepen their metacognitive awareness [40], and make connections between science and their daily lives [10]. According to Fang et al. [1] students who write in their science classrooms develop a deep understanding of science, clarify and consolidate their knowledge, and connect science to their daily lives. As they write, students learn how to clarify their ideas and develop critical thinking [1,2,9,27].

Research, such as the study of Hand et al. [41] of high school students' writing, suggests that the writing process helped students improve their metacognition and knowledge related to chemistry concepts. Students who engaged in a writing activity spent more time thinking about what they had learned, and their writing enabled them to explain concepts that a control group could not explain [41]. The revision process also enhances students' understanding of content [27,33,41]. For students who revised, “the second draft [of their writing] was crucial in allowing [students] to better engage with the science concepts and the language requirements of the task” [41] (p. 140). The act of revising in writing attuned students to monitor their text for contradictions, which led them to reconcile their (sometimes inaccurate) prior knowledge with new learning [41].

2.3. *Forward Search in Writing*

In addition, numerous studies indicate the apparent usefulness of the revision process for supporting students' science-based learning [27,33,41]. This work began most prominently in 1999, when Klein [33] presented four hypotheses about writing-to-learn. He argued that students develop new knowledge when they are supported in revisiting and reorganizing their initial writing. Students who do so engage in a “forward search”, or a process of reconstructing their knowledge as they rewrite compositions that they developed in the initial stages of their learning [33] (p. 211).

Within a forward search process, students repeatedly visit their initial drafts to identify and resolve contradictions or expand ideas in their writing [33]. Such thinking requires them to reevaluate their thinking and expand their capacity to infer more accurately about the world [27,33,34]. According to Hand et al. [41]:

[Writers] transform their ideas by ongoing analyses of their texts in terms of expanding inferences, reviewing idea development, noting contradictions, and

making appropriate revisions. In this view the writer learns from writing by attending to, and clarifying, the emerging meanings of the text. (p. 740)

Forward search is not limited to writing; it is a notion applicable to any kind of learning experience where students make inferences as part of a problem-solving process [34]. For instance, Klein's [34] research described how elementary students engaged in forward searching by reviewing experimental results to generate ideas and expand their inferences to solve problems. When students write to generate ideas, they effectively broaden and deepen their knowledge and relate their learning to their everyday experiences [2,42].

2.4. Knowledge Transfer in Writing

The reflective process of writing also supports learners in transferring knowledge from one context to another [43]. Since writing is inherently a process of discovery [43,44], it enables students to restructure their existing knowledge to generate new ideas. According to Flower and Hayes [45], such a process enables writers to "consciously...probe for analogues and contradictions, to form new concepts, and perhaps even to restructure their knowledge of the subject" (p. 28). This process of reconstruction is closely related to the process of knowledge transfer, or a means by which learners apply knowledge from a known context to an unfamiliar one.

Although knowledge transfer mechanisms are not universally defined, many studies have found crucial factors that facilitate knowledge transfer [8,9,44,46–48]. Students must be active participants in learning and have access to multiple examples of content linkages from one context to others, and they must also have some proficiency in terms of the content to carry out this work effectively [8,22,48,49]. Teachers effectively facilitate this for students by helping them be actively engaged in the learning process through interest-driven or highly motivating activities [8,22]. Learners must also be able to explore multiple examples of the same content in contexts that are linked to each other [8,9,49]. According to Engle [49], intercontextuality, or awareness of the links between two contexts, is important in helping students transfer knowledge. Without sufficient context to help them understand how the knowledge fits in various contexts, it is difficult for them to apply knowledge from one context to another [9,49]. Lastly, learners must be able to cultivate a deep understanding of content [50,51] to facilitate knowledge transfer. Learners who benefit from these conditions have increased opportunities and capability to extend their knowledge not only to different school-based contexts, but also to their lives outside of school [22,23].

Even though developing knowledge and effectively applying it to wider contexts is often considered the ultimate goal of education, many studies demonstrate that schools do not often reach this goal of helping students transfer their learning from school to the wider world [46,52]. Writing can help support this process because it not only engages students in a reflective process but enables them to flexibly reconstruct knowledge and apply it in multiple contexts [23,42,45].

3. Methodology

The multiple case study at the center of this article explored this writing-to-learn experience for six CLD students participating in an IBL-based science curriculum. Each student constituted a case, offering an in-depth analysis [53] of students' writing experiences both within and across the six cases. The following sections introduce the study's context, the participating students and teacher, along with the data sources and analytic processes for this study.

3.1. Context

This study was part of a joint effort among two universities and a public school district in the northeastern United States. Together with the Brown Public School District (BPSD) (pseudonym), we developed and implemented a STEM program for middle school students, with a special focus on the student groups underrepresented in STEM fields. The program utilized Lemelson-MIT's invention-based curriculum, aligned with Next

Generation Science Standards, and tailored for grades 6–10. Specifically, the “Chill Out” unit was adapted for seventh-grade CLD students, integrating culturally relevant activities and aligned writing instructions along with writing-to-learn tasks. In this unit, students build lunch box inventions while learning about heat transfer concepts, such as convection, conduction, and radiation. The curriculum was implemented by six seventh-grade science teachers across two middle schools in the district. This study examined the classroom of one of the six science teachers, Mr. Lee, and six of his CLD students during the 2019–2020 school year.

3.2. Procedures and Content

3.2.1. The Chill Out Curriculum

In the Chill Out program, students learned about heat transfer concepts, like convection, conduction, radiation, insulation, and thermal equilibrium. Mr. Lee guided them through class lessons and hands-on activities exploring insulation, the thermoelectric effect, and heat transfer prevention materials. Students then applied their knowledge to real-world problems, designing lunchboxes to maintain food temperatures. Working in groups of three to four, students used various materials, like shoe boxes, aluminum foil, bubble wrap, and old clothes, to create their lunchbox inventions. Each group tested their lunchbox’s effectiveness by comparing temperatures with a control test. Based on the results of this experiment, students individually wrote reports framed as patent applications to describe, reflect on, and promote their lunchbox inventions. Mr. Lee provided students with language and writing lessons on how to compose scientific reports. Throughout, students honed their writing skills through writing activities, fostering an inventor’s mindset and effective communication of their ideas.

3.2.2. Writing a Report

Students submitted both an initial and final draft of their report. They received written and oral feedback from Mr. Lee regarding the scientific concepts in their first draft and had an opportunity to revise them with support during school hours. As they wrote, students had the opportunity to discuss the science-based ideas embedded in the lunch box invention they created together and to ask their teacher questions about these ideas in their writing.

3.3. Participants

The student participants in this study were six seventh-grade CLD students. Using a purposive sampling method [53], students were selected based on the three criteria: (1) they self-identified as CLD students, (2) they fully participated in the Chill Out curriculum, and (3) they were willing to participate in initial and follow-up interviews. The participants were CLD students who were deeply embedded in both their heritage cultures and the dominant culture of the United States. All participating students were female, each with heritage roots from different countries, such as Italy, Guatemala, Greece, and others. Despite their varied backgrounds, they all self-identified as CLD students and were either children or grandchildren of immigrants.

3.4. Data Collection

Data for this study included classroom observations during the Chill Out unit, student writing samples, and semi-structured interviews with both students and their teacher, Mr. Lee. SLK, one of the authors of this article, collected field notes in Mr. Lee’s classroom two to three times weekly over the twelve-week period. In addition, two semi-structured interviews were conducted with the six CLD student participants.

3.4.1. Classroom Observations

SLK observed in Mr. Lee’s science classroom for twelve weeks, taking field notes two or three times each week for one hour per visit to gain insight into student participants’

experiences. She recorded as much detail as possible regarding lessons, materials, class activities, small-group interactions, and class interactions. Her observations centered on students' progress in learning and their interactions with peers and teacher. During this fieldwork, she also conducted informal conversations with Mr. Lee, which helped her expand and contextualize her field notes.

3.4.2. Semi-Structured Student Interviews

Two semi-structured interviews were conducted with students, one right after they completed the Chill Out unit and again at the beginning of the following semester. Both interviews were conducted individually during lunch hour in a science classroom. Interview questions were formulated based on the primary research objective: to explore the perceptions of CLD students regarding writing within the IBL program and to assess the evolution of their scientific understanding and its application throughout their writing journey.

The first interviews were conducted individually and took between ten and fifteen minutes per student. This interview included ten questions covering four different topics:

1. Student's demographic information (e.g., "Could you introduce yourself?");
2. Inventing experiences (e.g., "Could you describe your lunch box inventing experience?");
3. Writing experiences (e.g., "What was your experience with writing in the science class?");
4. Perceptions towards writing in science (e.g., "What do you think of writing in science?").

As a form of member-checking [54], SLK conducted follow-up interviews later, which took approximately 50 min. These interviews focused on specific questions about students' prior writing experience in science, changes made between initial and final drafts, and their perception of writing.

3.4.3. Report Writing Drafts

In addition to student interviews, their initial and final report drafts were crucial data sources. These drafts shed light on students' content knowledge development during the Chill Out unit. Initially composed on a computer, the drafts included teacher feedback and students' notes for revision. Comparing initial drafts with final ones allowed her to gauge changes in science knowledge. However, due to lost initial drafts, this comparison was possible for only four of the six participants.

3.5. Data Analysis

SLK, one of the authors of this paper, initiated data analysis by thoroughly reviewing interview transcripts, field notes, and student writing documents. This approach enabled her to gain a comprehensive understanding of students' experiences. Throughout this process, she made general notes in the margins to capture her overall impressions.

3.5.1. Analysis of Interview and Observation Data

Adding interview transcripts and field notes to Atlas.ti, a qualitative data analysis program, marked an early step in analysis. This process consolidated all data sources into individual documents for each student, facilitating the commencement of qualitative thematic analysis [55]. Inductively analyzing these documents allowed for the exploration of both explicit and implicit meanings within students' experiences [56]. To familiarize herself with the data, SLK initially listened to all voice-recorded interviews and read through interview transcripts. This listening phase helped in understanding students' experiences better, capturing nuances, such as tone, reactions, and expressions. Additionally, a thorough review of field notes from classroom observations ensured comprehensive data familiarity.

During the subsequent analysis phase, initial codes (e.g., writing helps clarifying, writing helps remembering, writing makes them to think, and writing helps understanding)

were generated based on the research questions and refined through a cyclical process of addition, combination, and splitting to encompass both interview and observation data. The third phase involved reorganizing codes into thematic categories (e.g., writing supports scientific understanding, benefit of forward searching (revising/ revising drafts), writing helped students understand the lunch box invention project, and benefit of forward searching lunchbox project in writing), ensuring alignment with the dataset through review and comparison. In the fourth stage, transcripts and field notes were meticulously revisited to refine themes, while remaining attentive to emerging codes and themes. The final phase comprised creating a visual report of themes to identify broader patterns within the data. Summarizing each theme into concise statements helped in refining analytic thinking, especially during discussions with an independent researcher to reconcile interpretations and resolve disagreements.

3.5.2. Analysis of Student Writing Documents

SLK employed a deductive content analysis [57] to assess students' writing, which involves evaluating data based on existing theories or frameworks [57]. Initially, she uploaded students' papers to Atlas.ti and coded them using categories derived from Garcia's [58] science literacy framework, further developed by Chiappetta and Fillman [59]. These categories—science as knowledge, investigation, extension, and meaningful interaction with society—served as the analytical lens. The four categories in this framework aligned with broader goals of fostering not just knowledge acquisition but also critical thinking and the application of science. By using this framework, the analysis captured the depth of students' scientific literacy, which is often a key objective in science education. In addition, using these categories as the analytical lens enabled to gain a more nuanced understanding of students' papers; it helped in identifying not just whether students understand scientific concepts, but how they investigated, extended, and applied these concepts in meaningful ways.

While conducting the analysis, she remained receptive to emergent ideas. To ensure systematic analysis, she developed definitions for each category and highlighted relevant sentences in students' compositions. Additionally, she cross-referenced Mr. Lee's rubric scores and her observations in students' compositions, followed by discussions with Mr. Lee to validate her findings. Seeking rigorous analytic processes [60], she crafted descriptive sentences for each category and engaged an independent researcher to compare her findings with the created word documents containing descriptions and excerpts. For instance, under the four major themes of science literacy (scientific knowledge, application of knowledge, extension of knowledge, and investigating methods), twelve categories are formed which include "presence of concepts or principles", "connection between concepts and experiments", "learning through the use of materials", and "scientific thinking and discovery". For each category, descriptive sentences are attached, such as "lunch box making experience is provided to illustrate the concept or describe the scientific phenomena" and "a discussion of the scientific method or procedure is demonstrated". Throughout the analysis, she integrated quotes from students' writing to support her points, leveraging their voices to illustrate the depth and complexity of learning.

4. Findings

Three major themes were evident as findings in this study. We first discuss students' experiences of writing, which centered on the way writing helped them better understand scientific concepts and clarify their thinking about how to build the lunchbox. The second theme related to how students' writing development between the first and final draft indicated their deepened scientific knowledge of the heat transfer concepts. In the third theme, we discuss the four science-based literacy skills evident in students' reports, to show how writing facilitated their science content knowledge and ability to transfer learning from one context to another.

4.1. Students' Experiences of Writing

All six students shared that they believed writing helped them learn science by helping them understand scientific concepts and helping them articulate why they did what they did in the lunch box invention process (Table 1).

Table 1. Themes, number of student responses, and selected student voices.

Themes	S#	Selected Student Excerpts
writing supports scientific understanding	6/6	<ul style="list-style-type: none"> - I feel like when you write something, it's easier to understand rather than, reading it from a book. Because it's coming from you. So, you can understand what you write. [When you read,] you don't know what you're reading until after you read it. But when you're writing it by yourself, you think about it more. So, it sticks with you more. - [Writing is] an actual thing to help [students] understand [scientific concepts].
benefit of forward searching in writing (revisiting and rewriting)	5/6	<ul style="list-style-type: none"> - I think [my understanding of the science concepts] developed because we started with one [draft] and we just wrote about our ideas. Then we went back and see what we needed to edit and add more to it and keep developing and more edits. - I knew what convection meant but it was just confusing because these two [convection and conduction] are very similar. But the next time I put it [in writing], even Mr. Lee told me it makes a lot more sense. - the first few times I read it, I had to think about it, but after that, then I got it more.
writing helped students understand the lunch box invention project	5/6	<ul style="list-style-type: none"> - The writing helps you understand more of what the project's about and uses a lot of details [in comparison to] if you just did the lunchbox project. . . I think the writing helped me connect [science concepts to the lunch box project] because I didn't really [understand] conduction, radiation before. But then when I write it and then have a good understanding of it. It helped make the project easier.
benefit of forward searching lunchbox project in writing	3/6	<ul style="list-style-type: none"> - I felt like writing it and doing it [are] two different ways to see it, like actually seeing [the] live version we've been making it. Sometimes I would go back to the writing, add a little more thing, [then] go back to the lunch box and see both. We can add [something to the lunch box] and go back to the writing, and then edit more.

4.1.1. Writing Facilitates Comprehension of Scientific Concepts

All students reported having a greater understanding of science concepts after working through the process of authoring their reports. Noa commented that writing helped her understand science better because writing is a personal form of expression and knowledge development that stays with the writer more than reading alone:

I feel like when you write something, it's easier to understand rather than, reading it from a book. Because it's coming from you. So, you can understand what you write. [When you read,] you don't know what you're reading until after you read it. But when you're writing it by yourself, you think about it more. So, it sticks with you more.

Maggie, Nikki, and Sarah also explained that writing is "an actual thing to help [students] understand [scientific concepts]" because using writing to offer a detailed explanation means they must understand the scientific concepts they were explaining. Caroline added that she believes writing helped her to understand the three main words for the unit (e.g., convection, conduction, and radiation), which made her feel confident. She exclaimed, "it's like, I know the main concepts!"

Five out of six students specifically acknowledged that engaging in the forward search process of revisiting and revising their own writing during the writing process helped them better clarify their understanding of science concepts. Caroline, Maria, Nikki, Sarah, and Noa all indicated that the process of revisiting their writing after completing the first draft and correcting their mistakes increased their scientific understanding. Caroline described the forward searching process as follows:

I think [my understanding of the science concepts] developed because we started with one [draft] and we just wrote about our ideas. Then we went back and see what we needed to edit and add more to it and keep developing and more edits.

Sarah added that writing multiple drafts helped because it required her to “look over, see mistakes, and rewrite”. She mentioned that writing helps her “get everything to the way it’s supposed to be [by] trying to make sense [of scientific concepts]”. Noa also said that the heat transfer concepts “made more sense” after she wrote about them the first time and then reread her draft to revise. She also said that the writing “came along better” after several rereads. She described the process as “the first few times I read it, I had to think about it, but after that, then I got it more”.

Maria’s example of how forward searching supported her learning was evident in how she was able to clarify her knowledge of heat transfer concepts. She explained that even though she understood what convection was, she was unable to explain how it differed from conduction in her first draft. In her second draft, she was able to distinguish between them:

I knew what convection meant but it was just confusing because these two [convection and conduction] are very similar. But the next time I put it [in writing], even Mr. Lee told me it makes a lot more sense.

Taken together, the students’ statements indicate how writing supported them to develop deeper content knowledge about science concepts.

4.1.2. Writing Helped Students Understand the Lunch Box Invention Project

In addition to increased comprehension of the science content, five out of six students reported that the writing enabled them to better understand the lunchbox inventing project. Caroline described the process in the following way:

The writing helps you understand more of what the project’s about and uses a lot of details [in comparison to] if you just did the lunchbox project. . . I think the writing helped me connect [science concepts to the lunch box project] because I didn’t really [understand] conduction, radiation before. But then when I write it and then have a good understanding of it. It helped make the project easier.

Sarah and Maggie also reported that they understood the project because of the writing tasks associated with the invention process. Maggie said that for her, “mak[ing] sense” of the lunch box project was difficult, but that writing helped to make “a lot more sense”. Sarah explained that writing helped her to “not just looking at [the project] but really think about it”, which enhanced her understanding of heat transfer.

Furthermore, Maria, Nikki, and Caroline explained that they understood the fundamentals of their lunch box inventions better as they wrote and revised their writing. For example, Maria explained that writing became the “backstory” of the project, which made “the whole project come together”. For Nikki, writing helped her “make more sense of the materials [she] used” in the project. She explained that writing was much more effective than “just getting materials and building something” because writing forced her to show her understanding of what she put into the lunchbox and why. Caroline also explained the writing process “helped make the project easier”. She identified the interconnectivity between the lunch box invention and writing experiences, saying she often referred to the inventing experience as a resource for knowing what to write:

I felt like writing it and doing it [are] two different ways to see it, like actually seeing [the] live version we’ve been making it. Sometimes I would go back to

the writing, add a little more thing, [then] go back to the lunch box and see both. We can add [something to the lunch box] and go back to the writing, and then edit more.

Her comment illustrated how the lunch box invention and writing experiences complemented each other to facilitate active knowledge construction. Students were noticeably clear about how supportive they found writing-to-learn was to their invention process.

4.2. Development of Writing: Comparison between Initial Draft and Final Draft

Analysis of students’ writing drafts indicated they grew not only in their understanding of science concepts, but in their writing development. Quotations from student writing in the following sections have been reproduced exactly with all spelling and grammar errors preserved, to maintain an accurate representation of what students knew and enacted as writers. As indicated earlier, Maggie and Caroline’s first drafts were missing, so this analysis was based on comparisons between initial and final drafts for Maria, Nikki, Sarah, and Noa. To varying degrees, all four students’ initial and final writings demonstrated they developed and deepened their knowledge of the scientific concepts in the Chill Out unit. As Maria put it, students’ initial drafts offered an incomplete articulation of science knowledge compared to their final drafts.

Maria’s explanation of radiation deepened significantly between her initial and final drafts. In her first draft, she was only able to explain the heat lamp as a source of radiation; in her final draft, she was able to explain how and where radiation took place within her lunch box invention (Table 2).

Table 2. Maria’s initial and final drafts: explanation of radiation.

Initial Draft	Final Draft
As of radiation the only thing that happened was the heat shinning [sic] from the heat lamp onto to our cooler.	Radiation is when heat is transferred through electromagnetic waves and in this project radiation was shown when the heat waves from the heat lamp are shining onto the cooler. In order to prevent radiation the top of the box is covered with white paper so the heat rays would reflect/bounce off. This step is helpful because the heat isn’t going transfer into the top and the walls of the shoes box as easily as it would without the paper.

In her writing, Sarah mirrored this approach. Initially, she described how the tinfoil in the lunchbox reflected radiation. However, in her final draft, she expanded on this by explaining that the lamp emitted electromagnetic radiation similar to sunlight rays. She further elaborated that the aluminum foil she incorporated in the lunchbox served as a method to restrict heat transfer, as it caused electromagnetic waves to bounce (Table 3).

Table 3. Sarah’s initial and final drafts: explanation of radiation.

Initial Draft	Final Draft
One good feature of the cooler is the tinfoil wrapped around the box which did a great job of reflecting the radiation light of the cooler	The radiation that is directed to the cooler is electromagnetic radiation which is basically sun rays. Radiation is present in the lab when the cooler is being tested by using sunlamp and putting it directly above the cooler and letting it sit there for over more than 4 h. . . Aluminum foil bounces the electromagnetic waves off the cooler. . . These steps were effective and limit heat transfer.

Nikki and Noa’s drafts were less detailed in their explanations compared to those of Maria and Sarah (Table 4). Nevertheless, all four students’ final drafts demonstrated an enhanced understanding and explanation of the science concepts compared to the initial drafts, demonstrating the development of their understanding and thinking.

Table 4. Noa’s initial and final drafts: explanation of radiation.

Initial Draft	Final Draft
Heat will bounce of the tin foil there for it helps keep our water cold. We also put white colored felt on the outsides of a box. Because felt is an insulator it will keep the water bottle cold but light colors (mainly white) reject the heat which is also a way to keep the water bottle cold.	The radiation in the cooler is what allows heat to get in or out of the cooler. . . Light colors and reflectors do not absorb radiation. The light and heat will not stay for long once it gets to the alumium [aluminum] foil. Heat will bounce of the alumium [aluminum] foil there for it helps keep out water cold.

These shifts between the initial and final drafts reveal how extensively students developed and articulated their scientific knowledge. All four students indicated an increased ability to demonstrate their learning; they moved from vague and incomplete explanations of heat transfer concepts to detailed and more complete explanations. This change highlights the initial challenges they faced in articulating these ideas in writing and demonstrates improvement as they revisited and revised their drafts to produce the final version. This analysis of students’ writing is aligned with what students self-reported in interviews about the writing-to-learn process.

4.3. Science Literacy Skills Evident in Students’ Final Drafts

Using the four elements of science literacy as an analytic lens on students’ final drafts revealed the presence of all four elements in their writing. In brief, these four elements are scientific knowledge, the application of knowledge, the extension of knowledge, and investigating methods (evidence-based reasoning).

4.3.1. Scientific Knowledge

All students’ final drafts effectively demonstrated their understanding of heat transfer concepts.

4.3.2. Application of Knowledge

While each students’ final drafts demonstrated the scientific knowledge of heat transfer, the degree of applying the knowledge into the lunchbox project varied by student. All six students’ final draft demonstrated their engagement in applying the three types of heat transfer to the lunch box invention experiment.

Conduction. All six students attempted to apply the concept of conduction to their lunch box invention; five of them successfully applied resourceful solutions to address conduction in their lunch box inventions. Caroline, Maria, Nikki, Sarah, and Noa’s application of knowledge demonstrated that they understood conduction and were able to use that knowledge to effectively combat it in their lunch box. However, Maggie’s application did not show the same level of comprehension. Table 5 illustrates this for each student.

Caroline applied knowledge by discussing how she prevented (or could have more effectively prevented) conduction in her lunch box. Caroline wrote, “to prevent conduction we could have put more insulators on the outside and a little bit near the water bottle”. This reflected her knowledge of conduction and how heat transfers.

Similarly, Maria’s report showed that she used physical evidence, such as the increased temperature of a lunch box’s surface, to determine that conduction was happening. She wrote, “in this cooler project conduction is shown when the outside of the box is getting warm”, which suggested that she was able to transfer knowledge from the invention process to her explanation of these ideas in her report.

Nikki, Sarah, and Noa also highlighted their knowledge of conduction by making logical assumptions about conduction taking place during the experiment. Nikki explained that she “mostly see[s] conduction when the water bottle and the heat connect”. Since conduction is invisible to the human eye, her use of the word ‘sees’ suggests she was referring to her ability to observe the effects of conduction in the experiment. Sarah and

Noa's writing excerpts demonstrate a similar inference about how conduction worked in the experiment.

Conversely, Maggie's explanation of using materials with a 'light color' to reflect heat relates to radiation rather than conduction. While this suggests she was attempting to apply her scientific knowledge in both her writing and invention, it also reveals that her understanding of conduction still needs further development.

Table 5. Application of knowledge based on the lunch box invention—conduction.

Name/Type	Examples of Student Writing
Maggie	Those materials used helped out the cooler because when you have something with light color it reflects. (Misapplication of conduction)
Caroline	To prevent conduction we could have put more insulators on the outside and a little bit near the water bottle.
Maria	In this cooler project conduction is shown when the outside of the box is getting warm.
Nikki	Mostly see conduction when the water bottle and the heat connect.
Sarah	When the cooler makes contact with the lab table and either the cooler emits heat transfer. . .based on the temperature of the heat transfer.
Noa	The conduction came into our cooler and heated the water bottle resulting the water bottle be a warmer temperature than it was to begin with.

Convention. Similarly, five out of six participating students attempted to apply their knowledge of convection to the lunch box experiment and explain it in their writing, with varying degrees of details (See Table 6).

Table 6. Application of knowledge during lunch box invention—convection.

Name/Type	Examples of Student Writing
Maggie	In the project the convection is all the heat lamps beating down on the water bottle inside the box. The cooler has bubble wrap on the side of the cooler and plastic bags on the water bottle to keep cool air on the inside and warm air on the outside.
Caroline	Student did not discuss convection.
Maria	A way convection is shown in this invention is when. . . [I] try to keep the warm air out and the cool air in. . . by sealing the lid so the air wouldn't move in or out. These steps are really effective because now the warm air wouldn't be going into the water bottle as easily.
Nikki	The convection [is] occurring mostly when the heat comes through the box and mixes with the cold air and make a gas from the warmer spot to the cooler spot. Some steps that we took to prevent heat from reaching the water bottle was covering the water bottle itself with bubble wrap and other materials such as plastic bags and packing peanuts.
Sarah	Convection is shown when the heat from the lamp begins to heat up the cooler and slowly the warm heat from all around the cooler starts to rise and the colder current sinks to the bottom and keeps the beverages cool.
Noa	During the project convection would occur when cold air in the cooler would escape or warm air would sneak in.

For example, the students' descriptions showed that they understood how convection occurred and were able to design their lunch box to combat it. Maria wrote, "a way convection is shown in this invention is when. . . [I] try to keep the warm air out and the cool air in. . . by sealing the lid so the air wouldn't move in or out". This excerpt indicates that she understood that convection takes place through the movement of fluid, such as a liquid or gas; she sealed the lid to prevent this. Nikki's explanation also indicated she knew how convection could change the water temperature: "covering the water bottle itself with bubble wrap and other materials such as plastic bags and packing peanuts" was

an explanation of the materials she used to prevent convection. This demonstrates that she had an understanding of convection in the project.

Radiation. Regarding the concept of radiation, five of the six student participants were able to apply and articulate accurate understandings of the scientific concept. Table 7 contains students' explanations of how they accounted for radiation in their lunch box projects.

Table 7. Application of knowledge during lunch box invention—radiation.

Name/Type	Examples of Student Writing
Maggie	To prevent the radiation from getting to the water bottle. The bottle was covered with white packing peanuts and that was added because when the heat lamps beat through the box, we needed their to be protection on the bottle. If it isn't covered with packing peanuts the radiation would go right through the box and straight to the bottle and that is defeating the puspose [purpose] of trying to elsius heat transfer.
Caroline	During the experiment radiation occurs when the heat from the lamp discharges some of the heat to the cooler. To prevent radiation the cooler was a light colored lunchbox
Maria	In this project radiation was shown when the heat waves from the heat lamp are shining onto the cooler. In order to prevent radiation the top of the box is covered with white paper so the heat rays would reflect/bounce off. This step is helpful because the heat isn't going transfer into the top and the walls of the shoes box as easily as it would without the paper.
Nikki	The radiation is most seen when occurring with the tin foil in the project because the movement from the heat going into[, and] the box hitting the tin foil on top and the white paper.
Sarah	Radiation is present in the lab when the cooler is being tested by using sunlamp and putting it directly above the cooler. . . Aluminum foil bounces the electromagnetic waves off the cooler. . . These steps were effective and limit heat transfer.
Noa	The radiation in the cooler is what allows heat to get in or out of the cooler. . . Light colors and reflectors do not absorb radiation. The light and heat will not stay for long once it gets to the alumium foil. Heat will bounce of the alumium foil there for it helps keep ou[r] water cold[.]

All students used a similar logic to explain the concept of radiation, showing they understood the heat lamps as the source of radiation in the experiment. They also referenced appropriate materials for ameliorating radiation, such as “white packing peanuts”, “light-colored paper”, and reflective “aluminum foil”, as materials that “bounce the electromagnetic waves off the lunch box to prevent radiation heat transfer”. All students' explanations demonstrate they had a strong understanding of radiation and how they addressed it in the lunch box experiment.

Overall, regardless of the varying degrees, these CLD students demonstrated their ability to directly apply scientific knowledge in the experiment and express their scientific understandings in written form.

4.3.3. Extension of Knowledge

Every student included one or more real-life examples beyond the lunch box experiment to support their explanation of heat transfer (Table 8). Five of the six students gave an example of conduction, three students gave examples of convection, and all six students gave examples of radiation. Sarah, who included real-life examples for all three types of heat transfer, wrote about a radiation shield:

In relation to limiting heat transfer, people [have] also created inventions to help prevent heat transfer such as a radiation shield. . . [S]ources of radiation can be shielded with solid or liquid material, which absorbs the energy of radiation. . .to reduce the radiation to a level safe for humans.

Sarah also included an example from daily life: “Oven mitts are used so you don't make direct contact with the metal and burn yourself [which] by the way is conduction,

so oven mitts are used to prevent conduction". Maria was also able to provide a real-life example of radiation: "Many people try to prevent radiation when being out in the beach. They do this by putting on sunscreen so the sun rays don't burn their skin".

Table 8. Students' real-life examples of conduction, convection, and radiation.

Name/Types of Heat Transfer	Conduction	Convection	Radiation
Maggie	Boiling water	-	Light-colored clothes, microwaves, light bulbs, and fire
Caroline	Opening a door	-	Stove (fire)
Maria	Wearing jackets	Keeping a window closed (heat transfer through the air)	Sunscreen, sunglasses
Nikki	-	Opening a door (heat transfer through the air)	Wearing white clothes
Sarah	Oven mitts	Thermos	Biological shield
Noa	Aluminum foil	-	Sunscreen

Every participant was able to make one or more connection between their science knowledge and real-world examples. Students offered a diverse set of examples and explanations, indicating that they all deepened their learning beyond simple memorization of the examples they learned in the classroom.

4.3.4. Evidence-Based Reasoning

In their final reports, five out of six students referenced experimental data to support the effectiveness of their lunchbox design, indicating another aspect of science-based writing: using data to support conclusions. Students' examples are contained in Table 9.

Table 9. Evidence-based reasoning.

Name/Type	Examples from Student Writing
Maggie	The cooler was successful because the water bottle started at 0.2 °C and it ended with 10.1 °C which made it have a 9.9 temp increase when the control had a 16 °C temp. Increase.
Caroline	The bottle of the temperature was 6 °C and the final bottle temperature was 22 °C.
Maria	This invention is a success because the control group[']s. . . initial temperature of the water bottle was 6 degrees Celsius and when putting it inside the shoebox under the heating lamp the temperature of the water was 22 degree Celsius which meant it went up 16 degrees Celsius. The invention made by 7th graders on the other hand started off at 0.8 degrees Celsius and ended at 8 degrees Celsius meaning it went up 7.2 degree Celsius.
Nikki	In conclusion, the initial control bottle temperature is 6 °C and the final control bottle temperature was 22 °C. The initial temperature of the bottle inside the lunchbox was 0.2 °C and the final temperature of bottle inside lunchbox was 10.1 °C we reduced radiation, convection, and conduction.
Sarah	Student did not include experimental data.
Noa	The cooler was successful at keeping the water bottle started at 0.6 degrees Celsius and it ended at 15.5 degrees Celsius.

Students recognized the importance of indicating how they investigated a certain concept (in this case, the temperature of the water), and used the data as evidence to support their design. Maggie wrote that her lunch box design was successful because "the water bottle started at 0.2 degrees, and it ended with 10.1 °C which made it have a 9.9 temp increase when the control had 16 °C temp. Increase". Her comparison between their lunch box and the control's water bottle was an effective way to show how the lunchbox design

was successful in preventing heat transfer. Maria also provided a detailed description of the control lunch box to validate her argument:

This invention is a success because the control group[']s... initial temperature of the water bottle was 6 degrees Celsius and when putting it inside the shoebox under the heating lamp the temperature of the water was 22 degree Celsius which meant it went up 16 degrees Celsius. The invention made by 7th graders on the other hand started off at 0.8 degrees Celsius and ended at 8 degrees Celsius meaning it went up 7.2 degree Celsius.

Caroline, whose lunch box water bottle temperature was the same as the control lunch box, acknowledged that her lunch box was not successful in preventing heat transfer. Each of these examples indicate that students were successful at investigating and logically reasoning out their conclusions based on scientific evidence.

4.4. Summary of Findings

While the students developed varying degrees of science literacy skills, their writing indicates the four elements of science literacy, namely scientific knowledge, application of knowledge, extension of knowledge, and investigating methods. An analysis of student writing in this study reveals that the participating students were able not only to demonstrate scientific knowledge but also to apply and extend that knowledge to both the lunchbox inventing experience and real-life examples. Furthermore, they were able to reach a conclusion using evidence-based reasoning, drawing on their experimental data to foster their own scientific literacy.

5. Discussion

The challenge of understanding complex and abstract scientific concepts is significant for CLD students who may already face the dual task of navigating both unfamiliar scientific terminology and the nuances of academic discourse in a second language [1,18,23,61]. The intricate language of science, characterized by dense vocabulary and specific discourse patterns, further complicates their learning process [1,23,30,31,61]. This discussion examines how writing can be a powerful tool for CLD students, helping them to deepen their understanding of scientific concepts, enhance their science literacy, and achieve academic success.

Previous research indicates that writing is a complex and challenging process requiring writers to reflect upon and elaborate the content they have acquired [2,8,9]. This process strengthens students' understanding of subject matter, promotes deeper comprehension of concepts, and encourages engagement in higher-order thinking skills [2,8,9,16]. The multifaceted nature of writing – which encompasses formulating ideas, analyzing, identifying, drafting, and revising – poses significant challenges for students [2,33]. Although this process of productive struggle, where students take time to think, write, and revise, can be time-consuming and difficult, researchers assert that it can be crucial for achieving deeper understanding [37–39]. Many scholars argue that productive struggles support subject matter learning and should be integrated into educational practices rather than avoided [37–39]. The concept of productive struggles is clearly reflected in this study, particularly in students' discussions of their writing experiences. Students reported that “we went back and saw what we needed to edit and add more to it and keep developing and making more edits”. The development from initial to final drafts also revealed productive struggles through writing. As the students describe, through multiple drafting stages they were able to reach a point where the concepts “made more sense” to them.

In addition to engaging in productive struggles to deepen their understanding of scientific concepts, the writing-to-learn approach helped connect their invention experience with science concepts addressed in the curriculum. While writing, students were able to use their lunchbox invention experience as a reference to visualize how the invisible “heat transfer” concepts occurred in the lunchbox invention. While the experiment may have been fragmented or lost in their memory, writing revived the experiment once more

and allowed them to visualize and reflect on the scientific concepts. By writing about and referring to the experiment, students were able to reflect on their lunchbox experience to better understand the science. The writing became a strong bridge to connect the hands-on experience to abstract scientific theories, enhancing their understanding and clarifying and solidifying their knowledge [23]. Through writing, the lunchbox invention experience became a solid foundation of background knowledge that students could build upon and refer to. This is particularly beneficial for CLD students, whose prior knowledge of the topic may differ from that of their peers or the teacher.

In addition, writing became a way for CLD students to expand their communicative and meaning making repertoires in science [62]. Writing allows students to articulate their understandings and engage with scientific concepts through specific discourse patterns, thereby solidifying their understanding of content and enabling them to contribute meaningfully to academic discussions [1,2,9,23,27,62]. By expanding students' communicative resources, writing equipped them with the tools necessary to express their understandings across a spectrum of scientific discourse. Furthermore, by connecting to the invention experience, students were able to use the lunchbox experimental results from their inventing project to engage in evidence-based reasoning in their compositions. This practice allowed them to connect the invention experience with science concepts and provided opportunities to articulate scientific concepts in a logical way by using the data set gathered through the experiment.

Another important takeaway from the findings was the forward searching process that took place through writing multiple drafts. According to Klein [33], forward searching is a process of revising the initial writing, which allows for the development of new knowledge. This is also a process of reconstructing their knowledge as they rewrite compositions from the initial stages of their learning. This forward searching process requires writers to reevaluate their thinking and communicate more clearly about the content [27,33,34].

Forward searching was clearly present and beneficial for CLD students in this study. Students were asked to write multiple drafts, and the differences between their initial and final drafts showed significant improvement in their articulation of concepts and the accuracy of information. At first, students struggled to use the language of science and make sense of concept in writing, but after revision the final drafts demonstrated more accurate understanding and clearer use of scientific language. Their final drafts not only developed the concept of heat transfer but also increased language articulation. As students put it, concepts "made more sense" and "came along better" as they revisited and rewrote. Through forward searching in writing, students not only developed their understanding of science concepts but also enhanced their science literacy skills.

An interesting finding in this study was that forward searching was not limited to revisiting writing only. Forward searching happened as students referred to their lunchbox inventing experience. Klein's [34] research has shown that forward searching is not limited to writing but can be applicable to any kind of learning. For example, Klein [34] describes how elementary students engaged in forward searching by reviewing experimental results to solve problems. In this study, students forward searched by utilizing their inventing experience, experimental results, and the data as evidence to support the logical reasoning in their writing.

This study has several important implications for educational practice. First, engaging students in productive struggles through writing-to-learn can be particularly beneficial for CLD students. Productive struggle involves students in a back-and-forth reflective process in which they are encouraged to grapple with complex ideas, revise their understanding, and refine their thinking [2,9,27,34,39]. This metacognitively challenging process may be frustrating for some students initially, but with sufficient time, structured support, and guidance from teachers, it can lead to significant gains in understanding. For example, when students are asked to write multiple drafts of their work, they are compelled to revisit and reconsider their initial ideas, and this can promote deeper cognitive engagement with the material. This iterative process helps students to develop more sophisticated

and nuanced understandings of scientific concepts, as shown by the improved accuracy in their final drafts [2,9,27,34]. Through sustained engagement in productive struggle, students build resilience and persistence, which are critical skills for scientific inquiry and problem-solving [2,9,27,34,39].

Second, writing-to-learn is an effective method for teaching the language of science [2,8,9,27,34]. Scientific language is often dense, abstract, and filled with specialized vocabulary that can be challenging for students, especially those who are culturally and linguistically diverse [1,21,30,31]. Many science teachers may feel that teaching language skills falls outside their purview, focusing instead on the delivery of content [26–28]. However, this study illustrates the benefits of integrating language instruction within the science curriculum. When students engage in writing-to-learn activities, they practice using scientific terminology and discourse patterns, which helps them internalize these concepts. For instance, by writing about their experiments and inventing projects, students learn to articulate their reasoning using appropriate scientific language. This practice not only enhances their science literacy but also prepares them to communicate their findings effectively. Incorporating writing-to-learn strategies into science instruction moves beyond rote memorization and encourages students to actively construct and express their understandings. This approach not only supports CLD students in overcoming potential barriers but also fosters an inclusive environment where all students can develop the skills needed to participate fully in academic discussions.

In addition, writing assignments that require students to draw on their experiences, such as the lunchbox inventing project discussed in the study, can make abstract scientific concepts more concrete and experience-near. By connecting hands-on activities with writing tasks, students are able to visualize and understand the principles behind key phenomena like heat transfer. Reflecting on and writing about their practical experiences helps to solidify their knowledge and provides a strong foundation for future learning. This approach not only enhances comprehension but also encourages students to see the relevance of science to their everyday lives, thereby increasing their engagement and interest in the subject.

In conclusion, this study demonstrates the critical role that writing can play in science education, particularly for CLD students. Writing-to-learn approaches can be a key tool, enabling students to connect their hands-on experiences with complex scientific concepts. The process of writing, including iterative drafting and revision, not only deepens cognitive engagement but also promotes the development of scientific literacy. The results demonstrate that by integrating writing into science instruction, educators can effectively support CLD students in developing science literacy and achieve academic success in science.

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References

1. Fang, Z.; Lamme, L.L.; Pringle, R.M. *Language and Literacy in Inquiry-Based Science Classrooms, Grades 3–8*; Corwin Press: Thousand Oaks, CA, USA, 2010.
2. Hand, B.; Chen, Y.C.; Suh, J.K. Does a knowledge generation approach to learning benefit students? A systematic review of research on the science writing heuristic approach. *Educ. Psychol. Rev.* **2021**, *33*, 535–577. [\[CrossRef\]](#)
3. Krajcik, J.; Mamlok, R.; Hug, B. Chapter VIII: Modern content and the enterprise of science: Science education in the twentieth century. *Teach. Coll. Rec.* **2001**, *103*, 205–238. [\[CrossRef\]](#)
4. Hoeg, D.G.; Bencze, J.L. Values underpinning STEM education in the USA: An analysis of the next generation science standards. *Sci. Educ.* **2017**, *101*, 278–301. [\[CrossRef\]](#)
5. Lederman, N.G.; Abell, S.K. (Eds.) *Handbook of Research on Science Education, Volume II*; Routledge: New York, NY, USA, 2014. [\[CrossRef\]](#)
6. Lederman, N.G.; Lederman, J.S. Standards for science education in the United States: Necessary evil? In *Making It Comparable: Standards in Science Education*; Waddington, D., Nentwig, P., Schanze, S., Eds.; Waxmann Verlag: Münster, Germany, 2007; pp. 347–371.
7. Lee, O. Science education with English language learners: Synthesis and research agenda. *Rev. Educ. Res.* **2005**, *75*, 491–530. [\[CrossRef\]](#)
8. Casado-Ledesma, L.; Cuevas, I.; Martín, E. Learning science through argumentative synthesis writing and deliberative dialogues: A comprehensive and effective methodology in secondary education. *Read. Writ.* **2023**, *36*, 965–996. [\[CrossRef\]](#)
9. Hand, B.; Shelley, M.C.; Laugeran, M.; Fostvedt, L.; Therrien, W. Improving critical thinking growth for disadvantaged groups within elementary school science: A randomized controlled trial using the Science Writing Heuristic approach. *Sci. Educ.* **2018**, *102*, 693–710. [\[CrossRef\]](#)
10. Baker, W.P.; Barstack, R.; Clark, D.; Hull, E.; Goodman, B.; Kook, J.; Kraft, K.; Ramakrishna, P.; Roberts, E.; Shaw, J.; et al. Writing-to-learn in the inquiry-science classroom: Effective strategies from middle school science and writing teachers. *Clear. House A J. Educ. Strateg. Issues Ideas* **2008**, *81*, 105–108. [\[CrossRef\]](#)
11. de Oliveira, L.C.; Lan, S.-W. Writing Science in an Upper elementary classroom: A genre-based approach to teaching English language learners. *J. Second. Lang. Writ.* **2014**, *25*, 23–39. [\[CrossRef\]](#)
12. Graham, S.; Kiuahara, S.A.; MacKay, M. The effects of writing on learning in science, social studies, and mathematics: A meta-analysis. *Rev. Educ. Res.* **2020**, *90*, 179–226. [\[CrossRef\]](#)
13. Chen, Y.-C.; Hand, B.; McDowell, L. The effects of writing-to-learn activities on elementary students' conceptual understanding: Learning about force and motion through writing to older peers. *Sci. Educ.* **2013**, *97*, 745–771. [\[CrossRef\]](#)
14. Pelger, S.; Nilsson, P. Popular science writing to support students' learning of science and scientific literacy. *Res. Sci. Educ.* **2016**, *46*, 439–456. [\[CrossRef\]](#)
15. Sampson, V.; Enderle, P.; Grooms, J.; Witte, S. Writing to learn by learning to write during the school science laboratory: Helping middle and high school students develop argumentative writing skills as they learn core ideas. *Sci. Educ.* **2013**, *97*, 643–670. [\[CrossRef\]](#)
16. Rivard, L.O.P. A review of writing to learn in science: Implications for practice and research. *J. Res. Sci. Teach.* **1994**, *31*, 969–983. [\[CrossRef\]](#)
17. Lee, O.; Fradd, S.H. Literacy skills in science learning among linguistically diverse students. *Sci. Educ.* **1996**, *80*, 651–671. [\[CrossRef\]](#)
18. Manchón, R.M. Situating the learning-to-write and writing-to-learn dimensions of L2 writing. In *Learning-to-Write and Writing-to-Learn in an Additional Language*; Manchón, R.M., Ed.; John Benjamins Publishing Company: Amsterdam, The Netherlands, 2011; Volume 31, pp. 3–14. [\[CrossRef\]](#)
19. Boughey, C. Learning to write by writing to learn: A group-work approach. *ELT J.* **1997**, *51*, 126–134. [\[CrossRef\]](#)
20. Brisk, M.E. *Language in Writing Instruction: Enhancing Literacy in Grades 3–8*; Routledge: New York, NY, USA, 2020.
21. Fang, Z.; Schleppegrell, M.J. Disciplinary literacies across content areas: Supporting secondary reading through functional language analysis. *J. Adolesc. Adult Lit.* **2010**, *53*, 587–597. [\[CrossRef\]](#)
22. Kim, D.; Kim, S.L.; Barnett, M. "That makes sense now!": Bicultural middle school students' learning in a culturally relevant science classroom. *Int. J. Multicult. Educ.* **2021**, *23*, 145–172. [\[CrossRef\]](#)
23. Kim, S.L.; Kim, D. English learners' science-literacy practice through explicit writing instruction in invention-based learning. *Int. J. Educ. Res. Open* **2021**, *2*, 100029. [\[CrossRef\]](#)
24. Zhang, H.; Estabrooks, L.; Perry, A. Bringing invention education into middle school science classrooms: A case study. *Technol. Innov.* **2019**, *20*, 235–250. [\[CrossRef\]](#)
25. Boscolo, P.; Mason, L. Writing to learn, writing to transfer. In *Writing as a Learning Tool*; Tynjälä, P., Mason, L., Lonka, K., Eds.; Springer: Berlin/Heidelberg, Germany, 2001; Volume 7, pp. 83–104. [\[CrossRef\]](#)
26. Drew, S.V.; Olinghouse, N.G.; Faggella-Luby, M.; Welsh, M.E. Framework for disciplinary writing in science Grades 6–12: A national survey. *J. Educ. Psychol.* **2017**, *109*, 935. [\[CrossRef\]](#)
27. Sedlacek, Q.C.; Lomeli, K. Towards authentic purposes for student science writing using culturally relevant pedagogy. *Cult. Stud. Sci. Educ.* **2024**, *19*, 141–162. [\[CrossRef\]](#)

28. Tan, M. Mathematics and science teachers' beliefs and practices regarding the teaching of language in content learning. *Lang. Teach. Res.* **2011**, *15*, 325–342. [CrossRef]
29. Moore, J.; Schleppegrell, M. A focus on disciplinary language: Bringing critical perspectives to reading and writing in science. *Theory Into Pract.* **2020**, *59*, 99–108. [CrossRef]
30. Schleppegrell, M.J. The knowledge base for language teaching: What is the English to be taught as content? *Lang. Teach. Res.* **2020**, *24*, 17–27. [CrossRef]
31. Brisk, M.E.; Zhang-Wu, Q. Academic language in K–12 contexts. In *Handbook of Research in Second Language Teaching and Learning*; Hinkel, E., Ed.; Routledge: New York, NY, USA, 2016; pp. 82–100. [CrossRef]
32. Brisk, M.E. *Engaging Students in Academic Literacies: Genre-Based Pedagogy for K-5 Classrooms*; Routledge: New York, NY, USA, 2014. [CrossRef]
33. Klein, P.D. Reopening inquiry into cognitive processes in writing-to-learn. *Educ. Psychol. Rev.* **1999**, *11*, 203–270. [CrossRef]
34. Klein, P.D. Elementary students' strategies for writing-to-learn in science. *Cogn. Instr.* **2000**, *18*, 317–348. [CrossRef]
35. Klein, P.D.; Kirkpatrick, L.C. A framework for content area writing: Mediators and moderators. *J. Writ. Res.* **2010**, *2*, 1–46. [CrossRef]
36. Knipper, K.J.; Duggan, T.J. Writing-to-learn across the curriculum: Tools for comprehension in content area classes. *Read. Teach.* **2006**, *59*, 462–470. [CrossRef]
37. Baker, K.; Jessup, N.A.; Jacobs, V.R.; Empson, S.B.; Case, J. Productive struggle in action. *Math. Teach. Learn. Teach. PK-12* **2020**, *113*, 361–374. [CrossRef]
38. Bolyard, J.; Curtis, R.; Cairns, D. Learning to Struggle: Supporting Middle-grade Teachers' Understanding of Productive Struggle in STEM Teaching and Learning. *Can. J. Sci. Math. Technol. Educ.* **2023**, *23*, 687–702. [CrossRef]
39. Warshauer, M. Productive struggle in learning. *J. Educ. Psychol.* **2015**, *107*, 665–679.
40. Balgopal, M.M.; Wallace, A.M. Decisions and dilemmas: Using writing-to-learn activities to increase ecological literacy. *J. Environ. Educ.* **2009**, *40*, 13–26. [CrossRef]
41. Hand, B.; Yang, O.E.-m.; Bruxvoort, C. Using writing-to-learn science strategies to improve year 11 students' understandings of stoichiometry. *Int. J. Sci. Math. Educ.* **2007**, *5*, 125–143. [CrossRef]
42. Langer, J.A.; Applebee, A.N. How Writing Shapes Thinking: A Study of Teaching and Learning. NCTE Research Report No. 22. 1987. Available online: <https://eric.ed.gov/?id=ED286205> (accessed on 10 January 2022).
43. Galbraith, D. Writing as a knowledge-constituting process. In *Knowing What to Write: Conceptual Processes in Text Production*; Amsterdam University Press: Amsterdam, The Netherlands, 1999; Volume 4, pp. 139–164.
44. Boone, S.; Chaney, S.B.; Compton, J.; Donahue, C.; Gocsik, K. Imagining a Writing and Rhetoric Program Based on Principles of Knowledge "Transfer": Dartmouth's Institute for Writing and Rhetoric. *Compos. Forum* **2012**, *26*. Available online: <https://eric.ed.gov/?id=EJ985819> (accessed on 10 January 2022).
45. Flower, L.; Hayes, J.R. The cognition of discovery: Defining a rhetorical problem. *Coll. Compos. Commun.* **1980**, *31*, 21–32. [CrossRef]
46. Perkins, D.N.; Salomon, G. Knowledge to go: A motivational and dispositional view of transfer. *Educ. Psychol.* **2012**, *47*, 248–258. [CrossRef]
47. Roux, D.J.; Rogers, K.H.; Biggs, H.C.; Ashton, P.J.; Sergeant, A. Bridging the Science—Management Divide: Moving from Unidirectional Knowledge Transfer to Knowledge Interfacing and Sharing. *Ecol. Soc.* **2006**, *11*, 1. Available online: <https://www.jstor.org/stable/26267817> (accessed on 11 January 2022). [CrossRef]
48. Thompson, G.N.; Estabrooks, C.A.; Degner, L.F. Clarifying the concepts in knowledge transfer: A literature review. *J. Adv. Nurs.* **2006**, *53*, 691–701. [CrossRef]
49. Engle, R.A. Framing interactions to foster generative learning: A situative explanation of transfer in a community of learners classroom. *J. Learn. Sci.* **2006**, *15*, 451–498. [CrossRef]
50. Bransford, J.D.; Brown, A.L.; Cocking, R.R. *How People Learn*; National Academy Press: Washington, DC, USA, 2000; Volume 11.
51. Chi, M.T.; VanLehn, K.A. Seeing deep structure from the interactions of surface features. *Educ. Psychol.* **2012**, *47*, 177–188. [CrossRef]
52. Engle, R.A.; Lam, D.P.; Meyer, X.S.; Nix, S.E. How does expansive framing promote transfer? Several proposed explanations and a research agenda for investigating them. *Educ. Psychol.* **2012**, *47*, 215–231. [CrossRef]
53. Merriam, S.B.; Tisdell, E.J. *Qualitative Research: A Guide to Design and Implementation*; John Wiley & Sons: San Francisco, CA, USA, 2015.
54. Creswell, J.W. *Research Design: Qualitative & Quantitative Approaches*; SAGE: Thousand Oaks, CA, UK, 1994.
55. Braun, V.; Clarke, V. Using thematic analysis in psychology. *Qual. Res. Psychol.* **2006**, *3*, 77–101. [CrossRef]
56. Guest, G.; MacQueen, K.M.; Namey, E.E. *Applied Thematic Analysis*; SAGE: Thousand Oaks, CA, USA, 2012.
57. Bingham, A.J.; Witkowsky, P. Deductive and inductive approaches to qualitative data analysis. In *Analyzing and Interpreting Qualitative Data: After the Interview*; Vanover, C., Mihás, P., Saldana, J., Eds.; SAGE: Newcastle upon Tyne, UK, 2021; pp. 133–148.
58. Garcia, T.D. An Analysis of Earth Science Textbooks for Presentation of Aspects of Scientific Literacy. Ph.D. Thesis, University of Houston, Houston, TX, USA, 1985.
59. Chiappetta, E.L.; Fillman, D.A. Analysis of five high school biology textbooks used in the United States for inclusion of the nature of science. *Int. J. Sci. Educ.* **2007**, *29*, 1847–1868. [CrossRef]

60. Hatch, J.A. *Doing Qualitative Research in Education Settings*; SUNY Press: Albany, NY, USA, 2002.
61. Brown, B.A.; Ryoo, K. Teaching science as a language: A “content-first” approach to science teaching. *J. Res. Sci. Teach.* **2008**, *45*, 529–553. [[CrossRef](#)]
62. Chung, Y.; Yoo, J.; Kim, S.W.; Lee, H.; Zeidler, D.L. Enhancing students’ communication skills in the science classroom through socioscientific issues. *Int. J. Sci. Math. Educ.* **2016**, *14*, 1–27. [[CrossRef](#)]

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