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Intersections of literacy, cognition, and culture in mathematics: Themes for advancing research and instruction

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Abstract
Relationships between literacy and mathematics have been robustly established in prior research. The current narrative literature review further examined scholarship on the literacy-math connection to articulate actionable themes for future research and instruction. We derived six broad themes via iterative exploration of numerous studies on skill measurement, language contexts, instruction, and cultural considerations. The overarching topics of the identified themes related to operationalizing literacy-math connections (themes 1 and 2), language and culture (themes 3, 4, and 5), and adult learners and Contexts (theme 6). The themes described contribute to work on operationalizing and researching math learning in children, instruction of various populations (e.g., children, adults, L2 speakers, different cultural contexts), and highlight a distinct skew toward studies of children.
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1. Introduction

Literacy and math are essential to both formal (e.g., schooling) and informal (e.g., shopping) aspects of everyday life. These competencies are often perceived as distinct, yet ample evidence suggests they are meaningfully interconnected (e.g., Bailey et al., 2020; Jaffe & Bolger, 2023; Martin & Fuchs, 2022; Morgan et al., 2014; Nelson et al., 2021; Peng et al., 2020; Rosa et al., 2016; Yang et al., 2022; Zoccolotti et al., 2020). For example, phonological awareness describes the ability to recognize the sounds of a language (e.g., Gillon, 2017), and rapid automatic naming (RAN) refers to the ability to quickly recognize letters, symbols, and sight words (e.g., Araújo et al., 2015). These basic competencies underlie more advanced skills like decoding and comprehension (e.g., Best, et al., 2008; Cain et al., 2004; Christopher et al., 2012). Notably, in one longitudinal study, Cirino and colleagues (2018) found that rapid naming and phonological awareness were also related to decoding skills in math (e.g., recognizing symbols and operations). Phonological awareness has also been linked to counting and solving word problems (e.g., Foster et al., 2015; Krajewski & Schneider, 2009; Navarro et al., 2011).

Similarly, measures of reading comprehension positively correlate with solving math word problems among English-language learners (Barbu & Beal, 2010), younger children (Boonen et al., 2013) and adults (Daroczy et al., 2020). For instance, Duncan et al. (2007) examined six longitudinal datasets to estimate the strongest school-entry predictors of later achievement. They found that early math skills, reading skills, and attention skills were collectively the best predictors. Interventions that support language comprehension also facilitate solving word problems (e.g., Fuchs et al., 2021; Fuchs et al. 2020). Thus, literacy competencies seem to be related to math competencies at various levels. Math and literacy both encompass a variety of skills and behaviors. We rely on UNESCO's (2023) literacy plan in defining literacy as a continuum of learning and proficiency, comprising the abilities to 'to read and write, to identify, understand, interpret, create, communicate and compute, using printed and written materials including on-line, as well as the ability to solve problems in an increasingly technological and information rich environment'. (UNESCO, 2023; p. 7). With respect the math proficiency, we align with common conceptualizations of mathematical competencies identify five relevant domains: conceptual understanding, procedural fluency, adaptive reasoning, strategic competence, and lastly, productive disposition (Corrêa & Haslam, 2021; Helsa & Juandi, 2024; Kilpatrick et al., 2001).

1.1 Prior Reviews

Several scholars have reviewed research on literacy and math connections. For instance, Peng and colleagues (2020) reviewed over 340 studies exploring the relationships between language and math. They found that numeric knowledge was strongly related to RAN. In addition, literacy and math seemed more closely connected for native language speakers, although the effect disappeared after controlling for working memory and intelligence. Working memory and intelligence explained about half of the variance in literacy-math associations. Performance in math also predicted future performance in language and vice versa. Similarly, Lin and colleagues (2021) reviewed relationships between math vocabulary and performance in foundational math tasks (e.g., number knowledge, number combinations, operations, and algorithms) and higher order tasks (e.g., word problems, fractions, and algebra). Their findings showed that math vocabulary displayed a moderate relationship to success in foundational tasks and stronger relationships among complex tasks.

Jaffe and Bolger (2023) synthesized research on language and communication in math instruction and word problems to generate an explanatory model of inhibitory performance. Their major findings pointed towards inhibitory control and working memory as key predictors of language behavior that influenced word problem-solving. An inability to inhibit certain math associations (e.g., that the word "more" always denotes "addition") can hinder constructing more appropriate solution schemas (e.g., recognizing that a word problem actually requires subtraction) and translating word problems into numerical equations.

Another thread of scholarship has reviewed research on math, language, and culture. For example, Morgan and colleagues (2014) reviewed historical and contemporary literature on the role of literacy in math education. One key argument was that all math education research involves language, even when language is not the direct focus of study. In this space, the researchers highlighted different operationalizations of math language, including the (a) vocabulary related with the teaching and "doing" of mathematics and (b) the symbolic systems used in math (e.g., notation and graphs). In addition, language played a unique role in math instruction within multilingual or non-monolingual settings. The researchers also noted that language and math always occur in context, which entails differences in social power related to language (or multiple languages).

Similarly, Rosa and colleagues (2016) have discussed the area of "ethnomathematics" along cognitive, conceptual, educational, epistemological, historical, and political dimensions. The scholars called for future research to examine how power influences the creation and use of math knowledge on different scales (i.e., local and global) along with the evolution of such power dynamics (e.g., colonialism and Western-centric educational views). The researchers also recommended deepening our understanding of cultural approaches to math, including similarities and differences in how distinct cultures conceptualize relationships between language, thought, and the quantification of objects, space, and time.

1.2 Promising Interventions

Inspired by associations between literacy and math, there has also been interest (and success) in improving math outcomes via literacy-based interventions. Espinas and Fuchs (2022) reviewed multiple cross-sectional and longitudinal studies on language and the development of math. Literacy instruction focused on "number talk" (see Gibson et al., 2020) and visual aids like story books (see Purpura et al., 2021) were observed to reinforce young students' number knowledge and word-problem solving (e.g., schema-based intervention in Fuchs et al., 2021), but not arithmetic performance (see Jordan et al., 2012; Powell & Driver, 2015).

Verbal narratives and visual presentations of math content and problems also positively affect success in solving math problems (e.g., Glenberg et al., 2012); solving inverse algebraic problems (Méndez-Balbuena et al., 2022); and skills in number, measurement, and geometry (van den Heuvel-Panhuizen et al., 2016). In settings where math learning occurs in a non-native language, beneficial outcomes have been observed when acknowledging language-related challenges and enhancing students' math vocabularies (Arizmendi et al., 2021). More generally, interventions that utilized personalized and clear language positively influenced comprehension and learning of STEM topics (Strohmaier et al., 2023). Researchers have likewise called for math instruction and interventions that recognize students' varied backgrounds, knowledge, and needs (Draper, 2002).

1.3 The Current Review

Wide-ranging scholarship on literacy-math connections (a) demonstrates links between literacy and math competencies and (b) argues that these associations can be leveraged to support learning. However, inspection of this research also reveals opportunities for better understanding these phenomena and implementing effective interventions. In this review, we consider this body of work to reveal insights for research and instruction that extend beyond general claims that "reading and math are linked" or that "addressing literacy can benefit math performance." We accept these claims to be largely true. Our overarching purpose is to synthesize this literature to articulate actionable directions for informing future research and instruction.

2. Method

This literature review explored published literature on the relationships between literacy and mathematics–spanning processes, learning, and instruction–via broad databases such as *Google Scholar*, *ERIC*, and *Scopus*. We iteratively employed combinations and permutations of (a) *domain-related* terms such as "literacy," "language," "reading," "mathematics," and "math," along with (b) *skill-related* terms such as "comprehension," "fluency," "decoding," "computation," "skills," "proficiencies," and "competencies." The review process surfaced additional terminologies to explore, with examples including "working memory," "executive function," "second language," "language learners," "culture," and "ethnomathematics." Our primary focus was peer-reviewed publications (e.g., journals and conference proceedings) that explored both literacy and math together. We did not restrict the search to any particular setting (e.g., school or workplace), educational level (e.g., primary, secondary, or higher education), or population. Likewise, we did not limit the search to studies of English, but only articles written in English were reviewed.

Our goal was to document meaningful themes for future research and instruction pertaining to relationships between literacy and mathematics. The current review incorporates around 130 selected sources; the source literature is vast and our intent was not to be exhaustive or comprehensive. Many obtained sources were not cited here for brevity. Thus, this work was not a "systematic" or full "scoping" review that obtained and synthesized all relevant sources. For our purposes, it was sufficient to reveal trends and examples without being exhaustive. Similarly, this work was not a "meta-analysis" to estimate quantitative effects and relationships among variables.

2.1 Identification of Themes

Observed themes were iteratively identified through source-driven (i.e., bottom-up) and conceptual (i.e., top-down) approaches akin to qualitative analysis (e.g., Braun & Clarke, 2012; Cresswell & Poth, 2016; Saldaña, 2014). Initial searches identified and documented relevant publications for annotation. Iterations then examined both references cited within a given paper and later publications that cited a given paper. Qualitative annotations tracked theoretical perspectives, methodologies, variables, findings, populations, and additional search terms to explore. Team members frequently discussed potential annotations and patterns. Proposed observations were explored via targeted searches to locate studies and refine terminology; more extensive searches followed once appropriate parameters were determined.

As potential patterns were observed, annotations also became more focused, thus allowing for (re)categorization of publications. For instance, through iterative review, factors such as "working memory" or "culturally responsive teaching" emerged. We then (a) updated annotations to clarify whether sources addressed such concepts and (b) conducted additional searches using such terms. As themes emerged, we could similarly denote whether and how papers participated in related discourse. For example, as we noted bifurcation between diverse domain-specific versus domain-general competencies, annotations evolved to indicate whether and which relevant variables were discussed in studies.

Initial searches focused on literacy constructs, math constructs, and their relationships (e.g., Cirino et al., 2018; Koponen et al., 2017; Lin et al., 2021; Peng et al., 2020; Yang et al., 2022). Inspection immediately revealed that highly diverse skills and constructs have been studied (see Theme 1), such as phonological awareness (e.g., Amland et al., 2021; Yang et al., 2022) or number knowledge (e.g., Östergren & Träff, 2013; Peng et al., 2019). These specific measures informed targeted searches on individual constructs and variables. In turn, these explorations identified research on cognitive abilities that were important to literacy and math yet not unique to either domain (see Theme 2), such as intelligence (e.g., Bryan & Mayer, 2020), working memory (e.g., Blankenship et al., 2015), and executive functioning (e.g., Bull & Lee, 2014; Butterfuss & Kendeou, 2018). Numerous studies examined foundational competencies that might be loosely separated into domain-specific or domain-general categories, which gave rise to two initial themes for consideration.

Searches on "literacy" versus "language" also highlighted how researchers have considered individual skills (e.g., RAN) versus general conceptions of language (e.g., math vocabulary). The terms "literacy" and "language" have sometimes been employed in distinct ways, which surfaced scholarship on "language of instruction" (e.g., Greisen et al., 2021) and "language of math" (e.g., Riccomini et al., 2015). Iterative search of both topics informed further divergence. Specifically, one strand of research explored how learners' native languages interact with the language of instruction (see Theme 3). A related but distinct thread examined how the domain of math itself is a language register, with specific communication norms and vocabulary (see Theme 4). These considerations seemed to warrant separation into two themes.

Several studies drew direct connections between language and culture (e.g., Abdulrahim and Orosco, 2020; Appelbaum & Stathopoulou, 2023). Learners' languages are intimately related to their identities and communities, and thus connections between language and math are also cultural (see Theme 5). Such studies surfaced concepts like "ethnomathematics" and "culturally responsive teaching" that informed subsequent exploration. Review of these literatures suggested that cultural concerns were thematically noteworthy, but ethnomathematics and culturally responsive teaching were conceptually aligned. Thus, we derived a single theme regarding language, math, and culture with strong ties to instruction.

Our annotations of studied populations observed a distinct skew toward children (see Theme 6). This pattern inspired a focused search on "adolescent" and "adult" learners, as well as adult contexts for literacy and math (e.g., "work" and "career"). Our general inability to identify a sizable body of literature comparable to studies of children led us to articulate a final theme on studying adults.

3. Thematic Findings

Evidence suggests that there are reliable associations between literacy and math competencies, and these connections can be productively leveraged in instruction (i.e., improving math performance through literacy-informed interventions). Our review generally affirmed such findings while deepening several aspects of the work. Specifically, we observed themes regarding (1) improving operational definitions, (2) underlying and shared cognitive resources, (3) addressing native languages, (4) teaching the language of math, (5) including culture, and (6) studying adult learners. In the following sections, we explicate each theme and related research, and consider how future research and teaching may develop.

3.1 Theme 1: Improving operational definitions

Literacy and math encompass diverse skills and abilities that can be operationalized in different ways. For example, literacy has been operationalized via measures such as *decoding* (Cirino et al., 2018; Nordström, 2016), *phonological awareness* (Amland et al., 2021; Cirino et al., 2018; Yang et al., 2022), *phonological processing* (Yang et al., 2022; Yang & McBride, 2020), *rapid automatized naming* (Cirino et al., 2018; Georgiou et al., 2020; Koponen et al., 2017; Navarro et al., 2011; Yang et al., 2022), *reading comprehension* (Cirino et al., 2018; Duru & Koklu, 2011; Georgiou et al., 2020), and *vocabulary* (Cirino et al., 2018; Collins & Laski, 2019; Lin et al., 2021). Similarly, math skills have been assessed in terms of both "knowing" math (e.g., understanding principles) and "doing" math (e.g., procedures and computations). Math competencies have thus been operationalized with regards to *arithmetic* (Amland et al., 2021; Koponen et al., 2016; Navarro et al., 2011; Siegler & Lortie-Forgues, 2015); *calculations* (Cirino et al., 2018; Cui et al., 2023); *counting knowledge* (Cirino et al., 2018); *geometry* and *algebra* (Duru & Koklu, 2011; Peng et al., 2019; Yang et al., 2022); *problem solving* and *number-fact skills* (Cirino et al., 2018; Jordan & Montani, 1997); *math communication* (Kotsopoulos, 2007; Lin et al., 2021; Pimm, 2018; Riccomini et al., 2015); *number knowledge* (Östergren & Träff, 2013; Peng et al., 2019; Yang et al., 2022); and *word problem solving* (Cirino et al., 2018; Duru & Koklu, 2011; Fuchs et al., 2020; Peng et al., 2019; Yang et al., 2022).

Although research on literacy-math connections has advanced our understanding of these linked proficiencies, the diverse operationalizations of key skills may be a roadblock for further work. Currently, it can be unclear whether measures reflect (a) distinct constructs with the same nomenclature or (b) capture the same constructs but with different nomenclature. Likewise, it can be ambiguous whether given constructs are separable or combinable (e.g., a single latent construct), or whether observed associations are unidirectional, bidirectional, and/or or driven by shared underlying variables (i.e., see Theme 2). Likewise, underlying mechanisms may be underspecified; the reasons why variables are causally associated may not be described.

To illustrate one specific case, RAN has been variously assessed as a proxy, correlate, or direct measure of reading ability (e.g., Koponen et al., 2016; Yang et al., 2022) that positively correlates with both math and reading performance (Peng et al., 2020). Koponen et al. (2017) conducted a meta-analysis of 38 studies to specify relationships between RAN and math proficiencies. Their results revealed a significant and moderate overall correlation between RAN and math proficiencies (r = .37). Notably, correlations were stronger with performance on arithmetic calculation measures than general achievement and were stronger with math fluency than accuracy. The researchers concluded that both math processing and RAN require quick access to the retrieval of phonological representations. Although these findings further illuminated the connections between RAN tasks and various math proficiencies, they did not explain *how* the two are connected. For example, it remained unclear whether RAN was a type of math and/or literacy process or a general, underlying cognitive skill.

Georgiou et al. (2020) conducted a longitudinal study of 183 Chinese 1st through 5th graders where measurements of RAN, reading, and math were collected annually. Assessments of math included numerical operations and calculation fluency, and literacy was assessed using character recognition and one-minute reading. Early RAN outcomes predicted all future reading and math fluency, but not all accuracy outcomes. Although the study found that there was a relationship between RAN and fluency in both reading and math, it was still unclear what cognitive skill(s) underlie RAN and the full extent of connections to literacy or math.

3.2 Theme 2: Underlying cognitive resources

Literacy and math proficiencies interact with a variety of domain-general cognitive resources, such as working memory (WM) and executive functioning (EF). One possible explanation is that literacy and math proficiencies are manifestations of the same domain-general cognitive resources applied to distinct tasks (e.g., decoding words versus calculations). Alternatively, literacy and math may represent distinct sets of cognitive abilities that culminate within a specific domain.

3.2.1 Working memory. Working memory (WM) refers to cognitive mechanisms and processes that temporarily hold information while performing mental tasks. Varying models have operationalized WM as a component of short-term memory and/or an extension of long-term memory with connections to attention (e.g., Baddeley, 2006; Logie et al., 2020; Oberauer, 2019).

Research on WM, literacy, and math provides evidence that WM is a shared resource that could explain literacy-math connections (e.g., Blankenship et al., 2015; Bryan & Mayer, 2020; Gathercole et al., 2016;

Krajewski & Schneider, 2009; Tsubomi & Watanabe, 2017). For example, Zheng et al. (2011) reviewed relationships between three components of working memory (i.e., phonological loop, visual-spatial sketchpad, and central executive), word problem solving accuracy and processes, and reading and math outcomes for 310 elementary school children (i.e., grades 2, 3, and 4). Results showed that all three WM components predicted problem solving accuracy; central executive and phonological components predicted reading skills and calculation proficiency. Thus, memory-related processes (e.g., retrieving and holding more simultaneous items in working memory) appeared to be a general cognitive resource that contributed to literacy-related and math-related skills.

Shvartsman & Shaul (2024) also tested relationships between WM math and literacy in children. The researchers operationalized WM components as "simple" (i.e., the phonological loop and the visuospatial sketchpad) and "complex" (i.e., a central executive that coordinates the other two components). 250 children aged 5-7 responded to tasks targeting (a) simple WM (e.g., word ordering, spatial memory, spatial sequential memory, and hand movements), (b) complex WM (e.g., object sorting and spatial sequential memory), (c) language skills (e.g., word recognition, letter naming, phonological awareness, vocabulary, and noun plural production), and (d) math skills (e.g., early numeracy, verbal counting, numeral identification, and number naming). Their results categorized participants' behaviors along three WM ability levels (i.e., "low," "medium," and "high"). Participants in the "low WM" group had the lowest academic performance across different measures and the "high WM" group outperformed the others. Although all three WM components (i.e., auditory, visuospatial, and complex) were related to literacy and numeracy, visual memory had a smaller role.

3.2.2 Executive functioning. Executive functioning (EF) is a high-level cognitive system that integrates diverse processes (e.g., remembering, selecting, managing, and coordinating) to enable adaptive and goal-directed control of behaviors, emotions, and thoughts (e.g., Best & Miller, 2010; Bull & Lee, 2014; Butterfuss & Kendeou, 2018; Miyake et al., 2000). Miyake et al. (2000) have operationalized EF as consisting of (1) *response inhibition* (the ability to override an initial response in favor of one related to the task), (2) *working memory*, and (3) *cognitive flexibility* (the ability to maintain focus and flexibility relevant to dynamic goals and stimuli).

Studies have found that EF relates to math (Bull & Lee, 2014) and reading (Butterfuss & Kendeou, 2018; Follmer, 2018) across age groups (e.g., Peng et al., 2020; Spiegel et al., 2021; Weiland & Yoshikawa, 2013). EF might thus potentially drive or explain connections between literacy and math (e.g., Cantin et al., 2016; Morgan et al., 2017; Ten Braak et al., 2022; Valcan et al., 2020). For instance, Schmitt et al. (2017) conducted a longitudinal study exploring the bidirectional relationship between EF and both math and literacy. EF, math, and literacy measures were collected from 424 participants in four "waves" between preschool and kindergarten. Findings showed that unidirectional relationships between EF and math in kindergarten became bidirectional after kindergarten. Bidirectional relationships between literacy and math also began in kindergarten. Finally, growth in EF, math, and literacy were also correlated (i.e., perhaps developed together).

Purpura et al. (2017) examined relationships between abilities related with EF, literacy, and math. In that study, EF abilities were operationalized as inhibitory control, working memory, and cognitive flexibility. The researchers measured skills related with response inhibition (e.g., modified Stroop task), WM (e.g., listening recall task), cognitive flexibility (e.g., a 3D sorting task), literacy (e.g., early numeracy, subitizing, set comparison, verbal counting, one-to-one counting, and cardinality), and math (e.g., print knowledge, definitional vocabulary, and phonological awareness) for 125 preschoolers. The researchers observed relationships between (a) response inhibition and most other variables, (b) working memory and more advanced mathematics skills (e.g., comparison, combination of numbers, and quantities), and (c) cognitive flexibility and abstract or conceptual mathematics skills (e.g., cardinality, print knowledge). Response inhibition and cognitive flexibility were found to be related to print knowledge (e.g., the familiarity with letter names and sounds), and working memory was related only to phonological awareness. However, none of the EF measures were related to vocabulary. These findings elaborated on the relationships between specific EF skills and specific proficiencies in literacy and math, further advancing the work on understanding the nature of those relationships.

In another longitudinal study of 243 children between kindergarten and fifth grade (ten Braak et al., 2022), researchers found that EF seemed to mediate relationships between math performance in kindergarten and later 5th grade performance in math, reading, and phonological awareness. Math skills were measured by tests of numeracy, geometric, and problem-solving. Literacy skills were measured via expressive vocabulary tests. Both domains were also assessed via Norwegian standardized tests. The researchers observed that EF mediated predictive relationships between earlier and later performance in math and reading; they inferred that EF may provide an explanatory mechanism for established relationships between early math skills, later math achievement, and reading achievement. However, further research was required to explicate the nature of the relationships between EF, math, and reading.

3.3 Theme 3: Addressing native languages

Literacy is often operationalized as the proficiency of learners in the language of instruction–often the dominant language where students reside–regardless of whether that language is students' native (L1) or non-native (L2) tongue (e.g., Antón & Dicamilla, 1998; Beal et al., 2010; Cui et al., 2022; de Araujo et al., 2018;Tavares, 2015).

In math instruction, Greisen and colleagues (2021) illustrated how learners whose home language differs from the language of instruction sometimes underperform on math and literacy measures. Learners' proficiency in instructional language(s) mediates performance. Learners' performance in the language of instruction is not necessarily reflective of their math competency. Attar et al., (2022) further complicate the matter when comparing Syrian refugees' (n =32, ages 9-15) math performance in their language of instruction (Dutch) relative to their native language (Arabic). Results show that math performance was significantly better in students' native language, meaning that assessment in students' language of instruction may hide their actual ability.

Interviews with students and teachers have revealed mixed perceptions (Culligan, 2015). Culligan (2015) interviewed L1 English and L2 French students and teachers in a Canadian French Immersion school (i.e., math was taught in French). Many students and teachers believed that delivering math lessons in an L2 did not impact achievement or comprehension. However, in contrast, several interviewees reported that learning math in their L2 was challenging and that using their L1 was helpful. Interestingly, one teacher reported using her L1 (English) to support students while also feeling guilty for doing so (i.e., violating the ideal of French immersion). Additional studies supported the benefits of using learners' L1 (Tavares, 2015) or letting learners choose the language of instruction (Moschkovich, 2007) to improve the experience and outcomes of mathematics instruction in L2 settings. In sum, there appear to be both instructional and cultural tensions about whether and how native languages should be incorporated into math instruction within non-native language environments.

Le Pichon and Kambel (2016) describe how the use of non-native instructional languages can be further complicated culturally and socially in cases like Suriname, where the schooling language (Dutch) is a remanent of colonial occupation, sociopolitical and ethnic and stratification. Suriname is a culturally and linguistically diverse country. Most citizens of Suriname are not native speakers of Dutch, especially those in rural areas and many who are descendants of enslaved people. Many students encounter Dutch for the first time when starting school, and schools have a high dropout rate in L2 (or L3, or L4) Dutch populations. The authors advocate for multilingual education, supporting education in Dutch with native language instruction.

L1 has been suggested to be a resource for students learning in their L2 (e.g., Karikari et al., 2022; Kurz & Pagliaro, 2019; Moschkovich, 2007) and not only for mitigating gaps in L2 vocabulary. Noriega & Zambrano (2011) used classroom observations and interviews to identify the types of scaffolding and instructions used by first-grade math teachers at a bilingual school in Colombia teaching in English. Their data suggested that visual aids along with the careful use of L1 played meaningful roles in supporting the simultaneous development of content and linguistics competencies. Speakers can switch between expressing ideas in L1 and L2, and can also switch between different registers or popular references linked to a given language (e.g., word choice, colloquial language, norms, or styles). This form of code switching seems to support L2 learners in building their target vocabulary without leading to significant detriments (e.g., Macaro, 2009).

3.4 Theme 4: Teaching the language of math

Language is also used in the enactment of mathematics. Math comprises terminology for specific math concepts (e.g., "divisor" and "integer"), processes (e.g., "divide by" and "solve for"), and problems (e.g., "how fast" or "how likely"). Schleppegrell (2007) and O'Halloran (2015) have discussed the differences between technical registers used to teach math and science versus everyday spoken registers used by students. These differences contribute to the difficulty of learning and understanding the language of instruction.

Beyond general literacy, specific proficiency in "the language of math" may be an important step in successful math education. Students must be able to "do" problem-solving and calculations while also communicating that work or translating between math and verbal representations (e.g., "word problems"). Several researchers have explored teaching math language directly. For example, Riccomini et al. (2015) argued for teaching math vocabulary as part of math instruction due to students' difficulties with such unfamiliar terminology (e.g., Lin et al., 2021). Such work has proposed explicit vocabulary lessons, mnemonic strategies, and game-like activities to directly target and improve students' math vocabulary, which have been shown to benefit math development (e.g., Riccomini et al., 2015; Wanjiru & O'Connor, 2015).

An additional path to making math language clearer and more approachable focuses on the use of language in instruction (Croce & McCormick, 2019; Erath et al., 2021; Hillman, 2014; Shanahan & Shanahan, 2012; Yang et al., 2020). Instructors might use straightforward, personalized, or "lay" language to introduce concepts prior to weaving in technical language. Math interventions using language-based instructions have benefitted number knowledge and word-problem solving, but not necessarily arithmetic performance (Arizmendi et al., 2021). Similarly, personalizing math texts and increasing clarity also improved STEM comprehension and learning. Strohmaier and colleagues (2023) reviewed 45 studies exploring the effects of linguistic text features on comprehension and learning of STEM texts. Their meta-analytic results found that both personalization and clarification had more positive effects than simply reducing text complexity or increasing text cohesion (Fuchs et al., 2021; Gibson et al., 2020; Purpura et al., 2021). In their review, Espinas and Fuchs (2022) reported that interventions and teaching strategies that explicitly clarified the language of mathematics were beneficial in improving number knowledge and word problem solving.

Finally, studies have reported benefits of combining verbal and visual support for understanding math. Interventions that supplemented math instruction with linguistic and visual and narrative aids (e.g., embodied text simulation, Glenberg et al., 2012) resulted in a better understanding of math concepts. Likewise, picture books improved children's performance (i.e., relative to control groups) on number, measurement, and geometry across nine different classrooms (van den Heuvel-Panhuizen et al., 2016). Wanjiru & O-Connor (2015) also found that math vocabulary instruction involving visual representation aided students' performance on a standardized math test focusing on the application of math vocabulary. Recently, Méndez-Balbuena and colleagues (2022) compared the use of verbal versus algebraic solutions for inverse function problems for 120 students, which showed that those who utilized verbal solutions were 3.75 times more likely to reach the correct solution.

3.5 Theme 5: Include culture and ethnomathematics

Culture broadly refers to beliefs, norms, traditions, and practices related to shared histories and identities within a community. The learning and "doing" of math are embedded within learners' spoken and written language(s), which necessarily includes their cultures. Learners' cultural and linguistic backgrounds affect the efficacy and uptake of math instruction (e.g., Abdulrahim & Orosco, 2020). Ethnomathematics and culturally responsive teaching propose ways of analyzing and (re)framing history, teaching and learning strategies, and implementations of math instruction that acknowledge the wealth of knowledge and tools available and utilized by diverse cultures and subcultures.

3.5.1 Ethnomathematics. Cultural analyses have highlighted how research on literacy-math connections and math education focuses on Western populations (Anderson, 1990; Powell & Frankenstein, 1997). Such research makes generalizations based on Western ways of teaching math, and largely tends to rely on interventions and data from the U.S. and Europe. To address this incongruence, research and practice can explore the generalizability of current findings to different countries, cultures, languages, and lived experiences, while also directly integrating ethnomathematics in the curriculum (e.g., Zhang & Zhang, 2010).

The field of ethnomathematics discusses relationships between math history, teaching, and their cultural contexts across research, teaching, and learning (e.g., Appelbaum & Stathopoulou, 2023; Fouze & Amit, 2023; Powell & Frankenstein, 1997). Importantly, ethnomathematics research does not necessarily focus on language as an explicit variable to be measured; the cultural focus is broader than language alone. Nonetheless, ethnomathematics expands our understanding of the influences of language and culture on math learning. Ethnomathematics specifically acknowledges the ways in which different cultures use math, supports the idea of linking pedagogy to students' cultures, and shifts focus in the history and teaching of math away from a Western-centric framing. For example, Appelbaum & Stathopoulou (2023) argued how historically Western-centric and colonial views inform our perceptions of math and math education, including the use of Western metrics for assessment of math ability, and devising interventions in the global south (example in Pitchford et al., 2019; Wang & Degol, 2017). These researchers proposed adopting a "critical ethnomathematics" perspective–an introspective framework advocating for the development of hybrid spaces, re-appropriating Western knowledge and practices, and fusing them with non-Western knowledge and practices in pursuit of dignity, equity, and social justice.

In addition to revealing diverse perspectives on math and history, ethnomathematics also explores less Western-centric curricula. Rowlands & Carson (2002) explored several possibilities for incorporating ethnomathematics into teaching, such as (1) replacing academic math, (2) supplementing math curricula, (3) serving as a springboard for academic mathematics, and (4) a lens for preparing and designing learning environments. The researchers argued that sensitivity to cultural differences is the only way to appreciate and understand the value of math in different cultures. D'Ambrosio & D'Ambrosio (2013) likewise discussed the role of educators in developing curricula that are relevant to students' lives.

Meaney and colleagues (2021) proposed a cultural symmetry model for meaningfully involving indigenous language(s) and traditions in math instruction. The authors recommended making cultural knowledge, values, and practices related to math explicit, and examining cultural themes from a range of perspectives including (but not limited to) math. They also recommended directly addressing how math can contribute to cultural practices and artifacts. Symmetry arises from embracing a reciprocal relationship between culture and math. The steps and examples outlined by the cultural symmetry model provided theoretical and applied ways to advance the implementation of ethnomathematics principles.

3.5.2 Culturally responsive teaching. The sentiments of ethnomathematics mirror other constructivist and asset-based approaches, such as culturally responsive teaching (CRT) (e.g., Gay, 2018; Ladson-Billings, 2023; Nieto, 2017; Sleeter, 2012; Villegas & Lucas, 2007) and specifically CRT in math (e.g., Abdulrahim & Orosco, 2020; Averill et al., 2009; Harding-DeKam, 2014; Hernandez et al., 2013; O'Keeffe et al., 2019; Parker et al., 2017).

In brief, CRT supports all learners by acknowledging, connecting with, and upholding their backgrounds, needs, and cultures. Responsive teachers build upon an understanding of their own and learners' worlds in ways that value diversity (González et al., 2006), and they leverage the cultural knowledge, prior experiences, and frames of reference of ethnically diverse students to make learning experiences more relevant and effective (Gay, 2010). Mathematics teaching that embraces learner cultural perspectives contributes to strengthening (a) cultural identity (e.g., Bonner, 2014; Raygoza, 2016), (b) academic achievement and persistence among marginalized populations (Driver & Powell, 2017; Hubert, 2014; Rubel & Chu, 2012), (c) positive responses to high expectations set by instructors (Abdulrahim & Orosco, 2020; Rubie-Davies et al., 2015), and (d) teachers' critical reflections on their own biases and societal biases (Bartell, 2013; Jackson, 2013; Gregson, 2013).

Abdulrahim and Orosco (2020; and see also Hernandez et al., 2013) reviewed 35 studies on culturally responsive mathematics teaching with culturally and linguistically diverse (CLD) learners in K-12 schools in the U.S. Reviewed literature also spanned multiple populations (e.g., early education, L2 education, and special education). Culturally responsive teachers used a variety of evidence-based, interactive, and collaborative methods that supported students' cultural and linguistic diversity, which Abdulrahim and Orosco (2020) summarized in several themes. Students' *cultural identity* (i.e., evolving alignment with one or more cultural groups) was promoted by relating learning to their knowledge, heritage, and experiences in culturally affirming ways. Connecting materials and learning environments to learners' cultural backgrounds also promoted deeper *instructional engagement*, and encouraged *critical thinking* (i.e., willingness and ability to be resourceful and strategic when solving math problems) by preparing students to recognize and apply more diverse school, personal, and community resources. Infusing themes of *social justice* (i.e., acknowledging inequities and enacting change to remove them) increased student awareness of injustice and empowered them to take action (e.g., activism). Student success was better supported when teachers communicated *higher expectations* (i.e., clear metrics of achievement and their attainability) compared to deficit-based attitudes (i.e., expectations of difficulty and failure), along with more *collaboration* between learners, teachers, families, and communities. Finally, explicit training on the role of culture in math also supported *educator reflection* (i.e., self-examination of values, beliefs, and perceptions) and more positive perceptions of CRT. which was particularly important when challenging stereotypes and/or interacting with less familiar cultures.

Abdulrahim and Orosco (2020) also discussed implications of their conclusion with respect to policy, practice, and research. For instance, administrative and educational policies must acknowledge challenges and assets experienced by students from marginalized communities (e.g., Celedón-Pattichis et al., 2018), and policies may be established for training schools, educators, and administrators CRT (e.g., Khalifa et al., 2016). With respect to practice, CRT training did not seem to be prevalent across math teachers. The researchers thus proposed exposing teachers to culturally responsive theories and applications (e.g., Turner, 2012). For future research, Abdulrahim and Orosco (2020) reiterated calls to document relationships between CRT of math and student outcomes (e.g., Sleeter, 2012). Finally, they advocated for advancing qualitative methods to further guide understanding regarding practices that may benefit CLD students.

3.6 Theme 6: Study adult learners

A handful of studies examined literacy and math connections for college students and adults (e.g., Cruz Neri et al., 2021; Croce & McCormick, 2020; Daroczy et al., 2020; Méndez-Balbuena et al., 2022), highlighting that language and math are interconnected among adults as well as children. For example, Darcozy and colleagues (2020) found that both linguistic and arithmetic factors contributed to the difficulty of solving word problems in adults. Méndez-Balbuena and colleagues (2022) observed that the use of verbal versus algebraic solutions for inverse function problems significantly increased the chances of participants reaching the correct solution.

Croce and McCormick (2020) explored the use of math language in work contexts, which were underexplored in the math-literacy literature. The researchers proposed that math and language are integrated within professional discourse. For example, individuals may talk with clients to determine the nature of problems at hand, brainstorm potential mathematical approaches and solutions, and then formulate a verbal narrative to describe these possibilities. In addition, workers may acquire math knowledge and skills via apprenticeship interactions with mentors who discuss math-related principles and practices. Thus, math concepts, processes, communication, and language can be tightly interwoven in the workplace.

In another study, Cruz Neri and colleagues (2021) explored interactions between literacy skills (e.g., printed vocabulary, sentence processing, and passage comprehension), the features of math questions (e.g., pictures, tables, complex verb forms, number of prepositions, and lexical density), and math achievement. Among 368 adult participants, stronger reading component skills at all levels were associated with better math performance. These outcomes corroborated trends observed among younger learners. The researchers interpreted these findings as evidence of general cognitive similarity in the interaction between literacy and math in adults and younger populations. Lower comprehension scores aligned with lower math performance, especially in the case of math questions with higher lexical density, a defining characteristic of math language (e.g., Schleppegrell, 2007). However, findings showed no interaction between adults' general vocabulary or sentence processing and their math performance. Given links between literacy and math for adults–along with the relevance of such skills, and sometimes low literacy and math proficiency among adult populations (e.g., Grotlüschen et al., 2016))–Cruz Neri and colleagues (2021) proposed making math instructors more aware of the role of literacy in math performance and introducing relevant interventions during school.

Other research has extended findings regarding L1 and L2 (i.e., language of instruction, see Theme 3) to adults. Ní Ríordáin and colleagues (2015) interviewed adult math learners who had to change their language of instruction from their native Gaeilge (Irish) to English. In accord with other studies of L2 math instruction (e.g., see Karikari et al., 2022; Tavares, 2015), interviewees reported English math vocabulary as a main source of difficulty. However, interviewees did not explicitly view language as a component of "doing" math (e.g., "solving stuff," p. 245). Interviewees reported greater confidence when they had received opportunities to learn math in their LI. In contrast, interviewees reported more negative experiences when math was mandatory and did not receive support in their LI (e.g., "... an eight foot wall that I couldn't get over," p. 247). It is worth noting that adults studying math in their L2 may be less immersed in other L2 settings than children in similar situations (e.g., children of immigrants). Consequently, L1 support may be even more crucial in adult education.

Overall, relatively few studies examined literacy-math connections among older students and adults. Future research with adult learners will need to provide (a) partial replications of prior research with younger learners (e.g., correlational and predictive studies between literacy and math measures) and (b) new studies that consider adults' unique needs and contexts (e.g., balancing work and childcare). These needs and contexts include the fact that adult learners need to make a conscious choice to acquire math education and determination to persist throughout that education. Persistence can be aided by various supports, like helping students develop a plan to achieve their goals, and different instructional modalities like lectures, group work, and remote learning (see Coming, 2023). A particularly interesting focus may be adults who are simultaneously navigating the demands of immigration, which may entail substantial changes in environment, culture, and language. For example, Gal et al. (2020) discuss specific adult populations within adult learners who are vulnerable in various ways, including within the context of acquiring math education. The authors discuss how acquiring math in adulthood can be especially difficulty for low numerate adults, people in financial debt, people vulnerable due variables of gender and age, migrants and refugees, aboriginal or indigenous persons, people with learning differences/difficulties, and imprisoned persons. Assisting (vulnerable) adults in the acquisition of math requires educational, psychological (see Jameson & Fusco, 2014), and policy related support.

4. Discussion

In this review of research on literacy-mathematics interconnections, we identified six themes for informing future scholarship and practice. Most themes were broad and several touched upon equity (e.g., Themes 3 and 5). Due to scope, we do not assert specific instructional methods (i.e., "how to" strategies) for addressing every theme, but relevant implications are highlighted.

Importantly, this review adopted a primarily exploratory narrative approach; our aim was not to be systematic nor to conduct a meta-analysis. As a limitation, there are naturally numerous relevant studies, terminologies, or research topics that were neglected. Our goal was to cast a wide net that permitted us to derive actionable themes, which does not preclude the existence of *additional* themes. Indeed, a more systematic review on any one theme would certainly provide further evidence, insight, and nuance. In future work, focused meta-analyses (e.g., Arizmendi et al., 2021; Peng et al., 2020) might be ideal for documenting aggregate and overall effects (along with mediating and moderating variables), which could help to quantify relationships between literacy skills, math skills, outcomes, instructional contexts, and cultures.

4.1 Operationalizing Literacy-Math Connections (Themes 1 and 2)

Two themes emerged regarding measures, variables, and constructs employed to understand relationships between literacy and math. Theme 1 recommended improving operational definitions of literacy (e.g., decoding and comprehension) and math (e.g., numeracy and computation) competencies and associated measures. Studies of literacy-math connections (e.g., (e.g., Cirino et al., 2018; Fuchs et al., 2020; Yang et al., 2022) have examined diverse and non-overlapping measures that were operationalized in very different ways. Moreover, the underlying mechanisms of observed relationships were not always articulated. Similarly, Theme 2 recommended greater attention to domain-general skills and abilities that are shared by literacy and math competencies. Literacy and math are frequently treated as distinct yet related domains. However, evidence suggested that links between domains might be partially explained by underlying cognitive factors such as working memory (e.g., Shvartsman & Shaul, 2024; Zheng et al. (2011) and executive functioning (e.g., Purpura et al., 2017; ten Braak et al., 2022).

One recommendation is to provide clearer and more consistent operationalization and testing of key proficiencies, proxies, outcomes, and relationships, which should in turn improve the commensurability, transfer, and synthesis of findings about literacy-math connections. These efforts will also support replication studies (in similar or diverse settings) that test whether observed relationships are robust across settings. The process of aligning operationalizations will likely be challenging and require further psychometric and validity testing. The "best" measure for each skill remains unknown, and different measures may be ideal depending on context. One outcome of this approach may be *composite* measures that reflect multiple proficiencies.

A related recommendation is to undertake future research with the understanding that literacy and math may be partly, but not entirely domain-specific. Evidence of covariance between literacy, math, and domain-general proficiencies (e.g., WM and EF; Shvartsman & Shaul, 2024; ten Braak et al., 2022) makes it unlikely that the domains are truly distinct. Future research should further explicate the nature of the relationships between domain-general proficiencies, literacy, and math. This research should answer questions regarding the cognitive abilities involved in learning and "doing" of literacy and math, and whether those cognitive abilities develop separately from literacy and math, or all influence each other (and how).

Instructionally, both literacy and math performance build upon a diverse array of underlying competencies and skills. There does not appear to be a singular "literacy ability" or "math ability" that predicts success in either domain. Instead, both areas depend on a variety of skills at different levels, which can be developed or cultivated with instruction and practice. These skills also intersect such that building competencies in one area (e.g., literacy) might then strengthen the other (e.g., math) (Fuchs et al., 2020, 2021). An implication for instructors is that supporting literacy and/or math development may require multifaceted support of multiple skills and both domains together. In addition, learners may demonstrate variability in which skills they individually master at different times (e.g., Cirino and colleagues, 2018; Duncan et al., 2007; Espinas and Fuchs, 2022; Georgiou et al., 2020; ten Braak et al., 2022). Thus, instruction should be cognizant of continuous variability in skill development, which is distinct from dichotomous perceptions of "able" versus "not able."

Shared underlying competencies (e.g., WM and EF) help to explain how and why math and literacy are linked and suggest that instructors may find it useful to directly address such factors. In particular, instructors could reveal and model strategies for coordinating complex tasks in ways that optimize working memory, executive functioning, and similar cognitive resources (e.g., schemas, heuristics, time management, rubrics, and multiple modalities) with awareness of learner variability. Because diverse cognitive factors are involved, it also seems wise to identify equally diverse strategies that learners can use in their work.

4.2 Language and Culture (Themes 3, 4, and 5)

Another three themes pertained to how language and culture were used to teach, talk about, and do math. Theme 3 recognized that the language of instruction may differ from learners' native (L1) language (Cui et al., 2022; de Araujo et al., 2018; Le Pichon & Kambel, 2016) and recommended incorporating L1 support in the teaching of math (Tavares, 2015; Karikari et al., 2022). The challenges of developing math competencies seemed to be exacerbated when learners also had to translate across multiple languages. Theme 4 further recommended directly teaching the language of math and/or simplifying math language. The language employed in "doing math" (e.g., mathematics terminology) represents a unique and relevant register that must be acquired alongside the ability to perform math operations and computations (Erath et al., 2021; Riccomini et al. (2015); Schleppegrell, 2007; Yang et al., 2022).

Themes 3 and 4 emphasized that "doing" math always involves language, both in terms of talking about math or in performing mathematical operations and procedures. For instance, we need language to explain math to students (e.g., teaching), to discuss data and solutions with collaborators (e.g., business clients), and to verbalize our math reasoning when solving problems (e.g., taking an exam). Thus, these themes further contributed to our understanding of how and why literacy and math are connected. In particular, these themes suggest reasons why the literacy-math connections often tend to flow from literacy-to-math rather than math-to-literacy.

Supporting math vocabulary acquisition benefits learners, and literacy-informed interventions can be leveraged to improve outcomes in math (Arizmendi et al., 2021; Glenberg et al., 2012). This focus considers both (a) the literacy skills of learners and (b) the work of educators to convey math concepts to learners in accessible language. Teachers should be mindful that the language of instruction (e.g., English) may not be learners' native language (and sometimes not even their second or third). Multilingual learners may be simultaneously acquiring math competencies while needing to translate (e.g., words, concepts, instructions, feedback, and their own questions) across languages. This situation can be a source of confusion or frustration for learners that impacts performance in ways that are entirely separate from learners' actual "math ability" or "math skill." Acknowledging these realities is an important initial step for researchers and instructors. Future work might explore additional ways to explain math concepts in plain language, using visual aids and supplements, or working with skilled translators to provide materials in multiple languages (Antón & DiCamilla, 1998; van den Heuvel-Panhuizen et al., 2016). For example, there may be alternative or comparable math textbooks available in other languages, which could be made available to multilingual learners.

In parallel, instructors may find value in exploring alternative words, analogies, and expressions of math concepts that initially sidestep technical jargon. Communicating math concepts in "plain language" first may help students acquire and "translate" technical vocabulary (Strohmaier et al., 2023). Math vocabulary and language norms may also be a worthwhile topic for direct instruction. Rather than expecting students to acquire new terms via exposure or textbook definitions, more care might be given to explain how and why certain terms originated and are used. Importantly, such support may not need to be provided by teachers in isolation. In school settings where multiple instructors can communicate amongst each other, one beneficial practice may be for students' "language teachers" to inform "math teachers" about students' specific language needs. Likewise, math instructors might seek help from language-oriented colleagues for ways to communicate math in more accessible ways.

Finally, language is intricately tied to culture. To understand and support connections between literacy and math, we must also consider key cultural connections (D'Ambrosio & D'Ambrosio, 2013; Driver & Powell, 2017; Le Pichon & Kambel, 2016; O'Keeffe et al., 2019; Zhang & Zhang, 2010). Theme 5 recommends explicitly acknowledging and welcoming students' language-related cultures in math instruction. We referenced two broad approaches–ethnomathematics and culturally responsive teaching–that offered evidence-based guidance. It may be crucial to study and teach math as intertwined with (and important to) everyday life, culture, recreation, career goals, and more (Gay, 2010; González et al., 2006). Instead of treating math as separate from societal concerns (e.g., "pure" and "objective" numeric operations), interventions may help learners to consider real-world applications and concerns. For example, the principles of CRT might encourage instructors to welcome learners to bring their own reflective questions and discussions to class (e.g., students recommending societal topics with math elements) (Abdulrahim & Orosco, 2020; Appelbaum & Stathopoulou, 2023; Powell & Frankenstein, 1997). Similarly, the principles of ethnomathematics encourage teachers to consider how math is talked about, understood, and enacted in diverse settings, including settings that may be distinct from "Western" schooling or jobs (Fouze & Amit, 2023; Rowlands & Carson 2002). Showcasing these examples, and harnessing learners' cultural contexts within instruction, may enable learners to appreciate the depth and value of math in the world.

4.3 Adult Learners and Contexts (Theme 6)

Theme 6 recommended conducting more extensive and systematic research on literacy-math connections for adolescent, college-age, and older adult learners. We observed a substantial skew in the literature toward younger or very young children. A handful of studies suggested that literacy and math were connected for adults in ways that were similar to younger learners (Darcozy et al., 2020; Méndez-Balbuena et al., 2022). However, adult learners of math possess unique considerations (e.g., more advanced literacy and math tasks, job demands, family concerns, and immigration) that introduce important factors (Croce and McCormick, 2020; Cruz Neri et al., 2021). Moreover, within the adult content, acquiring math education requires determination and persistence, and some circumstances make certain adults more vulnerable to gaps in education and difficulties in accessing it (e.g., financial problems, indigenous backgrounds, migration, and imprisonment; Gal et al., 2020).

Instructionally, it may be important for instructors of adult learners (e.g., college students, returning students, nontraditional students, etc.) to recognize the complexities of adult lives that give rise to learning barriers. However, instructors might also leverage these real-world demands and contexts for teaching purposes (see also Theme 5). For instance, adult learners may have stronger motivations for appreciating how math applies in the workplace and may be better prepared to value how to communicate about math with clients and coworkers. Thus, although adult lives introduce educational challenges that must be approached with empathy, there may also be culturally responsive teaching opportunities that can be leveraged through creativity.

5. Conclusion

Ongoing research on literacy-math connections can be leveraged to inform understanding of cognitive skills, literacy skills, math skills, and their relationships. Adolescent and adult learners represent a largely untapped population and focus for this work. Associations between skills, cognitive resources, and cultures also inform teaching practices. Instructionally, tactics include (a) supporting "literacy" skills that also manifest in "math" skills, (b) supporting students' language resources for discussing and doing math, and (c) inviting cultural concerns and histories into the classroom as motivating, personal, and relevant topics.

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