Cross-disciplinary language changes in 4th graders as a predictor of the quality of written scientific explanation

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Abstract: Upper elementary students face conceptual and linguistic challenges when writing in science. One way to scaffold science writing is the explicit teaching of cross-disciplinary language. Limited research has explored the dynamics of these language changes in instructional contexts. This study examines the micro-developmental changes in cross-disciplinary language skills and their contributions to the quality of 191 science explanations written by 65 fourth graders that participated in language and literacy-based instruction. The instruction's pedagogical design was focused on writing-to-learn and learning-to-write the scientific explanation genre. Each student wrote an initial, a scaffolded draft, and a final explanation that was scored for scientific quality and productive cross-disciplinary language skills. Students' prior and final scientific knowledge was also measured. The results showed large instruction size effects on the scientific quality (0.71), productive cross-disciplinary language skills (0.46), and explanation length (0.64). Stepwise regression analysis showed that prior and final science knowledge and productive cross-disciplinary language skills significantly predict the quality of the final explanation ($R^2 = .704$, $F(11,38) = 9.03$, $p < .000$). This research offers evidence of the dynamic relationships between language, literacy, and science in contexts of explicit cross-disciplinary language instruction for disciplinary literacy and learning.

Keywords: cross-disciplinary language, disciplinary writing, scientific explanations, school genre

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1. Introduction

To write scientific explanations, students must know the core concepts necessary to work out the cause-effect relationship and express it through the use of disciplinary language mainly by discipline-specific vocabulary and logical connectives (Evagorou & Osborne, 2010). However, students require a mastery of a more extensive set of language resources to construct school genres; this set is called cross-disciplinary language (Phillips Galloway et al., 2020; Uccelli, 2019). Cross-disciplinary language –also called school-relevant or academic language– refers to the mastery of a constellation of high-utility language resources and skills for learning through school content areas (Schleppegrell, 2004; Uccelli, 2019; Uccelli et al., 2015). Examples include logical connectives (e.g., *nevertheless*, *consequently*) and structures that pack dense information (e.g., nominalizations, embedded clauses). Although instructional proposals have been designed to teach school genre writing (e.g., de Oliveira & Lan, 2014; Fitts et al., 2020; Rappa & Tang, 2018; Seah, 2016; Seah et al., 2011), those proposals mainly address cross-disciplinary language resources as discipline-specific, hiding the contribution made by the cross-disciplinary language resources and skills to the genre. Students construct disciplinary knowledge through disciplinary and cross-disciplinary language (e.g., Fang & Park, 2020), and instruction needs to address them simultaneously.

Scientific writing is demanding for students because it involves writing descriptive, argumentative, and explanatory genres about abstract concepts and latent relations. Scientific explanations are challenging because they require students to write a complex clause that states the causal relation that produces a natural phenomenon, connect it with accepted scientific knowledge, and identify the scientific evidence that supports it. This intertwined use of language, literacy, and science knowledge is quite difficult for upper elementary students (9 to 12 years old) who are starting to use language as a tool for knowledge construction. As with any disciplinary practice, the scientific explanation requires explicit teaching that unpacks the literacy and language skills which facilitate student participation in constructing domain-specific knowledge (Myhill & Chen, 2020; Uccelli, 2019). Students will have difficulty learning these new language forms and functions without discipline-specific writing instruction.

The teaching of science writing has multiple entry points (Huerta & Garza, 2019). Writing has been employed as an epistemic tool to promote learning in science classes for drawing conclusions in inquiry activities. On the one hand, quantitative studies demonstrate the positive effects of writing on science learning (Chen et al., 2013; Graham et al., 2020; Hand et al., 2007, 2009), though these studies do not focus on the language demands of writing science genres. On the other hand, qualitative studies describe the linguistic resources deployed by students in their written explanations (Avalos et al., 2017; de Oliveira & Lan, 2014; Fitts et al., 2020; Rappa &

Tang, 2018; Seah, 2016; Seah et al., 2011). These resources enable technicality (disciplinary vocabulary and extended noun phrases), the development of evidence-based reasoning (causal patterns), and the projection of an objective voice, among others (Avalos et al., 2017; de Oliveira & Lan, 2014; Rappa & Tang, 2018; Seah, 2016; Seah et al., 2011). Little research explores the contribution of cross-disciplinary language to the quality of the science genre (Phillips Galloway & Uccelli, 2019; Phillips Galloway et al., 2020). Uccelli et al. (2019) examine the developmental trajectories of specific language skills for constructing science summaries from a longitudinal perspective; however, studies exploring the contribution of cross-disciplinary language to the quality of the authentic science genre are scarce.

To address the gaps identified in existing research, the present study examines the micro-developmental changes in cross-disciplinary language skills and their relation to the quality of written scientific explanations produced by fourth graders who participated in language and literacy-based instruction. This paper contributes to the analysis of a foundational genre for learning in science that offers critical insights into understanding cross-disciplinary language skills for writing-to-explain at the elementary school level. Moreover, a micro-developmental approach examines changes in cross-disciplinary language skills through three-hour weekly sessions over five weeks in which students participated in an instructional sequence for writing scientific explanations. This research offers insights into how explicit cross-disciplinary language teaching can improve disciplinary learning and genre writing by making students aware of mastering language resources used across disciplines. We give evidence of how upper elementary students can learn early social and epistemic ways in which communities construct knowledge through language (Myhill & Chen, 2020; Uccelli, 2019).

2. Theoretical framework

2.1 Writing in science: the interplay between *writing-to-learn* and *learning-to-write*

Writing in science is not a recent area of study; however, there is limited research on writing interventions that effectively promote science learning (Hand, 2017; Huerta & Garza, 2019). Huerta and Garza's (2019) systematic review of the literature reveals two instructional writing approaches: *writing-to-learn* and *learning-to-write*. *Writing-to-learn* proposes writing as an epistemic tool that enhances understanding of scientific concepts and builds scientific reasoning through heuristic processes during and after scientific inquiry activities (Chen et al., 2013; Hand et al., 2007, 2009). Quasi-experimental studies demonstrate the effectiveness of interventions from this perspective (Chen et al., 2013; Hand et al., 2007, 2009). They shed light on the mediating role of writing and its metacognitive potential, which is conceptualized from constructivist-sociocultural theory of learning (Huerta & Garza, 2019). While these studies explore the impact of different writing tasks (e.g., reflective journals, concept maps) on science learning, they do not explore the effects of authentic science genres on knowledge construction, nor do they attempt to understand the role of cross-disciplinary language in the writing of these genres.

Learning-to-write is an instructional approach that teaches the language resources of school genres by breaking them down. Most qualitative studies have been grounded in the framework of Systemic Functional Linguistics and describe in-depth the specific language resources involved in science genre construction (Avalos et al., 2017; de Oliveira & Lan, 2014; Fitts et al., 2020; Rappa & Tang, 2018; Seah, 2016; Seah et al., 2011). Specific instructional approaches explicitly teach school genres broadly with particular interest in support given to ELLs (Avalos et al., 2017; de Oliveira & Lan, 2014). The different discursive phases of organization of school genres, especially reports, explanations, and arguments, are described following genre-based literacy pedagogy (Avalos et al., 2017; Brisk, 2015; Rose & Martin, 2012). Although these studies are designed based on functional language theories, they do not incorporate evidence of, or reflections on, the impact of school genre writing and the mastery of school language registers on science learning (Avalos et al., 2017; de Oliveira & Lan, 2014; Fitts et al., 2020; Rappa & Tang, 2018; Seah, 2016; Seah et al., 2011). Likewise, under the assumption that science genre writing involves a deep understanding of scientific knowledge, these studies do not report how students learn to think scientifically and master scientific content for meaning-making within their texts.

Some quantitative studies have taken features of both approaches –*writing-to-learn*, and *learning-to-write*– and have shown positive effects on science learning (Cervetti et al., 2012; Chen et al., 2013; Huerta et al., 2014, 2016; Ruiz-Primo et al., 2004). However only Lee and colleagues (Lee, 2020; Lee et al., 2019) delve into the role of cross-disciplinary language in the learning of scientific practices, especially with English language learners. Still, how the writing of scientific explanations can be enhanced through *writing-to-learn* and *learning-to-write* with elementary school students has not been explored. Even less examined is the role of cross-disciplinary language skills in the learning of this science genre.

2.2 Scientific explanations: bridging scientific practice and school genre

The scientific explanation is an authentic practice that should be promoted early in schooling because students engage in sense-making about natural phenomena to understand the world, as the U. S. National Academies of Sciences, Engineering, and Medicine has declared (National Research Council, 2012; National Academies of Sciences, Engineering, and Medicine, 2022; NGSS Lead States, 2013). A scientific explanation involves reasoning to explain the causes of phenomena, based on evidence (National Council Research, 2012, NGSS Lead States, 2013). Although there is consensus about the relevance of teaching scientific explanations at school, research shows that there are tensions regarding how to differentiate explanation from argumentation (Braaten & Windschitl, 2011; McNeill & Krajcik, 2012; Osborne & Patterson, 2011). In this article, we understand an explanation as an account for a scientific phenomenon about which there is consensus. In contrast, argumentation arises from an unsolved controversy (Osborne & Patterson, 2011).

From a functional perspective of language, the school as a context of learning is comprised of genres that enable the building of content knowledge and simultaneously foster language development by amplifying students' linguistic repertoires (e.g., Myhill & Chen, 2020; Uccelli et al., 2020). *Genre* refers to a social practice characterized by a constellation of discursive and linguistic resources (Bakhtin, 1986). Therefore, scientific explanation is a school genre that is foundational to science learning (Avalos et al., 2017; Fitts et al., 2020; Seah, 2016; Tang, 2016).

In this study, scientific explanation is defined as a school genre whose purpose is to make explicit the underlying mechanisms that trigger a natural phenomenon and provide evidence to support a causal connection (McNeill & Krajcik, 2012; Meneses, Hugo, et al., 2018). This science genre is comprised of an *affirmation* that displays the causes of a given effect and the scientific *evidence* that supports the affirmation (McNeill & Krajcik 2012; Meneses, Hugo, et al., 2018).

Diverse interventions enable teaching to construct scientific explanations by testing different scaffolds, especially in elementary education (Cabello & Sommer, 2020; Hsu et al., 2015; McNeill et al., 2006; Sommer & Cabello, 2020). These scaffolds support the written production of the explanation as well as the metacognitive processes of revision. Written scaffolds exhibit significant pedagogical potential because they promote a common structure for a whole group and can be gradually withdrawn to transfer responsibility to the writers (Cabello & Sommer, 2020; Sommer & Cabello, 2020). Hsu et al. (2015) studied the effect of distributional scaffolding on earthquake explanations constructed by high school students. They showed that using organizers to scaffold the complex writing task helps students develop causal reasoning and improve the quality of their written explanations (Hsu et al., 2015). However, the latter research did not explore writers' specific cross-disciplinary language choices and how these language skills contribute to the quality of written scientific explanations.

2.3 The role of disciplinary and cross-disciplinary language skills development in scientific explanations

Writers require knowledge about the purpose and structure of the genre, along with language mastery to select specific language resources that allow for genre achievement (Myhill & Chen, 2020). Indeed, the development of disciplinary literacy involves knowledge of the genre and language proficiency to access and build knowledge across school disciplines (Brisk, 2015; Myhill & Chen, 2020). Several studies have noted the challenges of disciplinary language for students given the technicality of scientific vocabulary, evidence-based causal reasoning, and conceptual density through nominalizations (Evagorou & Osborne, 2010; Klein & Unsworth, 2014). Qualitative studies describe in-depth the role of these language resources in scientific explanations produced by middle school students and instructional proposals that promote the explicit teaching of scientific language (de Oliveira & Lan, 2014; Rappa & Tang, 2018; Seah, 2016; Seah et al., 2011). However, these studies do not distinguish between disciplinary and cross-disciplinary language resources and skills.

From a functional perspective of language, theoretical and empirical progress has been advanced in the definition of cross-disciplinary language –also known as school-relevant or academic language– as a trigger for learning across disciplines (Schleppegrell, 2004; Uccelli, 2019; Uccelli et al., 2020). This cross-disciplinary language is enacted through reading, writing, and speaking activities that build learning (Schleppegrell, 2004; Uccelli, 2019; Uccelli et al., 2020). Cross-disciplinary language skills operate in the communicative-discursive, textual, grammatical, and lexical dimensions and encompass, for example, the organization of analytical texts, logical connection of clauses, packing and unpacking of nominalization, and lexical precision (Uccelli, 2019; Uccelli et al., 2020). These cross-disciplinary resources have a receptive dimension (understanding how the resources work) and a productive dimension (using resources in constructing texts). Studies shown the significant contribution of receptive cross-disciplinary language skills to reading comprehension in both English (Uccelli et al., 2015) and Spanish among middle school students (Meneses, Uccelli, et al., 2018; Romero-Contreras et al., 2021) as well as the quality of school genre writing (e.g., Figueroa et al., 2018).

More research addresses how productive cross-disciplinary language resources (e.g., vocabulary, nominal group extension) contribute to the quality of school genres beyond the text length (Fang et al., 2020, 2021; Fang & Park, 2020). The contribution of receptive and productive cross-disciplinary language skills to the quality of science genres is explored minimally; only middle students' science summaries are considered (Phillips Galloway et al., 2020; Phillips Galloway & Uccelli, 2019; Uccelli et al., 2019). Phillips Galloway et al. (2020) found that, besides text length, receptive cross-disciplinary language skills and reading comprehension contribute to high-quality science summaries.

A longitudinal study by Uccelli et al. (2019) reported that in addition to receptive cross-disciplinary language skills in sixth grade, the diversity of connectives predicts the quality of summaries in seventh grade. These studies showed how productive cross-disciplinary skills are organized according to different language forms (discursive, textual, grammatical, and lexical) by documenting their frequency in written explanations. Aparici et al. (2021) examined changes in language resources both at the grade level (macro-developmental) and at the level of teaching contexts (micro-developmental), finding that resources show heterogeneous advances, some sensitive to writing instruction activities. These researchers do not explore how these micro-level language changes contribute to the quality of the genres written by students. Despite all that is described above, few scholars are looking into rubrics or coding systems to reveal how students display productive cross-disciplinary language skills in their written work –not only reporting the frequency of forms (resources) at word level– and the contribution of such skills to the quality of their writing (Huerta et al., 2016).

Writing in science is challenging for upper elementary students at least in two dimensions. First, they have to comprehend the causal mechanisms behind a scientific phenomenon; second, they need to master the disciplinary and cross-disciplinary productive resources and skills for crafting the science genre. Therefore, it is necessary to understand the contribution of cross-disciplinary language to changes in the quality of scientific genres resulting from instructional proposals aimed at scaffolding students' linguistic and conceptual learning. One way to achieve this objective is to quantify the frequency of language resources used by students within the scientific genre. Another less commonly adopted approach is to assess the mastery of language functions according to the expectations of use for building disciplinary genres.

2.4 This study

This study addresses two research questions:

(1) Do the quality of science explanations and the productive cross-disciplinary language skills deployed by fourth graders change through implementing an instructional unit that combines writing-to-learn and learning-to-write?

(2) Are the productive cross-disciplinary language skills associated with the final explanation quality, controlling for length and science knowledge?

3. Method

This study is micro-developmental because it examines changes in cross-disciplinary language skills within a limited period (Aparici et al., 2021; van der Steen et al., 2019). We use an intensive longitudinal design aligned to the one of Bolger and Laurenceau (2013) by employing multiple measures over an instructional unit. To answer the research questions, we developed a three-phases instructional unit. The two initial phases focused on writing-to-learn about scientific explanations, and the final focus on learning to *write* the scientific explanation genre.

3.1 Participants

The study participants were two fourth grade classes, a total of 65 students enrolled in a school in Santiago (Chile), serving students from low socioeconomic communities. Fourth grade students are between 9 and 10 years old (68% female, 32% male). Both classes were taught science by the same female teacher. This study followed ethical procedures required by the ethics committee of the authors' institution that was officially approved; procedures include the written consent of parents and students before participating in the instructional unit, and anonymizing data, among others.

3.2 Instruction's Pedagogical Design

Students participated in a two-unit instruction designed to learn how to construct scientific explanations. This study focuses on unit 1, about musculoskeletal movement. The unit is consistent with the Chilean National Science Curriculum (Ministerio de Educación de Chile; 2018) in its focus on the construction of scientific explanations. The instructional unit consists of weekly three-hour sessions for five weeks and includes nine activities organized in three learning phases. Figure 1 details the learning sequence and shows how the *writing-to-learn* and *learning-to-write* approaches are integrated.

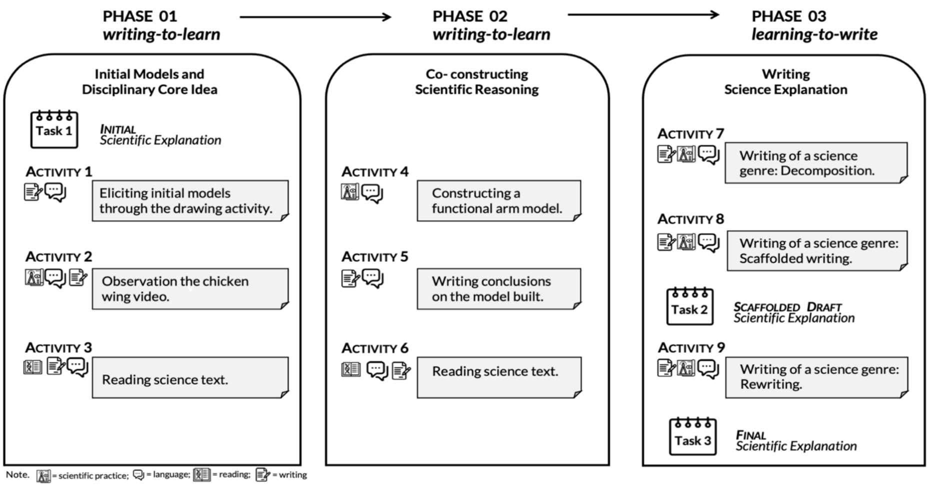


Figure 1. Instructional Unit for the Writing of Scientific Explanations

Phase 1 elicits students' initial models of components involved in arm movement, followed by observation of a video of a chicken wing dissection and concluding with reading a multimodal explanatory text that describes the relevant components to the phenomenon and characteristics. After observation and reading, students write a synthesis of the components involved in arm movement.

Phase 2 aims to develop causal reasoning through the construction of a functional model with concrete materials allowing students to inquire about how the movement occurs and advance from description to explanation. Students draw conclusions and reflect through scaffolded writing activities that provide cross-disciplinary language input. This phase concludes with the reading of a multimodal explanatory text. In phases 1 and 2, the *writing-to-learn* approach is used as a heuristic tool to support the construction of knowledge and scientific reasoning.

Phase 3 aims to explicitly teach scientific explanation as a writing genre (*learning-to-write*). The lesson incorporates elements of effective writing pedagogy including writing process and model study. We use the genre-based literacy pedagogy cycle (Rose & Martin, 2012) with particular attention to the cross-disciplinary language choices of specific resources in the crafting of scientific explanations (Myhill & Chen, 2020; Uccelli et al., 2020). The instruction aimed to produce a scientific explanation including affirmation and evidence (McNeill & Krajcik, 2012; Meneses, Hugo, et al., 2018). In the *affirmation*, students identify the scientific process and introduce causal ideas to determine how a phenomenon occurs. In the *evidence,* students present appropriate scientific data to support the *affirmation*: references to the model performed and the video observed.

3.3 Tasks

This study analyzes three scientific explanation tasks written by students at different times throughout the unit (see Figure 1). The question to produce the explanation was "Explain scientifically how the arm moves toward the forearm".

> *Task 1*. Initial explanations written before the beginning of the pedagogical unit without any scaffolding (64 texts).
>
> *Task 2*. Scaffolded draft explanations written during phase 3. Explanation support gave cues to students about genre organization and specific cross-disciplinary language resources (65 texts).
>
> *Task 3*. Final explanations written at the end of the unit without any scaffolding (62 texts).

The total corpus for this study is all previously detailed 191 scientific explanations identified to follow individual students' progress. All explanations were transcribed from handwriting to digital format, and spelling errors were corrected to avoid bias in subsequent coding.

3.4 Measures

Spanish Productive Cross-disciplinary Language Skills (S-P CLS). The analytical rubric determines students' performance in eight skills differentiated according to four dimensions of language: communicative-discursive, textual, grammatical, and lexical. These skills result in eight evaluation indicators, which specify the language expectations for the scientific explanation genre. Therefore, these cross-disciplinary language skills are analyzed as linguistic decisions made by the students to obtain effects in the meaning-making process of writing a scientific explanation. Table 1 shows the eight productive cross-disciplinary language skills, guiding questions, and operational definitions. This rubric was based on the framework for cross-disciplinary language for school literacy (Uccelli et al., 2020) and it can be provided by the authors for further details in its original Spanish version.

Each rubric indicator was scored between 0 and 4 points with a maximum total score of 32. Three experts validated the content of the rubric. Two experts in linguistics double-coded 65% of the data, achieving high inter-coder reliability (see Table 1). Cronbach's alpha for the rubric is .86, making it a reliable instrument.

Table 1. Spanish Productive Cross-disciplinary Language Skills (S-P CLS) for Written Scientific Explanations

Dimension/Skills	Guiding question	Definition	Cohen's Kappa
1. Communicative- discursive			
1.1 Genre Purpose Achievement	Does the written text achieve the purpose of the discursive genre expected in the task?	In a scientific explanation, the genre purpose is achieved by introducing and developing (1) a cause that explains the scientific phenomenon and (2) evidence that supports this causal relation.	.85
1.2 Stance's Adequacy	In the written text, is a stance adequate to the task constructed?	In a scientific explanation, the construction of a detached stance corresponds to an objective voice to refer to the events introduced in the discourse, typically through the consistent use of the third grammatical person.	.89
2. Textual			
2.1 Textual Unity	Does the written text function as an autonomous and cohesive unit?	The written production functions as an autonomous and cohesive whole that favors its global comprehension. That is, it is a textual unit, not context-dependent, in which the progression of the topic, the maintenance of the referents, and the connection between ideas guide the global comprehension of the explanation.	.77

2.2 Logical-semantic Relations Pertinence	Are ideas logically related to build relevant disciplinary reasoning in the written text?	In written production, disciplinary reasoning is developed through explicit and pertinent logical-semantic relations that articulate the text locally and globally. In a scientific explanation, the reasoning is expected to be oriented by cause-effect relation with explicit textual marks to sign the logical-semantic links developed.	.93
3. Grammatical			
3.1 Syntactic Pertinence	In the written text, are ideas packaged in syntactic structures relevant to the task purpose?	In written production, disciplinary reasoning gets developed in syntactic structures pertinent to achieving the discursive purpose. The purpose of a scientific explanation becomes enhanced by the complex syntactic constructions that crystallize causal scientific reasoning, such as causal, comparative, consecutive, conditional, or explanatory structures.	.93
3.2 Syntagmatic Precision	In the written text, are grammatical resources used in a manner appropriate to the co-text to favor text progression and ideas comprehension?	In written production, linguistic choices make grammaticality of the structures constructed, the correlation of resources in the (co)text, and the effective clause construction, among others, foster the text progression and the ideas' comprehension.	.93
4. Lexical			
4.1 Lexical Pertinence	In the written text, are words and expressions relevant to the disciplinary and cross-disciplinary domains required by the task integrated?	In written production, a relevant disciplinary and cross-disciplinary vocabulary is deployed. In a scientific explanation, all or almost all the words and expressions used belong to the disciplinary and cross-disciplinary domains and are conceptually linked to the phenomenon to be explained.	.93

4.2 Lexical Precision	In the written text, are the words and expressions used with a conceptually precise meaning that favors understanding the entities and processes involved?	In written production, words and expressions are used with a conceptually precise meaning that favors representing the entities and processes introduced in the production. In a scientific explanation, the vocabulary choices enable the representation of the phenomenon to be explained and the precise designation of the scientific entities and processes involved in this phenomenon.	.92

Scientific Explanation Quality. Every student's explanation was evaluated for the scientific quality of its affirmation and evidence through randomly distributed comparative judgment, where each judge compared two randomly chosen writing samples. After evaluating every sample by comparing pairs, an ordered scale was generated. Since this scale is based on the decisions of several judges, it represents a consensus on performance (Lesterhuis et al., 2017). The comparisons of ten trained judges were conducted with No More Marking® software. Each sample was compared ten times, resulting in a reliability coefficient of .90.

Explanation Length. It was calculated by counting the words per text.

Science Prior Knowledge. This variable was assessed with a paper-and-pencil test to measure science knowledge specified in the Chilean National Science Curriculum (Ministerio de Educación de Chile; 2018) for fourth graders at the beginning of the school year. This group-administered assessment consists of 40 multiple-choice items covering physics, chemistry, life science, and earth science topics declared in the mandatory Chilean Curriculum up to 4th grade. All items were scored as correct (1 point) or incorrect (0 points), with a total possible score of 40 points. Cronbach's alpha on this measure for this sample was .85.

Science Unit Achievement. A pencil-and-paper test assessed what students learned about musculoskeletal movement at the end of the instructional unit. The assessment included 34 multiple-choice items on the unit's main topics. The test had high reliability with a Cronbach's alpha of .83.

3.5 Analytic Plan

To answer research question 1, we applied a means comparison test for explanation quality and productive cross-disciplinary language skills (the eight indicators of the S-P CLS rubrics, the four-dimension scores, and the total score) over time. Research question 2 was answered by calculating correlations among explanation quality (initial and final), cross-disciplinary language skills (S-P CLS total score at each time), explanation length (at each time), science prior knowledge, and science unit achievement. To better understand the relations between the relevant variables, we calculated the correlations among final explanation quality, length, and each productive cross-disciplinary language skill (eight indicators of the S-P CLS rubrics) by time. Furthermore, we estimated five nested linear regression models of the final explanation quality as a function of the final explanation length, science prior knowledge, science unit achievement, and S-P CLS rubric indicators' scores by time. This analysis permitted observation of the interplay between scientific and language skills and their impact on the quality of explanations. The analysis was conducted in R version 4.0.4 (R Core Team, 2021), applying pairwise deletion, and figures were produced with the package ggplot2 version 3.3.5 (Wickham, 2016).

4. Results

4.1 Changes in scientific explanations quality and productive cross-disciplinary language skills

Table 2 shows the mean and the standard deviation for explanation quality and length, skill indicators, dimensions, and total S-P CLS rubric scores for each time (all scores were scaled from 0 to 1). All the variables show a statistically significant difference across time after a non-parametric Friedman rank-sum test. A post hoc Dunn's test for pairwise comparison with a Bonferroni correction reveals only significant differences between the initial and draft for all measures. The differences between initial and final explanations are significant for all measures except to syntagmatic precision and stance's adequacy. Size effect (η^2) is small for syntagmatic precision; moderate for stance's adequacy but is large for the rest of the variables. Notably, students tripled their score for explanation quality and length five times after the instructional unit. Their productive cross-disciplinary language skills also improved: their total score in the final explanation was almost double. Students' scores were highest for lexical skills, followed by communicative-discursive, textual, and grammatical skills. These results are confirmed by Figure 2, which shows a plot of S-P CLS indicator scores for each time.

As Figure 2 shows, all students improved their initial score except for stance's adequacy and syntagmatic precision indicators, which decreased slightly. Moreover, the statistical comparison showed that S-P CLS of the draft and final scientific explanations was not entirely different, suggesting that the efficacy of the scaffolding introduced in the draft carried through to the final explanation. Students learned to write a scientific explanation as a disciplinary genre and use scientific ideas to explain how the forearm moves towards the upper arm.

In sum, our results show that the quality, length, and productive cross-disciplinary language skills of scientific explanation increases steadily across the unit due to the instruction.

Table 2. Descriptive Statistics for Explanation Quality, Length, and S-P CLS Indicator Scores by Time

	Initial		Draft		Final						
	M	SD	M	SD	M	SD	df	N	χ2	p	η^2
Explanation Quality	0.26	0.11	-	-	0.73	0.13	1	65	61.00	0.000	0.71
Explanation Length	10.09	5.29	53.45	16.05	48.71	14.75	2	65	93.49	0.000	0.64
S-P CLS Indicator Scores											
Genre Purpose Achievement	0.30	0.11	0.73	0.13	0.75	0.19	2	65	99.87	0.000	0.65
Stance's Adequacy	0.84	0.30	0.74	0.21	0.80	0.21	2	65	12.89	0.002	0.07
Textual Unity	0.37	0.26	0.65	0.20	0.71	0.16	2	65	50.30	0.000	0.30
Logical-semantic Relations Pertinence	0.30	0.13	0.70	0.19	0.76	0.17	2	65	93.00	0.000	0.60
Syntactic Pertinence	0.19	0.12	0.59	0.18	0.64	0.21	2	65	95.81	0.000	0.58
Syntagmatic Precision	0.67	0.29	0.55	0.24	0.66	0.19	2	65	9.05	0.011	0.03
Lexical Pertinence	0.50	0.21	0.85	0.16	0.86	0.16	2	65	73.63	0.000	0.44
Lexical Precision	0.40	0.23	0.83	0.16	0.85	0.17	2	65	86.49	0.000	0.53
S-P CLS Dimensions Scores											
Communicative-discursive Dimension	0.55	0.19	0.72	0.16	0.73	0.23	2	65	47.20	0.000	0.35
Textual Dimension	0.33	0.15	0.67	0.18	0.69	0.22	2	66	86.98	0.000	0.48
Grammatical Dimension	0.42	0.20	0.56	0.20	0.61	0.22	2	66	32.54	0.000	0.15
Lexical Dimension	0.44	0.20	0.83	0.17	0.80	0.25	2	66	81.47	0.000	0.44
Total S-P CLS Score	0.43	0.16	0.70	0.15	0.71	0.21	2	66	75.01	0.000	0.46

Note. Mean (M) and standard deviation (SD) for explanation quality, length, and S-P CLS indicator scores by time. All the scores are scaled from 0 to 1. The results of a Friedman rank-sum test for means' difference across type (χ2) and the size effect (η2) are shown in the last five columns.

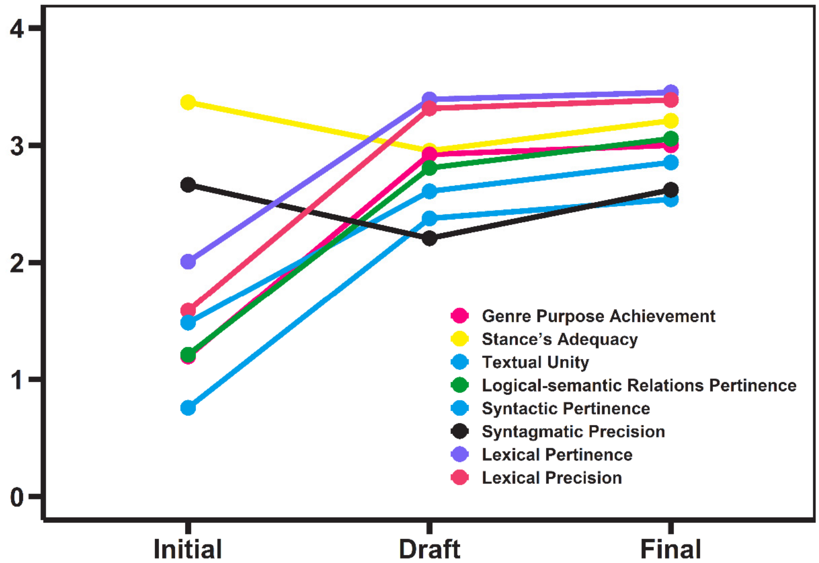


Figure 2. Graph of the S-P CLS Indicator Scores by Time

4.2 Contributions of productive cross-disciplinary language skills over time in the quality of final explanations

To answer research question 2, we conducted a correlation analysis among all the variables to identify those relevant to perform nested linear regression models subsequently (see Table 3). The quality of the initial explanation only correlates significantly with the S-P CLS scores and the explanation length, revealing that prior knowledge predicts posterior performance. The absence of a significant correlation between initial quality and science prior knowledge suggests that students could not fully express their scientific knowledge in the initial written explanation prior to the instructional unit.

The quality of the final explanation correlates positively with the S-P CLS scores from the draft and final explanations, as well as with the final length. Interestingly, it correlates significantly with both science prior knowledge and science unit achievement. The quality of the final explanation has a significant and a higher correlation with science prior knowledge than the initial explanation quality, despite the specific knowledge acquired through the unit. Apparently, the greater mastery of the science genre enhances the deployment of scientific knowledge at that stage. S-P CLS scores are positively related only between those displayed in the draft and final explanations, and these, in turn, correlate positively with the length of the respective explanations.

Lastly, final explanation length is one of the variables that had more significant and higher correlations with other variables, such as the quality of the initial explanation and S-P CLS indicators displayed in the initial explanation, which suggests an association with the fourth graders' language skills. The correlation between initial explanation length and science unit achievement is significant, although it is a non-linguistic and posterior measure; this result shows that some of the unit achievement is related to some prior linguistic skill rather than only to scientific knowledge. The positive associations between science unit achievement and the final quality of the explanations, the S-P CLS scores displayed in the draft and final explanations, and the lengths of these explanations reveal the relevance of the disciplinary knowledge in the writing of the genre.

Table 3. Correlations among Explanation Quality, S-P CLS Rubric Scores, Explanation Length, Science Prior Knowledge, and Science Unit Achievement

		1	2	3	4	5	6	7	8	9
1	Initial Scientific Explanation Quality									
2	Final Scientific Explanation Quality	.244								
3	Initial S-P CLS score	.577*	.116							
4	Draft S-P CLS score	.380*	.429*	.149						
5	Final S-P CLS score	.256*	.741*	.117	.493*					
6	Initial Explanation Length	.459*	.207	.443*	.233	.120				
7	Draft Explanation Length	.193	.222	.022	.322*	.268*	.135			
8	Final Explanation Length	.309*	.528*	.178	.485*	.521*	.210	.703*		
9	Science Prior Knowledge	.053	.283*	-.161	.142	.214	.061	.456*	.311*	
10	Science Unit Achievement	.249	.311*	.255	.323*	.503*	.301*	.374*	.323*	.236

Note. *:p<.05

Table 4 details how explanation length and S-P CLS indicators relate to final explanation quality by showing their correlations by time. Results reveal that the strength of the relations between S-P CLS and final quality increases as students progress throughout the instruction, resulting in relatively strong and significant positive correlations at the end. Especially noticeable is the high correlation between final explanation quality and three S-P CLS indicators: genre purpose achievement, logical-semantic relations pertinence, and syntactic pertinence deployed in the final explanation. Furthermore, there is also a moderate correlation between final explanation quality with both genre purpose achievement and logical-semantic relations pertinence deployed in the draft explanation. These results and previous correlations indicate that the quality of scientific explanation can be considered an expression of the multiple relations between scientific knowledge and language mastery. They cannot be studied separately and should be incorporated into a disciplinary genre to develop scientific reasoning.

Table 4. Correlations among Final Explanation Quality, Length and S-P CLS Rubrics Indicator Scores by Time

	Final Explanation Quality Correlation to		
	Initial	Draft	Final
Explanation Length	.208	.245*	.611*
Genre Purpose Achievement	.198	.428*	.725*
Stance's Adequacy	.075	-.035	-.033
Textual Unity	.021	.300*	.598*
Logical-semantic Relations Pertinence	.299*	.373*	.649*
Syntactic Pertinence	.182	.149	.633*
Syntagmatic Precision	.045	.370*	.160
Lexical Pertinence	-.006	.286*	.537*
Lexical Precision	-.048	.396*	.500*

Note. *: $p<.05$

After correlation analysis, a series of nested regression models were analyzed to answer research question 2 by adding variables that could predict the quality of the final explanation. Model 1 includes gender and final explanation length as predictive variables. Model 2 added science prior knowledge and science unit achievement as additional predictors. Model 3 included all the S-P CLS indicator scores for the initial explanation. All the S-P CLS indicator scores for the draft explanation were added in Model 4. Finally, final explanation length, science prior knowledge, science unit achievement, and the S-P CLS indicator scores for the initial, draft, and final explanations were considered in model 5. Each model was analyzed both fully and as an AIC (Akaike information criterion) version. In the full version, all variables were used to calculate the regression model's coefficient.

However, in the AIC version, a stepwise algorithm was applied backward and forward, and the model with the lowest AIC value was finally chosen.

Table 5 shows the fitting parameters for both versions of every model. The *F* statistics show that all models have regression coefficients that are statistically significantly different from zero, validating the procedure. As expected, adding more parameters increases the variance explained (R^2) and the generalizability of the regression model (AIC). Model 5 explained most of the variance in both versions (full model, 88.3%; AIC version,70.4%) and had the lowest AIC value. However, when comparing versions, the Model 5 AIC version could explain as much as 70.4% of the variance with only 12 parameters (df=11), surpassing even the full versions of Model 3 and 4 with more parameters. Although the selected variables in a stepwise procedure depend on the procedure conditions, the results confirmed that the AIC version of the models included the minimum set of model variables that could explain most of the sample's variance.

Figure 3 is a graph of the final explanation quality as a function of the independent variables for the AIC version of Model 5 as an illustrative example. Given that this model has 11 independent variables, we applied multidimensional scaling to consolidate them so they could be plotted.

Table 5. Fitting Parameters of the Full Model and the AIC Version for the Series of Regressions Models to Predict Final Explanation Quality

	Full Model						AIC Version					
Model	df	Res *df*	F	p	R^2	AIC	df	Res *df*	F	p	R^2	AIC
1	3	56	21.72	0.000	0.437	204.8	2	56	36.37	0.000	0.394	191.9
2	5	45	9.04	0.000	0.446	168.6	3	46	13.85	0.000	0.376	150.9
3	13	37	3.73	0.001	0.548	174.5	4	45	10.87	0.000	0.420	149.3
4	21	29	2.64	0.008	0.646	178.2	4	45	10.87	0.000	0.420	149.3
5	29	21	5.66	0.000	0.883	138.8	11	38	9.03	0.000	0.704	130.4

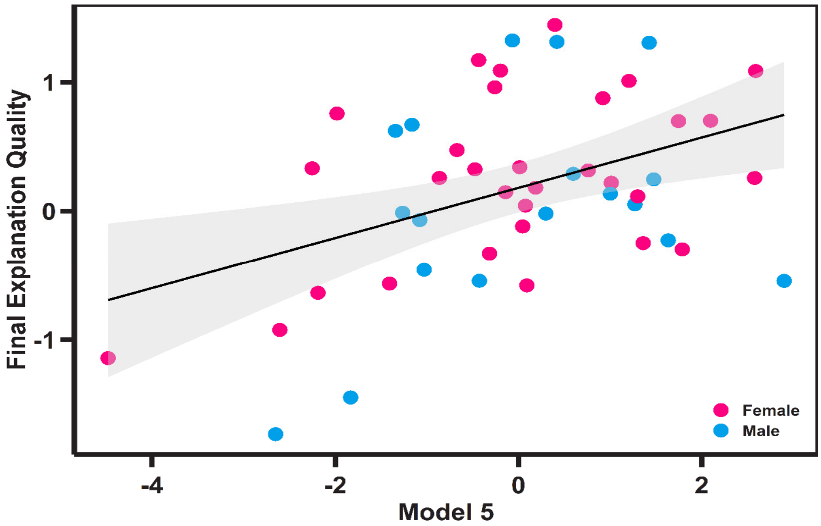


Figure 3. Graph of the linear regression for the AIC Version of Model 5 (black line) and students' data (dots).

Table 6 presents the standardized coefficients (β) and their standard errors (SE) for the AIC version of the regression models used to predict final explanation quality. Not all the previous models' variables appear in the next version, showing that their role differs when other variables are considered, mainly due to correlations among the independent variables. Gender was never selected, revealing that there was not a statistical difference between boys and girls. Noticeably, final explanation length is predominant in explaining the final quality of only the first four models but disappears in the fifth model.

Science prior knowledge remains a predictive variable and is approximately consistent in all models with a β value of 0.16-0.19. This is also true in the case of logical-semantic relations pertinence scores for the initial explanation, with a β value larger in the last model. The inclusion of the draft S-P CLS indicator scores in the fourth model does not change the relevant predictive variables found in the previous model. However, introducing the final S-P CLS indicator scores in the last model changes the outcome.

In model 5, all explanation times have S-P CLS indicators that contribute to predicting the final quality. Draft syntactic pertinence has a negative β value, indicating that the more advanced use of this skill in the draft explanation contributes negatively to the quality of the final explanation. Meanwhile, the lexical pertinence of the draft predicts final explanation quality.

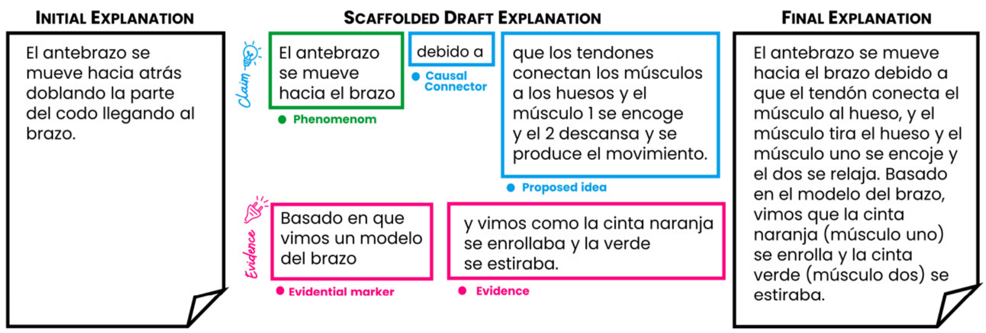
Table 6. Standardized Coefficients (β) and Their Standard Errors (SE) for the AIC Version of the Series of Regressions Mod
Explanation Quality

	Model 1		Model 2		Model 3		Model 4	
	β	(SE)	β	(SE)	β	(SE)	β	(SE)
(Intercept)	0.09	(0.09)	0.17*	(0.08)	0.16	(0.08)	0.16	(0.08
Final Explanation Length	0.66*	(0.11)	0.47*	(0.11)	0.46*	(0.11)	0.46*	(0.11
Science Prior Knowledge			0.16	(0.09)	0.19*	(0.09)	0.19*	(0.09
Science Unit Achievement								
Initial Explanation								
Logical-semantic Relations Pertinence					0.16	(0.09)	0.16	(0.09
Draft Explanation								
Stance's Adequacy								
Logical-semantic Relations Pertinence								
Syntactic Pertinence								
Lexical Pertinence								
Final Explanation								
Genre Purpose Achievement								
Stance's Adequacy								
Logical-semantic Relations Pertinence								

The adequacy of final stance has a negative β value, although it is high in the final explanation. Interestingly, students who produced the highest quality final explanations used the first person singular or plural and incorporated evidence from the video of the chicken wing dissection or the arm model built. In addition, the final logical-semantic relation pertinence score and genre purpose achievement contributed significantly to the quality of the final scientific explanation.

Three results are especially noteworthy in model 5. First, the contribution of the length of explanation disappears, which could be explained by the incorporation of final S-P CLS showing that it is not just about the number of words students use but rather how their writing decision-making shows language skills operating at the lexical, grammatical, textual, and discursive levels for the meaning-making process. Second, the manifesting of draft S-P CLS contributions shows the dynamic relationship between language skills over time, just as the incorporation of the final S-P CLS allows for the demonstration of draft skills. Third, the appearance of the unit science achievement as a predictor in this model reveals the interplay between language and science because unit science achievement has no isolated predictive power over the explanation quality, although it is directly related to the scientific topic of the explanation. It only has predictive power in conjunction with the language skills of the final explanation.

Figure 4 is an example that illustrates the relations over time between S-P CLS, length, science, and explanation quality.



	INITIAL EXPLANATION	SCAFFOLDED DRAFT EXPLANATION	FINAL EXPLANATION
COMMUNICATIVE- DISCURSIVE DIMENSION			
Genre Purpose Achievement	2	3	4
Stance's Adequacy	3	3	3
TEXTUAL DIMENSION			
Textual Unity	3	3	3
Logical-semantic Relations Pertinence	2	4	4
GRAMMATICAL DIMENSION			
Syntactic Pertinence	2	3	3
Syntagmatic Precision	3	3	3
LEXICAL DIMENSION			
Lexical Pertinence	2	3	4
Lexical Precision	3	3	4

Figure 4. Example of Initial, Scaffolded Draft and Final Explanations of a 4th Grader

To summarize our results, the correlations show that improvements in productive cross-disciplinary language skills are correlated to improvements in scientific explanation quality, and explanation length. Moreover, the positive correlations between science unit achievement and scientific explanation quality and cross-disciplinary language skills show the relevance of disciplinary knowledge in genre writing. Furthermore, our regression analysis shows that the quality of scientific explanation can be predicted by prior and current science knowledge and productive cross-disciplinary language skills across time, without consideration of explanation length, a variable that has a predominant predictive power in previous studies.

5. Conclusion and discussion

This study examines micro-developmental changes in cross-disciplinary language skills and their contribution to the quality of scientific explanations written by fourth-grade students. Students participated in a language and literacy-based instructional unit that integrated *writing-to-learn* and *learning-to-write*. The improvements seen in this study in the quality of students' explanations are consistent with other studies, highlighting changes after participation in explicit teaching sequences (Avalos et al., 2017; Fitts et al., 2020; Huerta et al., 2016; McNeill et al., 2006; Tang, 2016), namely, an increase in explanation quality, organization and length, and a higher presence of cross-disciplinary language skills.

5.1 Changes in scientific explanations quality and productive cross-disciplinary language skills

The present study shows that productive cross-disciplinary language changes vary by skill: outcomes are better for those skills that operate at the lexical and communicative-discursive levels but lower for the syntactic skills (Figure 2). The heterogeneous changes found may be associated with the teaching foci of the instructional unit. Indeed, the results of Aparici et al. (2021) underline that micro-developmental language changes are not homogeneously sensitive to all pedagogical work. The instructional unit in which the fourth-grade students participated employed writing as an epistemic tool for generating scientific reasoning –*writing-to-learn*– (Chen et al., 2013; Hand et al., 2007, 2009) and as a construction of disciplinary genre that unpacks specific language resources –*learning-to-write*– (Avalos et al., 2017; de Oliveira & Lan, 2014; Fitts et al., 2020; Rappa & Tang, 2018; Seah, 2016; Seah et al., 2011). The *writing-to-learn* approach was applied when explicitly teaching scientific knowledge from a constructivist learning theory perspective (Hand et al., 2007) whereas the *learning-to-write* approach was used while utilizing specific language to create a science genre, as functional theory of language proposes (Myhill & Chen, 2020; Rose & Martin, 2012; Uccelli, 2019).

Cross-disciplinary language skills were unpacked to help produce scientific explanations (Uccelli, 2019; Uccelli et al., 2020), meaning students learned the school language register along with the writing processes. However, the focus was on mastering the purpose of the genre and there were fewer opportunities for explicit teaching of grammatical skills. The results of this study also show that conceptual and linguistic scaffolding improves cross-disciplinary productive language mastery without decreasing achievement after the scaffolds are withdrawn. This result is consistent with other instructional proposals at the elementary level that promote whole group scaffolding which is gradually removed to give students more responsibility on their writing processes (Cabello & Sommer, 2020; Hsu et al., 2015; McNeill et al., 2006; Sommer & Cabello, 2020).

5.2 Contributions of productive cross-disciplinary language skills over time in the quality of final explanations

The correlations found among explanation quality and language skills highlight the relations between school genre writing, language proficiency, and science learning (Table 4). First, the strong positive correlations between final explanation quality and several productive cross-disciplinary language skills highlight multiple linkages between language and school genre writing. Second, the changes in the correlations throughout the unit show the dynamism of these relations over time: as students go from *writing-to-learn* to *learning-to-write*, the positive correlations between the final explanation quality and the productive cross-disciplinary language skills increase. The significant correlations found between cross-disciplinary language proficiency and the quality of scientific explanation writing agrees with previous studies that explore these relationships within other scientific genres. Indeed, studies of the quality of science summaries and receptive language skills proficiency show moderate positive correlations (between .38 and .66) (Phillips Galloway & Uccelli, 2019; Phillips Galloway et al., 2020; Uccelli et al., 2019). Fang and Park (2020) found a moderate positive correlation (0.61) between a composite of 11 cross-disciplinary language resources and the quality of school genres for a sample of seventh and ninth graders. Furthermore, the present study assesses the mastery of productive cross-disciplinary language using a rubric that captures associations between productive skills and scientific explanation quality (r=. 741, p<.05), as well with the acquired scientific knowledge (r=. 503, p<.05).

Moreover, this study offers novel evidence regarding the prediction of the quality of explanations by the productive cross-disciplinary language skills deployed by 4th graders (Tables 5 & 6). Our regression analysis shows that the predictive power of explanation length found in previous studies (Phillips Galloway & Uccelli, 2019; Phillips Galloway et al., 2020; Uccelli et al., 2019) disappears as the productive cross-disciplinary language skills are included as predictors, revealing that explanation quality significantly depends on language skills operating at the lexical, grammatical, textual, and discursive levels. Mastery of language skills develops in a sequence of growing complexity; the simplest skills being mastered earlier with their positive impact on explanation quality remaining over time. Finally, although current scientific knowledge is relevant for explanation quality, it only can be expressed when a minimal set of language skills is mastered. These results suggest that the mastery of cross-disciplinary productive language skills requires explicit teaching opportunities and that their mastery in contexts and genres relevant to the discipline allows for knowledge expression (Myhill & Chen, 2020; Uccelli, 2019).

The contributions of this study fall in two domains. First, previous research explores gradual changes in cross-disciplinary language and conceptual understanding by language status and gender groups (Huerta et al., 2016), showing significant language gains for all groups with important differences in conceptual domains by gender. However, the contributions of disciplinary knowledge to the quality of explanations have not been explored. Second, longitudinal studies on cross-disciplinary language development have looked at receptive language and the contribution of connective diversity, explaining up to 32% of the variance (Uccelli et al. 2019). The present study included productive language and was able to explain 70.4% of the variance with noteworthy contributions of final skills at the textual (construction of disciplinary reasoning) and communicative-discursive (mastery of the school genre) levels.

5.3 Limitations and future research

This study is limited by a medium sized sample of 65 fourth graders. A larger sample would add depth to the understanding of the associations identified. Research over a longer time span would shed more light on cross-disciplinary language development in students who participate in more than one instructional unit or in subsequent grades (macro-developmental). Given the relationship found between all productive cross-disciplinary language skills by time and prior and achieved science knowledge, further studies could explore the direct and indirect relations between productive cross-disciplinary language skills, scientific knowledge, and the quality of scientific explanations.Future research may incorporate either receptive cross-disciplinary language skills or cross-disciplinary language resources to understand the connections between receptive and productive skills and resource frequency as predictors of science explanation quality.

In conclusion, this study documents the changes of productive cross-disciplinary language skills over time, in a science writing teaching unit based on the integration of writing as an epistemic tool to trigger scientific reasoning and as an object of learning through the scaffolded writing process of a school genre. The results show that the development of cross-disciplinary language skills is not exclusively associated with age but can be related to writers' skills (Myhill & Chen, 2020) and it is sensitive to instructional work (Aparici et al., 2021). Therefore, unpacking productive cross-disciplinary language skills according to lexical, grammatical, textual, and communicative-discursive level, allows for revealing the hidden connections between school register language skills and the quality of a school genre (Uccelli, 2019; Uccelli et al., 2020). Thus, the current study provides evidence that encourages further exploration of writing as a linguistic decision-making activity in which cross-disciplinary language proficiency and science knowledge interact to construct disciplinary reasoning (Myhill & Chen, 2020, Uccelli 2019).

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