Title: Interweaving Pedagogy, Content, Language, and Technology: Digital Tools to develop Bi- and Multilingual Disciplinary Literacies in CLIL Math classrooms.

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Abstract

Research in Content and Language Integrated Learning (CLIL) is beginning to examine learners' development of bi-/multilingual disciplinary literacies (BMDLs). Digital technologies play a key role in this process, yet little is known about how teachers integrate them in CLIL mathematics classrooms. This article presents a comparative case study of two secondary mathematics teachers: one in an English-medium school in Spain, the other in an Irish-medium school in Ireland. Data were generated through semi-structured interviews and resource-stimulated recall sessions, and analyzed thematically within and across cases. Findings show that tools like Desmos, GeoGebra, GimKit, and Quizlet supported distinct literacies—procedural, graphical, modeling, and terminological—but their effectiveness depended on teachers' technological pedagogical content and language knowledge (TPCALK). While digital tools increased engagement and multimodal reasoning, their monolingual design constrained bilingual scaffolding. The study concludes that BMDL-sensitive design and explicit attention to language

are essential in CLIL mathematics pedagogy and recommends further classroom-based research.

Key words: TPCALK, CLIL, immersion education, multilingual education, plurilingual education, bi-/multilingual disciplinary literacies (BMDLs), mathematics education

1. Introduction

Over the past decade, Content and Language Integrated Learning (CLIL) research and practice have increasingly moved from language-informed approaches towards literacies-based perspectives (Llinares et al., 2012), placing greater emphasis on developing learners' discipline-specific literacies in CLIL learning. Drawing on Shanahan and Shanahan (2012), this perspective foregrounds the relationship between academic subjects and their distinct ways of using language to construct, communicate, and evaluate knowledge, which must be explicitly taught alongside content learning in order to socialise learners into thinking, talking, and acting as members of particular disciplinary communities (Rainey & Moje, 2012).

The process of disciplinary socialisation is complex, especially in CLIL contexts where the learning environment is bi- or multilingual in nature. This calls for an enhanced understanding of literacy development in such pedagogical settings. The conceptualisation of bi-/multilingual disciplinary literacies (BMDLs) proposed by Nikula et al. (2024) provides a multidimensional model, suggesting that BMDLs encompass several interrelated dimensions (e.g., critical, functional, technological, multimodal and transsemiotic, and bi-/multi-/translingual). These dimensions are underpinned by their interconnectedness, brought about by the integrated nature of content and language in CLIL classrooms, in which all play a role to a greater or lesser extent in disciplinary socialisation in CLIL classrooms. In line with Nikula et al. (2024), we refer to the technological dimension, which encompasses the role of digital tools and technology-mediated meaning-making in disciplinary teaching and learning. The present study focuses principally on how this BMDL dimension interacts with the other dimensions to explore how teachers of mathematics in CLIL contexts use their Technological Pedagogical and Content Knowledge (TPACK) (Mishra & Koehler, 2006) together with their language knowledge for content teaching (LK-CT) (Morton, 2018) to develop mathematical disciplinary literacies in bi-/multilingual contexts and, in particular, the role that the technological dimension plays in mediating the language of the classroom.

Research into the role of digital tools in mathematics education is well documented (Clark-Wilson et al., 2020; Drijvers, 2013; Leung & Bacclaglini-Frank, 2017) as well as the role of language in mathematics and mathematics education (Erath et al., 2021; Moschkovich, 2015; Schleppegrell, 2007). More recently, pan-European data gathered to explore the role of extramural language exposure through digital activities can also aid students' familiarity with mathematical terminology and problem-solving skills to support their CLIL learning in school (Ghamarian et al., 2024). However, little research has examined how teachers' use of digital tools inside CLIL classrooms can support the wider development of learners' BDMLs in mathematics. Our focus on the technological dimension of BMDLs stems from the fact that digital tools provide a tangible site where content and language integration becomes visible through classroom artefacts. Moreover, digital technologies are a key pedagogical site through which multimodal meaning can be built by learners in mathematics.

The purpose of this study is to examine how two CLIL mathematics teachers use digital tools in their everyday teaching and learning to support the development of BMDLs. Also, through a comparison of an English-medium school in Spain and an Irish-medium school in Ireland, the study explores how teachers' technological, pedagogical, content and language knowledge (or TPCALK) shapes their decision to use such tools. The study will also explore how language is mediated within those practices. The research questions, therefore, that guide this study are as follows:

RQ1: How are digital tools used in CLIL mathematics classrooms to support the development of learners BMDLs?

RQ2: How does teachers' TPCALK shape their decisions about when, why, and for what purposes digital tools are used in preference to non-digital approaches in CLIL mathematics?

RQ3: How do digital tools mediate language use in CLIL mathematics classrooms, and how do teachers mobilise language knowledge for content teaching (LK-CT) to support learners' disciplinary meaning-making across languages?

2. Literature review

2.1. Bi- and Multilingual Disciplinary Literacies in CLIL mathematics contexts.

Research on disciplinary literacies has established that learning should go beyond meeting content standards to engage learners in the multiple literacy practices through which disciplines are enacted in and out of school (Moje, 2015). In mathematics, these literacies include the ability to interpret, model, and apply mathematics in real-world contexts (Geiger et al., 2015; Niss & Højgaard, 2019). In contexts where mathematics is taught through an additional language, approaches to disciplinary literacies and mathematical literacies are connected and reconceptualised through the integration of language in the framework of bi-/multilingual disciplinary literacies (Hüttner et al., 2025).

Learning mathematics involves more than mastering content knowledge; it requires participation in a variety of literacy practices that are socially and linguistically situated. We therefore intentionally adopt the plural form, 'literacies', to reflect the diversity of literate practices that constitute doing mathematics in school and beyond. In line with broader research in disciplinary literacies (e.g., Fang, 2012; Rainey & Moje, 2012; Shanahan & Shanahan, 2012), mathematical literacies are an ensemble of different practices that call on different semiotic resources, linguistic registers, and ways of reasoning such as proof and argumentation, algebraic-symbolic manipulation, modeling, spatial and diagrammatic reasoning, data/statistical reasoning, etc. Each has distinct representational demands and discourse norms.

Such practices must be orchestrated coherently by learners (O'Halloran, 2005) both cognitively and through distinct linguistic realisations, which differ from everyday language and require explicit mediation (Schleppegrell, 2007). For instance, mathematical discourse entails reasoning, explaining, and justifying, practices which are often developed through (social) interaction (Erath et al., 2021; Moschkovich, 2015). In turn, these practices within the discipline of mathematics are diverse. For example, a learner's ability to reason statistically (e.g. interpreting distributions and uncertainty) is not the same as their ability to construct a geometric proof or to develop a functional model). Each activity draws on a partly different set of skills, knowledge, and ways of communicating, and, therefore, represents a distinct set of literacies. Hoogland et al. (2018) also show that communication in mathematics and, in particular, reading extends beyond text to include images, diagrams, and multimodal cues, which significantly shape learners' acquisition of mathematical disciplinary literacies.

The bi-/multilingual character of CLIL settings amplifies the complexity of mathematical discourse and practices even further. Ní Riordáin, Neville, and Daly (2024) identify five components of mathematics discourse based on Pimm and Keynes (1994): genre/register, spoken language, inner mathematical mediation, written language, and symbolic/graphical systems all of which can take place in different linguistic codes, sociolects and idiolects. The choice to use a particular linguistic code can be both intentional and unintentional. In such classrooms, translanguaging practices and strategic movement across representations become central resources for meaning making in mathematics (MacKenzie et al., 2022;

Moschkovich, 2015). While such dynamic forms of communication can foster deeper learning (Coyle & Meyer, 2021), particularly in mathematics (see Kuzu, 2023), mathematical discourse in bi- and multilingual settings offers a unique and complex case of disciplinary literacies development.

To offer a definition of BMDLs in mathematics in CLIL contexts is, therefore, equally complex. Building on the general definition of BDMLs from Hüttner, Llinares and Nikula (2025), we define BMDLs in mathematics as the multilingual, multimodal, and digitally mediated literacies through which learners engage in the plurality of mathematical practices (e.g., proving, modeling, data reasoning). They describe how learners purposefully mobilise their linguistic varieties, semiotic resources, and digital tools to engage with the full spectrum of mathematical practices to construct, communicate, and critically evaluate mathematical meaning across the five aforementioned dimensions: the bi-/multilingual, the functional, the multimodal, the critical and the technological.

The bi-/multi/-translingual dimension highlights how meaning is negotiated across languages as learners move between everyday talk, school registers, and specialised disciplinary discourse. This strategic use of language is modelled by the teacher who also not only shifts between languages, but also explicitly connects the language varieties and representations (Erath et al., 2021). Such strategic language choice can help learners to develop understanding and make sense of content (Moschkovich, 2015; Prediger & Wesser, 2013) as well as promote increased pedagogical inclusion (Planas & Setati, 2014). For example, to explain the reasoning, logic, and structure behind a proof may involve drawing on a home language, the language of instruction, and the symbolic “language” of mathematics, with translanguaging enabling articulation of reasoning and clarification of terminology.

The functional dimension foregrounds the purposeful nature of mathematical communication. This involves not only teaching and learning *through* language, but also explicitly *of* language or, in other words, the discourse practices necessary for communicating mathematics (Erath et al. 2021). In CLIL classrooms, the functional dimension also involves the combination of different cognitive discourse functions (CDFs) (Dalton-Puffer, 2016). Cognitive discourse functions refer to the ways in which language is used to perform discipline-specific thinking processes, such as describing, comparing, evaluating or explaining. In mathematics classrooms, learners frequently combine several CDFs within a single topic. For instance, when working with statistical data, students may be required to describe patterns, explain possible causes, and evaluate the reliability of conclusions. Even within a single CDF the linguistic and conceptual demands may vary: describing a statistical distribution differs from describing a geometric conjecture, as each draws on distinct disciplinary registers and forms of reasoning.

The multi- and transsemiotic dimension illustrates how mathematics is inherently multimodal, combining algebraic symbolism, graphs, diagrams, natural language, and digital visualisations to create meaning. Learners must navigate between these symbolic, visual, and linguistic modes to build meaning, a task that requires careful design and scaffolding by the teacher to ensure that mathematical representations are connected with disciplinary practices (Leung & Baccaglini-

Frank, 2017). Similar to the way image-rich versus word problems shift cognitive and literacy demands (Hoogland et al., 2018), digital tools such as GeoGebra or Desmos alter the semiotic landscape of a task.

Beyond the role that digital tools play in developing multisemiotic meaning, the technological dimension expands the semiotic landscape of mathematics by enabling new forms of representation and manipulation. Technology supports learners in mathematics by transforming abstract concepts into interactive, visual representations that deepen understanding and develop both technical and conceptual fluency. When teachers guide this process through instrumental orchestration, they intentionally manage how and when tools are used in the classroom to support specific learning goals, acting as conductors who synchronise interactions between learners, representations, and mathematical content (Clark-Wilson et al., 2020). This promotes active engagement, collaborative reasoning, and positions the teacher as an orchestrator of disciplinary thinking rather than a transmitter of fixed knowledge. Moreover, BMDLs offer scope to move beyond navigation across multiple languages towards critical engagement with the epistemic status of technology-mediated outputs, including potential reflection on how meaning is constructed, represented, and validated through digital tools.

Finally, the critical dimension goes beyond procedural fluency to involve evaluating representations, questioning assumptions, and assessing the validity of arguments, while also making strategic decisions about which languages, registers, or semiotic forms to deploy that are most appropriate for the communication of content or the enactment of mathematical practices (Monteleone et al., 2023). Language is, therefore, agentive, meaning is relational and language is diverse, stratified and stratifying (Barwell, 2018).

While we acknowledge the "mathematical literacy" tradition (e.g., Jablonka, 2003; Ojose, 2011), the application of BMDLs allows us to understand and interpret the inter and intra dimensional heterogeneity in which CLIL teachers and learners engage in CLIL today's mathematics classrooms. It is the BMDLs framing that we adopt as the analytical approach in this study to help us understand how CLIL educators create the appropriate environment (Hoogland et al. 2018) in which they develop learners' BMDLs in mathematics. To guide our examination, we adopt the technological dimension of BMDLs as the primary analytics lens and draw on the Technological Pedagogical Content Knowledge (TPACK) construct to interpret how CLIL mathematics teachers integrate digital tools in their practice.

2.2. Technological Pedagogical Content Knowledge (TPACK) in CLIL contexts.

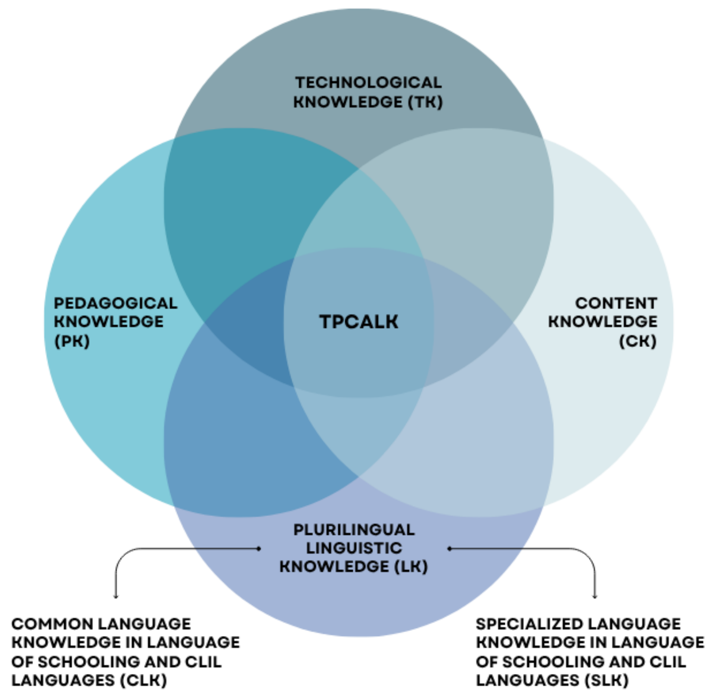
Research on the integration of digital technologies into teaching has demonstrated their potential to transform both subject learning and classroom interaction (Clark-Wilson et al., 2020; Drijvers, 2013; Leung & Baccaglini-Frank, 2017). The TPACK framework extends Shulman's (1986) concept of pedagogical content knowledge by incorporating technology (Mishra & Koehler, 2006) and is a useful tool to understand how teachers achieve this potential.

The framework recognises the differing ways in which technology mediates these two domains and shows how considering their interaction in this way can support the planning of teaching and learning sequences (Angeli & Valanides, 2009; Harris & Hofer, 2011). Research in this area has also shown that various technologies across different educational contexts can offer distinctive ways of illustrating how technology shapes the development of content-related pedagogy and the subsequent teaching and learning of subject matter (Angeli & Valanides, 2009; Doering et al., 2014; Lee & Tsai, 2010; Porras-Hernández & Salinas-Amescua, 2013; Tunjera & Chigona, 2020; Yeh et al., 2014). Research, however, in specific disciplinary areas (i.e., subject areas) is limited. In the discipline of mathematics, for example, research has focused both on the use of specific tools such as interactive whiteboards (Jang & Tsai, 2012) or on the development of technology integration as a fundamental skill in initial teacher education (Niess, 2005). However, little empirical research has examined how and why teachers use technologies to support the integrated teaching of content and language in bi/multilingual settings. One reason for this lack of research could be attributed to the empirical difficulties in measuring such integrative phenomena (Lee et al., 2022), an issue that is highlighted by Wei and Lee (2024) in terms of the complexities of technologically mediated communication.

We would also argue that language specifically has not been considered in sufficient depth in the interplay between digital tools, mathematical content, and language development, particularly in disciplinary areas such as those found in CLIL contexts. The Integrated Pedagogical Content Knowledge (I-PCK) framework developed by Troyan et al. (2017) offers some understanding of this interplay in immersion settings by emphasizing the interplay between language (content knowledge of language, CK-L), subject matter knowledge (content knowledge of the curriculum area, CK-C) and pedagogical knowledge (PK). The intersections of these domains—language pedagogical content knowledge (PCK-L), referring to strategies for effective language teaching, and curriculum area pedagogical content knowledge (PCK-C), referring to strategies for teaching specific content areas—demonstrate that CLIL teachers require not only proficiency in the language of instruction but also a thorough understanding of its systems and structures for successful language and content integration (Ó Ceallaigh et al., 2021). Morton (2018) focuses on this aspect of language knowledge for content teaching (LK-CT), which expands teachers' pedagogical knowledge by addressing the specific language skills needed for teaching content. A CLIL teacher's LK-CT includes the subdomains of common language knowledge for content teaching (CLK-CT) and specialized language knowledge for content teaching (SLK-CT). Therefore, CLIL teachers' language knowledge includes everyday language and subject-specific language knowledge (or CLK-CT) that "allows them to carry out routine tasks and converse about everyday topics [...] and also to understand, read, write and talk about their academic subjects" (Morton, 2018, p. 5). Additionally, teachers need to be proficient in the academic language used to represent concepts and, in some ways, to make such language accessible for learners (i.e., their SLK-CT). However, perhaps an element that is missing here is recognising that teachers should also be competent in both the languages of schooling and the CLIL language to capitalise on and develop the plurilingual competences of their learners.

Figure 1.

TPCALK Framework for CLIL.



Both the I-PCK and LK-CT frameworks emphasise the dynamic and integrated nature of linguistic and content knowledge in teaching. Building on TPACK (Mishra & Koehler, 2006), the I-PCK model (Troyan et al., 2017) and Morton's (2018) LK-CT conceptualisation, we propose the Technological Pedagogical Content and Language Knowledge (TPCALK) as an integrated framework to conceptualise how technology, pedagogy, content, and language knowledge intersect in CLIL classrooms. Figure 1 illustrates this model, which provides the analytical foundation for this study.

Extending TPACK to include language considerations underscores that technology integration cannot be fully understood without accounting for how teachers support both subject-specific content and language development. The integration of the I-PCK and LK-CT frameworks into our proposed TPCALK model (see Figure 1) makes this dimension visible, emphasising that digital technology use cannot be fully understood without considering how teachers support both subject-specific and linguistic development. This perspective provides the foundation for linking TPCALK to the development of BMDLs.

3. Case Study Contexts

This case study examines two school contexts in Spain and Ireland, offering a valuable comparison between two differing CLIL settings. In both the Spanish and Irish case, the model of CLIL in which participants work professionally is partial immersion. In both cases, the majority of school subjects are taught through the immersion language. In the case of Spain, this is English and in the case of Ireland, this is *gaeilge* or Irish.

In Spain, CLIL programs are usually delivered through partial immersion, whereby part of the curriculum is taught through an additional language (in most cases, English) while the remainder is delivered through the normal language of schooling. Nonetheless, in private education, such as in international schools, full immersion is also common where the entire curriculum is delivered through an additional language such as English. Plurilingual education is also gaining traction, particularly in linguistically diverse regions where regional languages are taught alongside Spanish and other foreign languages (Ministerio de Educación, Formación Profesional y Deportes, 2023). Across Spain, in 2022/23, 46.6% of primary and 41.1% of secondary students received classes in a foreign language (Ministerio de Educación, Formación Profesional y Deportes, 2023). However, the rapid expansion of CLIL programs has surpassed teacher training and resources, with challenges including integrating content and linguistic goals and addressing diverse learning needs due to insufficient training opportunities (Pérez Cañado, 2014; Pérez Cañado, 2021).

Conversely, in Ireland, CLIL is implemented through immersion education in Irish (Gaeilge), a minoritized language protected by legislation since the early 20th century (Government of Ireland, 2020). As of the 2023/24 academic year, over 9% of primary school students (approximately 49,319) are taught in 293 Irish-medium (or IM) primary schools and 3.3% of secondary school students (around 28,000) are educated in 81 IM secondary schools (DoE, 2024). These students are taught in either Gaeltacht areas, where Irish is the main community language, or non-Gaeltacht areas, where students attend *gaelscoileanna* (primary) or *gaelcholáistí* (secondary). While foreign-language CLIL has expanded in Spain over the last decades, IM education has existed for over a century and continues to grow, including the reintroduction of Irish in English-medium primary schools as a CLIL language for some subjects (mainly Art and PE) in 2024 (An Roinn Oideachais, 2024).

4. Methods

This study follows a comparative case study methodology to explore how and why teachers use digital tools to support learners' development of BMDLs.

4.1. Participants.

This study draws on two in-depth case studies of mathematics teachers working in distinct CLIL contexts. LM is an experienced mathematics teacher with over 18 years of teaching experience, working in a private international secondary school in Spain (12-18 years old). His school follows an English-medium curriculum and serves predominantly high socioeconomic status families, with students originating from diverse national backgrounds. While English is the main language of instruction, most students speak at least one additional language, typically Spanish, at home. LM is a native English speaker with no formal training in bilingual or CLIL pedagogy and limited engagement with disciplinary literacy frameworks. Although his students are plurilingual, LM's teaching practice reflects a greater emphasis on mathematical content delivery than on explicit language support. Despite students' multilingual profiles, he does not routinely address language issues, viewing them as secondary to mathematical problem-solving.

SF, by contrast, is an early-career mathematics teacher with three years of experience in an Irish-medium secondary school in Ireland. She teaches in a bilingual immersion secondary school context (12-18 years old) where Irish is the primary language of instruction for all subjects. Most of her students speak English as their home language, with Irish acquired through schooling, and live in a diverse urban area. SF is herself bilingual in Irish and English and has formal training in bilingual education, which shapes her attention to language in mathematics instruction. She actively incorporates strategies to address linguistic demands, often designing tasks to develop both mathematical concepts and related terminology in Irish and English. Her pedagogical approach reflects an awareness of the role of language in learning mathematics, even though she had limited prior knowledge of BMDLs as a formal concept before participating in the study.

An important feature of both teachers, however, especially for the purposes of this research, is that they were not aware of BMDLs. They had not received formal training in disciplinary literacies or in integrating language and content in mathematics. Therefore, where we suggest that their pedagogical actions support the development of BMDLs, such developments are not undertaken consciously by either professional. However, during the interviews we did provide them with an explanation of what BDMLs were in CLIL contexts and, most importantly, when the interview had finished, we explained why it was important to develop them and how their current approaches support this endeavour.

4.2. Data collection instruments.

Two data collection methods were employed to gather teacher insights. We conducted semi-structured interviews with each participant teacher to gather in-depth information on their experiences, beliefs and practices regarding the use of digital tools in teaching mathematics in the CLIL language, and the teachers' perceptions on how those tools supported the development of BMDLs in CLIL mathematics. The interviews also explored the reasons behind the teachers' choice of digital tools, and the specific challenges and strategies related to their linguistic context.

Following each interview, a resource stimulated-recall session (RSR) was conducted with each participant. Based on more general approaches to stimulated-recall (Zhai et al., 2024), this method allowed us to explore participants' cognitive and affective responses to their digital resources and pedagogies after they had been used to gather implicit data related to their effectiveness in developing disciplinary literacies in differing CLIL settings. In this session, teachers were asked to choose digital-based activities or material that they had designed and used in their CLIL Maths classes and share their reflections on how these materials supported the development of BMDLs. RSR sessions helped us understand the decision-making process behind the purposeful use of digital tools in CLIL Math classes and the contextual factors influencing the use of digital tools, such as the teachers' and students' linguistic backgrounds.

Data were analyzed qualitatively through thematic analysis. Each case was first examined individually to identify patterns emerging from the interview and RSR data. These themes were then compared across cases to examine similarities and differences in how the two teachers described their use of digital tools in relation to BMDLs and the mediation of language use in their respective CLIL mathematics contexts.

5. Findings

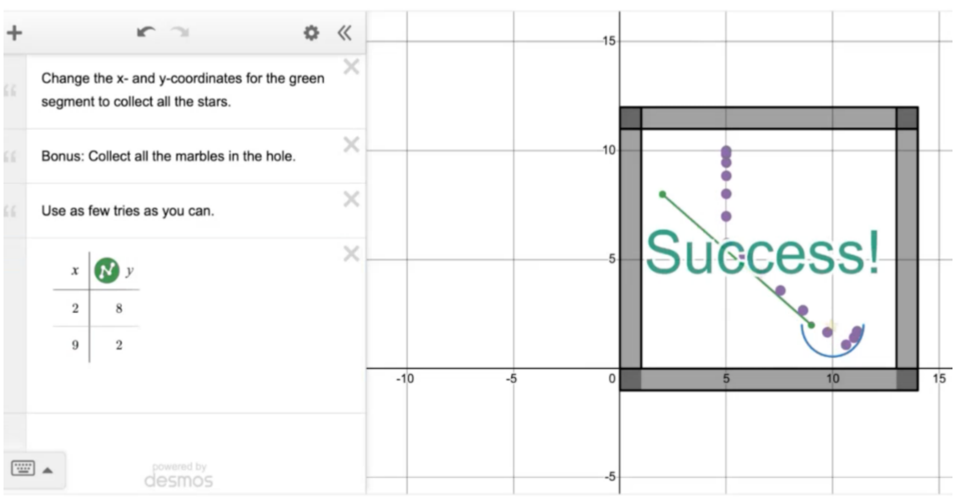
This section presents the findings organised around three themes aligned with the research questions of the study: 1) use of digital tools in CLIL mathematics classrooms to develop BMDLs, 2) teachers' TPCALK and how it shapes their decision to use technology or not; 3) digital tools as mediators of language and the role of LK-CT in CLIL mathematics classrooms. The organisation reflects a progression from reported classroom practices to the underlying teacher knowledge shaping these decisions, and finally to the mediation of language use through digital tools across contexts.

5.1. Use of digital tools in CLIL mathematics classrooms to develop BMDLs.

This section presents the findings for RQ1, outlining how both mathematics teachers use digital tools to develop BMDLs in their specific CLIL contexts.

Across both contexts, teachers employed digitally mediated tasks to make concepts more tangible, promote interaction, and encourage independent exploration. Both teachers described a range of tools that supported mathematical learning through dynamic representations, interactivity, and opportunities for collaboration.

LM frequently used the graphing calculator Desmos with upper secondary learners to introduce coordinate geometry. He described how the Marble Slides activity (see Figure 2) engaged students in experimenting with line equations: "The whole thing with this game is where you put the points […] It's the introduction to coordinate geometry […] Then we move to gradient, slope, parallel and perpendicular lines." By encouraging manipulation of equations to see immediate changes, Desmos helped students move “from plotting points to understanding gradients and slopes,” which LM contrasted with the static nature of worksheets: “It’s much better […] [than] a worksheet.” These activities draw on the multisemiotic dimension of BMDLs, creating opportunities for spatial/graphical reasoning and functional modeling through experimentation. LM also reported that this helps learners translate algebraic input into visual output while narrating their reasoning in the language of instruction (English), fostering movement between the representational language of algebra and spoken language.



Source: LM resource from stimulated recall session.

Figure 2.

Marble slides activity created with Desmos to work on a cartesian plane with 17 year olds.

LM also relied on game-based platforms to consolidate content and language fluency with core concepts and build engagement. When using GimKit, an online game-based learning platform in which teachers can create quizzes or activities, he explained: “I can look at Question Breakdown […] for instance, this [question]: ‘least common multiple of 7 and 12.’ That might be something I need to look at, but all this is instant as soon as the game is over.” He recalled a sixth-grade class that answered “359 questions correctly” in five minutes, adding: “It’s a lot of fun, and it’s one of the greatest feelings in the world when students answer so many questions correctly.” Such a tool also allowed him to offer students a non-competitive option, while still enabling them to receive immediate feedback: “Some students don’t like competition, so I give them the option to work at their own pace and still see results.” This illustrates how LM used the platform not only for consolidation but also to accommodate different student preferences within the same task structure.

Similarly, SF used GeoGebra with lower secondary learners to explore quadratic functions in Irish with the aim of enhancing learners’ visualisation and supporting the development of multisemiotic and technological dimensions of BMDLs, as in LM’s use of Desmos. She explained that interacting with dynamic graphs gave “meaning to what’s behind the numbers,” allowing students to connect algebraic notation with graphical behaviour. By moving sliders and observing how graphs changed, learners explored how changes in variables affected the graph, fostering functional modeling literacy and enabling them to articulate conceptual relationships in Irish.

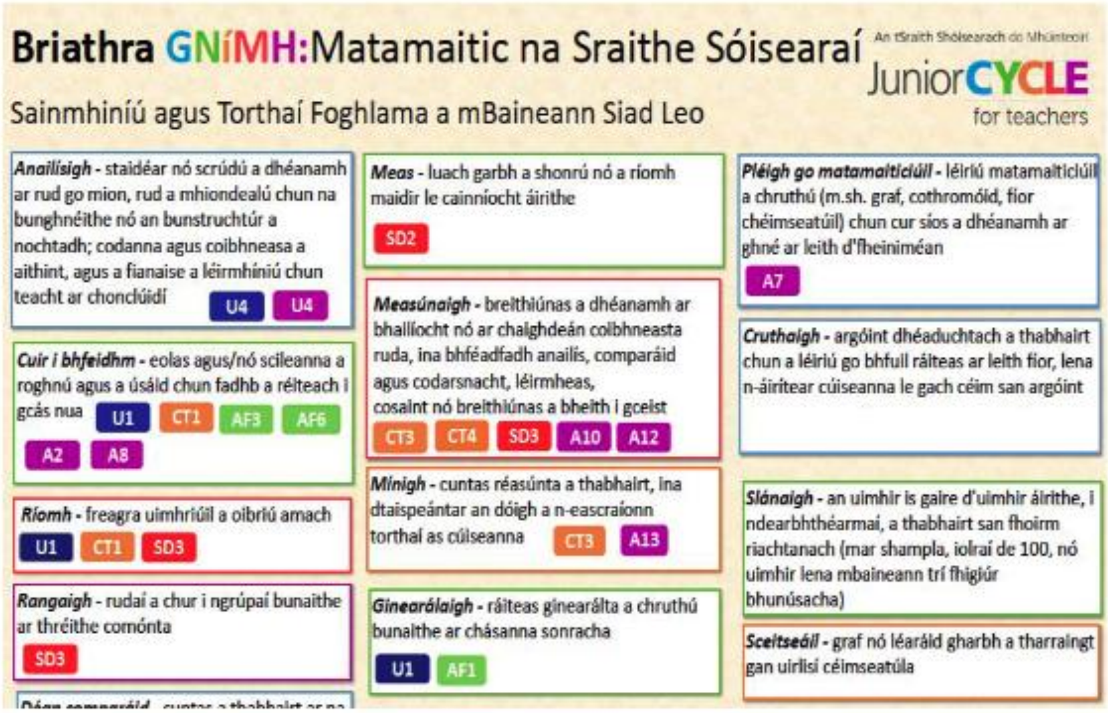
Alongside this, SF used Quizlet with lower secondary learners to prepare and practise specific terminology in Irish (see Figure 3) in a multimodal and multisemiotic learning environment: “Quizlet is great […] you can also put an auditory setting on for them to hear the words, try and guess the definitions, flip it over, get the definition, and then you can also put in a little hint or an extra explanation in easier terms.” Through the structured practice of definitions and explanations, Quizlet supported the functional dimension of BMDLs by scaffolding cognitive discourse functions (CDFs), particularly defining and explaining key mathematical terms. SF mentioned that this was particularly important for learners who came to the school through late immersion (i.e. undertook primary education in English and secondary learning in Irish). Figure 3 is an example of a task used to develop the language of questioning. In her view, using Quizlet to build their linguistic repertoire prior to the lesson made mathematical terminology in Irish less intimidating and supported the scaffolding of bilingual disciplinary registers (the functional dimension) in Irish and English. SF also presented an extract of Figure 4, a support sheet outlining key mathematical terminology required in Junior Cycle Mathematics (ages 12-16), that she used to create Quizlet activities.

Figure 3.

Quizlet task from SF to develop the language of mathematical problems with 14 year olds in Junior Cycle.

Source: SF resource from stimulated recall session.

Figure 4. *Resource produced by Junior Cycle for Teachers to support the development of mathematical terminology in Irish CLIL contexts.*



Source: https://jct.ie/perch/resources/maths_ga/action-verbs-poster-lg-pdf.pdf

Together, these findings show how task design with digital tools can promote distinct BMDLs across contexts. While in Spain the emphasis was on procedural and graphical literacies in English that support the development of the multisemiotic and technological dimensions of BDMLs, in Ireland the focus was similar but extended more explicitly to the functional dimension, through the scaffolding of terminology and definitions in Irish.

5.2. Teachers' TPCALK and how it shapes their decision to use technology or not

This section addresses RQ2 by examining how teachers' technological pedagogical content and language knowledge (TPCALK) shapes their decisions about the use of digital and non-digital approaches in developing mathematical BMDLs in CLIL classrooms.

On the one hand, LM's reflections illustrate a selective, critical approach. He highlighted the motivational effect of timed game-based activities and linked them to working under time constraints and exam preparation, noting that students "don't realise this. It's timed…putting stress and pressure on them and kind of preparing them for exams." However, LM also demonstrated critical Technological Pedagogical Knowledge (TPK) by discontinuing tools when their pedagogical integrity was compromised: "I found out in the first year the students know how to hack [some platforms] and change the outcome of the games." This reflexivity extended to a broader pedagogical stance that prioritised kinaesthetic and analogue approaches for developing reasoning and representation literacies. LM emphasised maintaining manual problem-solving: "Mathematics is […] kind of hard to do on the computer […] it's this kinetic thing where you have to write and understand and show your work." This belief led him to propose "screen-free Fridays" to ensure learners still practiced handwriting-based reasoning. For LM, the technological dimension, despite its potentially powerful role in developing multiple aspects of BMDLs, is a complement to non-technologically mediated learning rather than a replacement. When it came to the interaction of technology, content and language in his classroom, LM rarely referred to attending to linguistic aspects of mathematics, except: "sometimes, I'll stop and let them ask a partner in Spanish."

In contrast, SF described technology as integral to her pedagogy: “Playful learning is less easily achieved through traditional methods.” GeoGebra and Quizlet were embedded throughout her practice, not just as add-ons. Quizlet was used as part of a flipped learning strategy whereby learners were asked to learn key vocabulary that would be used in subsequent lessons rather than to review retrospectively key vocabulary from lessons that had already been taught. GeoGebra was used to provide the conceptual bridge between equations and graphs. She explained how visualisation tools reduced language load. As she admitted, using them “remove[d] a lot of the language-related issues because there’s not much language in there,” thus helping students focus on the mathematical idea without being overwhelmed by simultaneous content and linguistic demands: “If I can take out some of the language challenge beforehand, then I will I always reinforce it though during lessons moving between English and Irish when I need to.” This deliberate movement between English and Irish illustrates the bi-/multilingual dimension of BMDLs, as SF strategically used both languages to support disciplinary meaning-making. SF’s choice of how she uses the languages in combination with technology reflected contextual pragmatism guided by her pedagogical understandings and professional experience of the levels of language and content that are appropriate for the learners in front of her.

The two cases illustrate different enactments of TPCALK. LM demonstrated strong TCK (e.g., by selecting Desmos to visualise coordinate geometry) and TPK (e.g., discontinuing hackable platforms and propose ‘screen-free Fridays’ to preserve handwriting-based reasoning), with implicit language mediation largely through unplanned translanguaging and vocabulary clarification. SF, by contrast, systematically incorporated both CLK-CT and SLK-CT into technology use, deliberately embedding language aims alongside mathematical content. She incorporated CLK-CT through scaffolding classroom instructions and bridging disciplinary language across Irish and English, and incorporated SLK-CT through Quizlet activities targeting bilingual mathematical terminology. The decision to use digital tools in CLIL mathematics classrooms was shaped by teachers' pedagogical priorities. For both LM and SF, digital tools were valued for their capacity to visualise abstract concepts, provide immediate feedback, and sustain engagement, yet their selection was far from indiscriminate, displaying strong TCK in both cases.

5.3. Digital tools as mediators of language and the role of LK-CT in CLIL mathematics classrooms

This section addresses RQ3 by examining how digital tools mediated language use in the classroom and how teachers mobilised their language knowledge for content teaching (LK-CT) in bi/multilingual CLIL settings.

Digital tools mediated classroom language in different ways across the two CLIL contexts, revealing how both teachers assembled their language knowledge for content teaching (LK-CT) alongside mathematical goals. This mediation involved both common language knowledge for content teaching (CLK-CT) — supporting everyday and bridging language— and specialised language knowledge for content teaching (SLK-CT) —developing precise technical vocabulary and the specialised, non-pedagogical discourse of mathematics as conceptualised within

LK-CT. This included the scaffolding of the language needed to engage with mathematical tasks, particularly the interpretation of visual and symbolic representations and use of specialized terminology. The extent and manner of this mediation differed in the English-medium and Irish-medium contexts, reflecting teachers' distinct linguistic environments, language awareness and pedagogical choices.

In the Spanish context, LM emphasised that mathematical terminology was inseparable from problem-solving. As he put it: "It's all about learning the language in order to solve the problem. While I'm walking around, many times [students] ask questions, and I'm there to explain it. It brings up the importance of what [a term] means, like gradient or integer, not so much its translation." This illustrates his focus on specialised language knowledge for content teaching (SLK-CT), where precision in technical terms supports students' ability to complete mathematical tasks. GimKit and Desmos reinforced this exposure by embedding terminology into repeated practice and visual representation. In Gimkit, for instance, progression in the game depended on correctly interpreting terms embedded in problem statements (e.g., identifying the gradient of a line from a contextualised description). In Desmos, students were prompted to articulate relationships between graphical changes and disciplinary terms, thereby engaging in CDFs such as describing variation and explaining mathematical relationships (e.g. how the gradient varies as the slope increases), linking symbolic, visual and verbal representations. In both cases, specialised language functioned as an epistemic tool rather than isolated vocabulary, directly aligning with SLK-CT. So, digital tools functioned as structured environments for reinforcing specialised language knowledge within disciplinary activity. Yet LM also noted the structural limitations of current digital platforms: “Most tools don’t have multilingual options […] they’re primarily English-based, so students who aren’t fluent in English might need additional support.” To address this gap, he allowed informal peer scaffolding: “Sometimes […] I’ll stop and let them ask a partner in Spanish.” These practices reveal an implicit orientation to common language knowledge (CLK-CT), where translanguaging was permitted pragmatically to ensure comprehension, but not systematically integrated into task design.

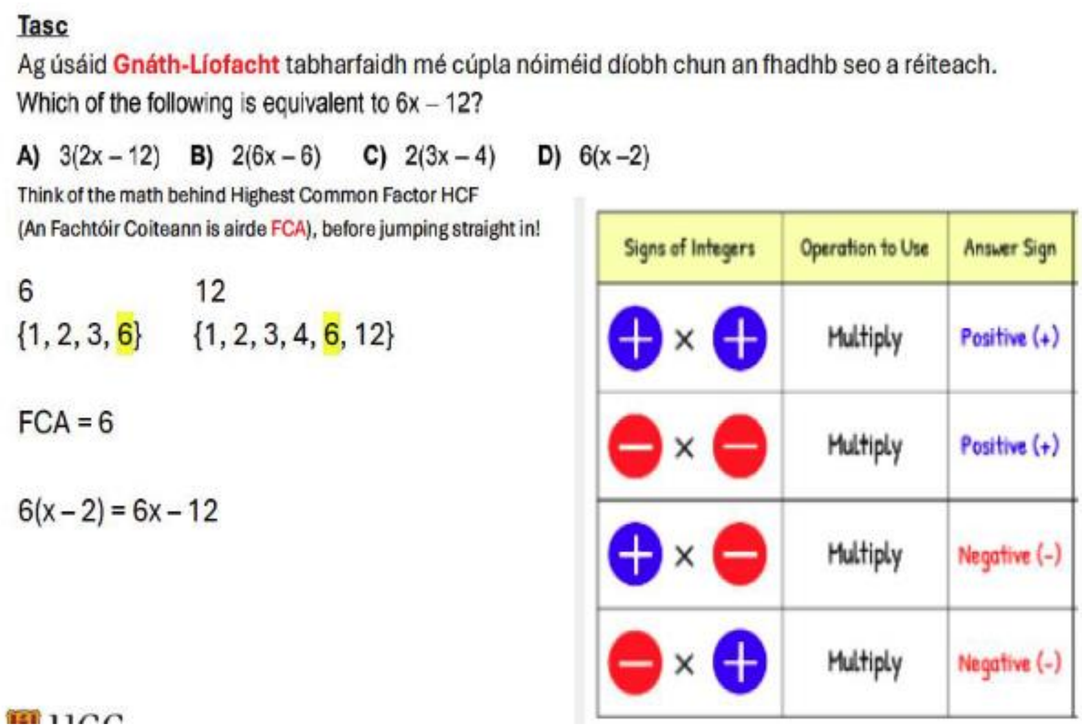
In Ireland, SF described a more deliberate strategy for connecting technology use with language aims. She regularly adapted English-language resources into Irish and used Quizlet to prepare students with bilingual terminology before lessons. She explained, “Quizlet is great […] you can also put an auditory setting on for them to hear the words, try and guess the definitions, flip it over, get the definition, and then you can also put in a little hint or an extra explanation in easier terms.” SF placed particular emphasis on the action verbs used in mathematics tasks, aligning with the revised Junior Cycle mathematics curriculum (see Figure 3). She integrated these into digital vocabulary sets to enhance students’ awareness before starting a topic, supporting procedural reasoning literacy across both languages. This allowed her to target both CLK-CT (general disciplinary terms in Irish and English) and SLK-CT (technical vocabulary for mathematics topics).

When working with tools available only in English, interactions that SF would have with the learners would be through Irish to help check and formatively assess their progress: “In a classroom scenario, if you’re teaching through Irish and using that tool in English […] verbal prompts [in Irish] would be checking in.” At the same time, she was attentive to the risks of overloading students with dual-language input: “If students are trying to listen and read in two different languages at the same time, this can be really confusing then they can lose confidence.” She also observed how students themselves mixed codes in natural ways: “Students would translanguage. They might speak in Irish but then say the term ‘subtraction’ in English because that’s the new term they’ve been learning.” This reflects how bilingual students appropriate available resources to engage with disciplinary language, constructing BMDLs across languages.

It is clear that digital tools play a role in shaping language use but also pose a challenge given that most tools are monolingual in nature. LM relied on monolingual tools that reinforced technical vocabulary in English but created barriers for less proficient students; his language support came largely through spontaneous clarification and tolerance of peer translanguaging due to his lack of proficiency in students’ L1, which was mostly Spanish. SF, by contrast, designed systematic bilingual scaffolds around her tool use, integrating Quizlet and oral translanguaging into planned sequences. This was probably due to the fact that Irish is a minoritized language and the availability of digital resources in this language is very scarce. For example, she adapted English-language resources to present notes in Irish using OneNote projected onto the whiteboard while annotating them with English translations (see Figure 5). This approach not only supported students' mathematical learning but also strengthened their pluriliteracies, which she believed contributed to their overall academic success.

Figure 5.

Plurilingual resources used as part of SF's OneNote page projected on the board at the front of the room used with 12 year olds in Junior Cycle.



Source: SF resource stimulated recall session.

In both cases, the teachers' practices reveal the importance of teacher LK-CT in linking technology to BMDLs: while digital platforms provide opportunities for repeated exposure and representation, it is the teacher's linguistic decisions—whether implicit (LM) or explicit (SF)—that often mediate how students engage within the functional dimension of BMDLs across languages of schooling. The findings indicate that digital tools can scaffold the development of the language dimension of BMDLs by connecting everyday and academic registers, but their potential in multilingual CLIL contexts might be constrained by various limitations (e.g. the status of the target language, and the teachers' language knowledge and awareness). Teachers' TPCALK therefore plays a crucial role in adapting tools and orchestrating language use, in conjunction with translanguaging, to meet both mathematical and linguistic learning goals.

6. Discussion

6.1 Digital tools use and BMDLs

In both contexts, digital tools were used as frameworks within which to develop elements of mathematical BMDLs. This was clearly seen in LM's use of Desmos to support the development of procedural reasoning and graphical literacy in coordinate geometry, while SF's use of GeoGebra and Quizlet fostered conceptual modelling and bilingual terminological literacy. The use of digital tools in these two examples illustrates how such tools integrate both content and language. On the one hand, students directly engage with the content by manipulating the tools to experiment with different outputs; on the other, they are required to articulate their reasoning in the target language(s) to explain how outputs change depending on how the content is manipulated. This, in turn, creates opportunities to rehearse key CDFs, such as defining, describing variation, and explaining mathematical processes (Dalton-Puffer, 2013). However, the strength of this functional dimension varied with task design: where CDFs were explicitly scaffolded (e.g., SF's use of Quizlet to prepare definitions and action verbs in advance of lessons) digital tools created structured opportunities for disciplinary communication. By contrast, in LM's case, while terminology was embedded in tasks through Desmos and GimKit, CDFs were less systematically foregrounded. As a result, the digital tools were used mainly to support procedural fluency, with fewer structured opportunities for students to articulate mathematical reasoning.

Digital tools were particularly significant in developing the multisemiotic dimension of BMDLs when learners develop their understanding of mathematical concepts in certain tasks. Desmos and GeoGebra required students to coordinate between graphs, equations, and written explanations, reflecting O'Halloran's (2005) argument that mathematical activity requires the teacher to semiotically orchestrate how meaning and learning is communicated: that is, how the teacher intentionally coordinates multiple meaning-making resources to support learners in understanding mathematical ideas more deeply. SF's modelling tasks in GeoGebra exemplified how digital tools can support conceptual understanding by linking algebraic, visual, and linguistic modes. Similarly, LM's graphing activities promoted graphical literacy by making coordinate geometry more tangible. These practices resonate with Ni Riordáin et al.'s (2020) emphasis on the importance of task authenticity and multiple representations in digital learning. At the same time, as Hoogland et al. (2018) argue, representational change alone does not guarantee deeper engagement; the orchestration of modes and the linguistic mediation around them remain crucial.

It was not clear from participants the extent to which the critical dimension of BMDLs (e.g., questioning assumptions, evaluating representations, and reflecting on the epistemic status of mathematical outputs) was developed. While digital tools provided opportunities to visualise and manipulate mathematical objects, teachers rarely required students to interrogate the validity of these representations or to critically compare alternative forms, although this would need to be confirmed through classroom observation. This echoes wider concerns that the critical dimension of mathematics education remains under-conceptualised (Barwell, 2018; Monteleone et al., 2023). At the same time, our findings point to the unrealized potential of digital tools to support evaluative and critical disciplinary practices. In CLIL contexts, such practices are particularly significant, as engaging in evaluation and justification requires learners to mobilise more complex disciplinary language across one or more languages of schooling. For instance, teachers could leverage digital tools not only to display solutions but to support evaluation, justification, and critique of those solutions, including exploring the limits of mathematical models or comparing alternative solution strategies. Such uses position digital tools not merely as instruments for calculation or display, but as resources for engaging learners in evaluative, reflective, and linguistically demanding mathematical activity across languages.

6.2 Teachers' TPCALK and pedagogical decision-making

From the perspective of TPCALK, both teachers demonstrated high levels of professional competence; however, the ways both were deployed in the classroom varied given their differing professional experience and context. LM selectively integrated tools when they aligned with his priorities of balancing manual problem-solving literacies with digital fluency, discontinuing platforms he felt compromised fairness or rigour. SF, as an early-career teacher, placed technology at the centre of her practice and prioritised repeated practice and independent learning for procedural fluency. These differences highlight how TPCALK is mediated by teacher experience, curricular context, and language policy, although other factors, such as familiarity with technologies and prior exposure to specific professional development may also influence how digital tools are integrated into classroom practice. However, our study was not designed to examine these factors. Within our data, pedagogical beliefs and language awareness emerged as the most salient influences shaping technology use across the two cases. Importantly, our findings support Clark-Wilson et al.'s (2020) and Drijvers' (2013) notes of caution that digital tools do not inherently deepen disciplinary engagement; rather, their contribution to BMDLs depends on how affordances are orchestrated pedagogically.

Overall, our findings highlight both the potential and the limitations of current digital tools for developing BMDLs. While tools such as Desmos, GeoGebra, Quizlet, and GimKit support the development of BMDL-sensitive tasks that develop learners' procedural, graphical, and terminological literacies, these affordances show that teachers require specific TPCALK for CLIL mathematics teaching to allow them to develop tasks that connect different dimensions of BMDLs. Moreover, a key element of TPCALK for CLIL mathematics teachers is understanding how to support critical engagement with multimodal resources (Monteleone et al., 2023) and more generally in mathematics.

6.3 Digitally mediated language development, LK-CT and monolingual tool design.

Both teachers' practices illustrate how LK-CT shaped classroom practices in different ways. LM, working in an English-immersion context, emphasised specialised language knowledge (SLK-CT), using Desmos and GimKit to reinforce precise mathematical terminology within problem-solving activities, principally with upper secondary learners. Translanguaging was largely informal and student-initiated, acting as a supplementary bridge for learners with lower English proficiency. By contrast, SF, in the Irish-immersion context, integrated common and specialised language knowledge (CLK-CT and SLK-CT) into her digital practice. Through tools like Quizlet, she systematically incorporated bilingual scaffolding, pre-teaching terminology in both Irish and English and designing tasks that required students to move flexibly between languages, steps which have been shown to help reduce and manage the cognitive load that mathematical register can impose on learners (Chan, 2015). This reflects Moschkovich's (2015) emphasis on meaning-making across semiotic and linguistic resources and García and Lin's (2017) view of bilingual classrooms as requiring deliberate language mediation. In this respect, our data confirms that digital tools can create structured opportunities for developing not only the technological dimension of BMDLs but also the bi-/multilingual and functional dimensions as well, though such opportunities require careful teacher adaptation.

However, one factor which affects the bi-/multilingual dimension of BDMLs is that many digital tools are designed either for monolingual classrooms or exist only in English. For English-medium CLIL contexts, the use of tools in English can be particularly useful in supporting learners to develop conceptual understanding in the CLIL language. The use of learners' other languages to develop the bi-/multilingual dimension could then occur while using the tool or afterwards during discussion or feedback. In the minorized language context, especially in Ireland, the same process occurs, but conceptual understanding is likely to develop through English first and then be scaffolded in the CLIL language afterwards. While not ideal, both approaches support the development of the bi-/multilingual dimension but, particularly in the latter case, teacher adaptations may be required to ensure that such conceptual development does not bypass the CLIL language entirely. Despite this challenge, the fact that digital tools often exist only in English or other majority languages also offers opportunities to develop the critical dimension of BMDLs, especially in relation to power relations between languages. This suggests that future digital mathematics education research should address how tool design might better accommodate linguistic diversity (Clark-Wilson et al., 2020).

Building on this, the predominantly monolingual design of digital tools not only constrains how the bi-/multilingual dimension is enacted, but also places greater emphasis on teacher mediation and task design. As the cases suggest, multilingual meaning-making is not absent, but is largely mediated through task design and classroom interaction rather than the tools themselves. At the same time, these constraints can open up space for critical engagement, particularly where learners reflect on how language choice shapes access to knowledge. Ultimately, this suggests that the development of BMDLs depends less on the tools themselves than on teachers' ability to orchestrate them through a language-aware TPCALK lens.

7. Conclusion

This study examined how two CLIL mathematics teachers in two contrasting contexts integrated digital tools to support the development of Mathematical BMDLs, and how these practices were shaped by their technological, pedagogical, content, and language knowledge (TPCALK). By integrating the BMDLs framework and TPCALK, the study offers a conceptual lens for analysing how technology, language, and disciplinary knowledge intersect in CLIL mathematics classrooms.

The cross-case comparison highlights how the use of digital tools supported the development of other BMDLs dimensions, particularly the bi-/multi-/translingual, multisemiotic and functional dimensions. However, the extent to which opportunities were created for learners to construct, communicate, and evaluate mathematical meaning in an additional language appeared to depend largely on task design and on how teachers aligned technology with content and language aims. While these practices supported learners' broader digital literacies, including managing information across languages and engaging with multiple semiotic modes, opportunities for critical engagement with these modes remained limited.

These findings emphasize the importance of BMDL-sensitive task design in CLIL mathematics. Effective integration requires teachers to draw on their TPCALK to plan activities that deliberately target specific dimensions of BMDLs and mathematical literacies (e.g., modelling, graphical reasoning, terminology work). The study also illustrates that TPCALK in CLIL contexts cannot be limited to the coordination of technology, pedagogy, and content knowledge alone. It must also include an explicit orientation to language knowledge for content teaching (LK-CT) and critical awareness of the linguistic and technological environments in which learners operate. In particular, the predominantly monolingual nature of many digital platforms calls for purposeful planning of and for translanguaging as well as informed decisions about the affordances and drawbacks of certain technologies in achieving learning aims. Finally, the use of digital tools and technologies in this way should also support learners' wider development of their critical awareness. If built into the learning sequence, the use of such technologies should enable learners to reflect on how the use of particular tools in certain languages (predominantly English) shapes meaning-making practices and their own attitudes towards language use.

While these findings suggest that the use of technology and digital tools can serve as a valuable means of supporting learners' BMDLs more widely, they are limited in scope. Future research should endeavour to include a wider range of CLIL teachers across disciplinary areas. Nonetheless, the use of stimulated recall as a methodology to gather such data has proven to be fruitful. Combined with classroom observations, data triangulation would allow for a deeper understanding of BMDLs development, particularly if the research is broadened to other disciplinary and subject areas. Nonetheless, the findings also suggest that, by understanding the dynamic interaction between technology, content, language, and pedagogy in CLIL classrooms, educators can design BMDL-sensitive learning that fosters richer plurilingual engagement within and beyond mathematics, reflecting evolving forms of meaning-making in the twenty-first century.

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