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Systematic Review

On the Relationship Between Bilingualism and Mathematical Performance: A Systematic Review

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Abstract: As part of the demands of a globalized and interconnected world, studying second languages has become a major priority. Bilingual programs implemented in recent decades have motivated an educational strategy in which content area courses are taught through L2. The potential costs of this strategy in academic performance are debated, especially in challenging areas such as mathematics. The present work systematically reviewed 71 papers based on experiments measuring mathematics performance in bilinguals in order to establish if bilinguals show a (dis)advantage in mathematics compared to monolinguals. The results of a total of 305,136 participants (57,703 bilinguals and 247,503 monolinguals) show that bilingualism does not seem to affect mathematical performance, but this is dependent on whether subjects are highly proficient bilinguals. This type of bilingual may only be affected by lower reaction times depending on the testing language. On the other hand, low language proficiency negatively impacts mathematical performance. Lastly, bilingualism enhances mathematical encoding and processes in non-language-related tasks.

Keywords: bilingualism; monolingualism; mathematics; arithmetic; language proficiency; cognitive abilities

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1. Introduction

In a globalized world, bilingualism is a common phenomenon not only in multilingual societies but also in monolingual communities, where the development of a language acquired after the mother tongue (L2) [1] serves both personal and professional development [2,3]. In the current study, we review papers published between 1979 and 2023 that addressed the impact of bilingual status (i.e., monolingual, low-proficiency bilingual, or high-proficiency bilingual) on mathematics performance. So far, the literature shows two largely independent motivations for studying the link between bilingualism and mathematics: bilingual education programs and bilingual cognitive advantages. Below, we first outline each of these motivations separately and then link them together in order to inspire the goal of the current review.

1.1. Motivation I: Bilingual Education Programs

Bilingual programs are seen by many as an opportunity to increase both natural exposure to and learning of L2. However, these programs have been criticized for putting students' learning ability and academic performance at risk because teaching is not conducted through the mother tongue (L1), i.e., the first language learned at home in childhood and ordinarily used by the speaker during his/her life [1].

Prior to the 1960s, such criticism was based on a strongly ideological perspective that bilingual education (and bilingualism in general) is accompanied by harmful effects [4]. Later, this ideological perspective was replaced by an active, scientific pursuit to demonstrate the advantages of bilingual education through quantitative analysis of students' results in different school courses [5–7]. Yet, this pursuit still has not silenced criticism [8], and instruction in L2 is controversial as students with a low proficiency level in the language of instruction (LoI) show more difficulty in understanding and assimilating new content [9].

One specific discipline in which the impact of L2 teaching is intensively explored is mathematics. This subject presents a high complexity to be learnt, as evidenced by many students showing difficulties [10,11]. These difficulties seem to be partially related to the particularity of its conceptual expression. Mathematics has been understood as a language in itself [12], grounded in a specific linguistic code in which numbers, symbols, and operations are transcoded. Therefore, discourse is crucial for mathematical teaching and learning processes [13,14].

As the National Assessment of Educational Progress (NAEP) shows, English language learners (ELLs) in the US show significantly lower performance in mathematics than other students [15,16]. However, these data are mainly sourced from weak forms of bilingual education. The most common US bilingual programs (submersion, mainstream with withdrawal classes, and transitional) only gather students from linguistic minorities who have recently been incorporated into a new educational system and still struggle with the country's language [17].

On the other hand, students from strong bilingual programs (i.e., two-way immersion programs) that show balanced bilingualism, defined here as a balanced use and a balanced level of proficiency in two languages [18], do not perform worse than monolinguals in mathematics. Academic reports in Canada have shown that students who showed worse results in mathematics (among other areas) at the start of the immersion later fully caught up and finally outperformed monolingual students [19–21]. The same progression in academic results has been found in other content areas, not only in the referred immersion programs in Canada and the US but also in Europe [22–27].

This correlation between the development of bilingualism and cognition found its first theoretical formulation through the Threshold Hypothesis [9,28]. This hypothesis assumes that bilingualism has negative cognitive effects below a certain proficiency threshold. Above this level, there is no negative effect, and if the proficiency rises above the second threshold level, positive effects can be found. In other words, high-proficiency bilinguals—also called balanced bilinguals, and understood here as individuals fluent in two languages—showing similar receptive and productive skills across various contexts [17] would show a general cognitive advantage over monolinguals. On the other hand, a negative impact would be found with low-proficiency bilinguals, also called weak bilinguals, which are individuals with a low level of language competence in L2 in terms of content acquisition.

Since the Threshold Hypothesis was postulated, the effect of L2 proficiency on general cognition has been widely explored. A positive correlation has been found not only in the development of memory and executive functions but also in cognitive reserve, among other areas [29–31].

1.2. Motivation II: Bilingual Cognitive Advantages

The above-mentioned bilingual cognitive advantage is the second motivation for the current review. Even though the longitudinal analysis of academic results in immersion programs can indicate the presence and extent of general cognitive advantages in bilinguals compared to monolinguals, most work on this topic centers on dedicated (quasi-) experimental designs. The latter shows the benefits of bilingualism, especially in studies testing executive functions, namely: attention control [32–36], inhibitory control [37–39], cognitive flexibility [40], and working memory (WM) [37,38,41,42].

The apparent outperformance of bilinguals in this kind of executive process has been linked to structural changes from bilingual language use [43,44]: the areas used for language control in the frontal lobe overlap with those of general executive functions. The higher demands placed on those areas for using two languages lead to a broader development of the prefrontal area related to general control, so executive functions are enhanced in bilinguals. This enhancement of executive function in bilinguals has been logically related to other cognitive tasks in which attentional control has a central role [32–36]. Other than a better metalinguistic awareness [45–47] or a better capacity to learn new words [48,49], some studies have also shown a bilingual advantage in creativity or divergent thinking (for a review, see [50]), an earlier development of the theory of mind [40,51], or even IQ improvement [52].

Since mathematics strongly builds on domain-general cognition, a positive impact of bilingualism on executive functions, creativity, metalinguistic awareness, and/or general IQ [52] predicts that, with everything else being equal (e.g., socio-economical state, baseline intelligence), bilinguals should, on average, outperform monolinguals in terms of mathematics performance.

Several studies [53–55] have pointed to a bilingual advantage in developing the concept of number and quantity in early childhood. That this benefit growing with bilingualism [56] is demonstrated by further advantages in algebra tasks, solving complex problems, and abstract reasoning [57,58]. Children with a larger WM capacity, for instance, might resort to arithmetic strategies that result in stronger associations between basic addition problems (e.g., 1 + 2) and their sums, thus reinforcing conceptual understanding [59].

However, those results are inconsistent: multiple studies in primary and secondary education bilingual programs i.e., have shown lower mathematics performance in low-proficiency bilinguals than monolinguals and only similar results between high-proficiency bilinguals and monolinguals [60]. Moreover, high-proficiency bilinguals have also shown worse results than monolinguals in number decoding or simple arithmetic calculations in experiments measuring reaction times [61,62].

Conflicting results have also been shown in experiments measuring bilingual performance in L1 and L2. While some studies indicate a better mathematics performance when students operate in their L1, other studies show similar results in L1 and L2 or even better in L2. One major reason may be the effects of the language of application (LoA). Hence, beyond the impact of the proficiency of the LoI, bilingualism has been said to affect mathematics performance irrespective of the acquisition phase. Bilinguals could underperform on mathematical tests when there is a mismatch between the LoI and the LoA due to transcoding processes [63,64]. Also, due to competition effects between the languages, bilinguals could be slower in mapping numbers into words, as happens with other objects or symbols [65] or even because of a lack of full comprehension of the test instruction written in L2. The assessment of potential bilingual cognitive advantage effects should thus consider the impact of the LoA in reference to the LoI.

1.3. The Current Review and Its Goal

The present work offers a systematic review of studies exploiting (quasi-)experimental designs to determine the impact of bilingualism on mathematics performance. To achieve this, we first analyzed the features of the empirical designs across studies to determine their sensitivity. Concretely, we arranged our Results section according to the two types of designs found: (1) a within-subjects design (i.e., bilinguals solving mathematical tasks in their two languages) and (2) a between-subjects design (i.e., bilinguals versus monolinguals, or high- versus low-proficiency bilinguals). In each of the studies, we analyzed differences in designs across studies to determine why the previous literature shows conflicting results on whether (or not) there is a general bilingual (dis)advantage in mathematics performance. To anticipate the Results section, our findings provide evidence that mathematics achievement in bilingual subjects is highly dependent on three interrelated factors: (1) language proficiency, (2) the language used in the test, and (3) test typology (proficiency measures and the type of mathematical task).

2. Materials and Methods

This systematic review focused on determining the effect of bilingualism on mathematical performance.

2.1. Information Sources and Search Strategy

Data collection was conducted in the following databases: Pubmed, Web of Science, and Scopus. The Boolean operators "AND" and "OR" were used to connect keywords in the following search equation: "bilingualism" OR "bilingual" AND "arithmetic"; bilingualism" OR "bilingual" AND "mathematics"; bilingualism" OR "bilingual" AND "calculation"; "bilingualism" OR "bilingual" AND "number" OR "numbers"; "transcoding" AND "number" AND "bilingualism" OR "bilingual".

2.2. Selection of Studies

Our search found over 400 articles, counting the results from the three databases. After articles found in each database were consolidated and duplicates were eliminated, 231 were selected for a first screening.

2.3. Inclusion Criteria

To be included, articles had to meet inclusion criteria that we set with respect to their design, type of tasks, measure of performance, language, and publication date. Specifically, (1) articles were only considered when mathematical performance in bilinguals was compared either within bilingual subjects (between L1 versus L2) or between bilingual (L1 or L2) versus monolinguals. Moreover, (2) mathematical performance was considered only when indexed via accuracy and/or reaction time measures derived from tasks involving arithmetical operations using Arabic numbers, mathematical symbols, or number words; the solving of word problems; the comparison or ordering of numbers; or the transcoding (word to number), naming (number to word), counting (word to physical objects/physical objects to word in preschoolers), or recalling (repeating sequence of numbers) of numbers. Finally, (3) only English articles published between 1976 and 2023 were considered.

2.4. Studies Excluded

After the first screening of the 231 articles, a total of 142 were excluded. We found four main types of papers that included the keywords but were not actually measuring mathematical performance in bilinguals: studies on mathematics teaching practices in bilingual education, or bilingual policy and its impact on mathematics teaching (e.g., [61]); studies on language strategies for the teaching of L2 in L2-medium mathematics (e.g., [62,63]); studies on innovative methodologies and materials for the teaching of mathematics in L2 [64,65]; literature reviews on mathematics performance in bilinguals (e.g., [66,67]); and academic reports on bilingual children with language impairment (e.g., [68,69]). This left 89 articles.

In a second screening, from the total of 89 articles that measured mathematical performance in or between bilingual subjects, 18 articles were excluded due to not meeting one or several of the inclusion criteria, namely, (1) studies comparing mathematics performance in multilingual (more than two languages) versus monolingual learners (e.g., [70,71]); (2) studies using lexical decision task comparing regular words and number words (e.g., [72]), the translation of numbers from L1 to L2 or L2 to L1 (e.g., [73–75]), or number memory span (e.g., [76–80]); (3) studies that assessed mathematics performance in bilinguals in only one of their languages (e.g., [81–85]); or (4) studies providing incomplete data for the current purposes (e.g., measuring the compatibility effect with Arabic digits providing only the mean difference between compatible and incompatible trials in each language (e.g., [86–88])). Figure 1 presents a simplified diagram of the study selection process.

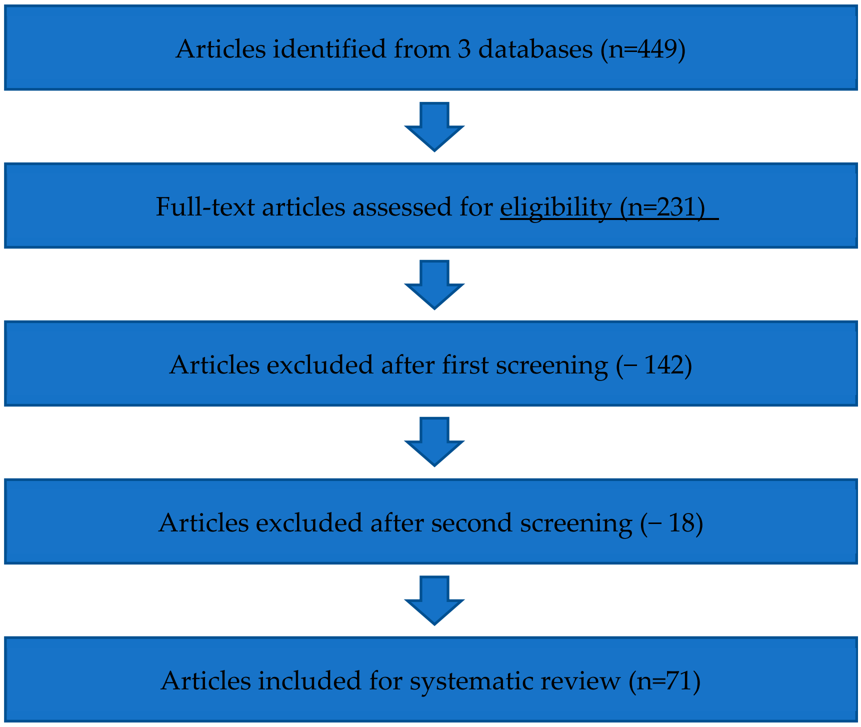

Figure 1. Study selection process for a systematic review.

3. Results

3.1. General Results

Within the 71 articles included for systematic review, 82 different studies (experiments) were run. A total of 305,136 participants were considered (57,703 bilinguals and 247,503 monolinguals).

A total of 30 (36.6%) studies compared the mathematics performance of bilinguals and monolinguals, and 52 studies (63.4%) examined the performance of bilinguals in both their languages (their language of instruction and their non-instructional language).

This division constitutes the two main categories of our review. The first one is of bilinguals versus monolinguals, with 30 identified studies, and the second one is of only bilinguals, with a total of 52 studies.

In the first category, bilinguals versus monolinguals, bilinguals performed the tasks in their mother tongue (5), the second language (9), or both (12)—there were four cases in which this information was not indicated within the studies. The language of instruction can be the bilinguals' mother tongue (13), their second language (14), or a combination of languages (5)—there were two cases with the language of instruction not indicated within the studies.

Regarding the type of task, in 20 out of the 30 studies, participants were asked to judge (true/false) the given result (3) or to give the result (17) in tasks with the basic four operations—addition, subtraction, multiplication, and division. Of the 17 studies, a total of 13 studies combined those tasks with the four basic operations with other tasks, such as word problems, transcoding, or other mathematical symbols.

Lastly, three studies evaluated only word problems (questions stated in one or more sentences that require the use of math skills in a real-world scenario), and ten were based on school grades or other institutional sources where proficiency in bilingualism and mathematics was evaluated through several tests in longitudinal studies.

In the 30 studies, the measures considered were reaction time (2), accuracy (19), or both (9).

In the second category, studies where only bilingual subjects were tested, the same type of task was performed in their first and second language, with one of them being their language of instruction.

The most commonly used type of task (46 out of 52 studies) was to solve the four basic operations by judging (true/false) the given result (24), by giving the result (19), or both (3). Of the 21 experiments in which participants had to give the result of basic arithmetic operations, a total of 15 studies combined this task with others, such as word problems, transcoding, or other mathematical symbols.

Of the six other studies, two covered school grades, and four were word problems.

For these 52 studies, the measures considered were accuracy (12) or both reaction time and accuracy (40). A total of 14 studies used neuroimaging and scanning techniques (functional magnetic resonance imaging, fMRI; event-related potential, ERP; magnetoencephalography, MEG) that measured brain activity when exposed to arithmetical operations using language and/or response times when judging the correctness of number word operations in their language of instruction and non-instructional language [63,66–77].

In the context of language pairs, out of the entire sample, 22 studies (27%) tested Spanish–English bilinguals; 10 (12%) tested Chinese (Mandarin or Cantonese)–English bilinguals; 7 (8%) tested German–French bilinguals; 7 (8%) tested English–Other bilinguals; 6 (7%) studies tested French–English bilinguals, 4 (5%) tested English–Filipino bilinguals; 3 others tested English–Russian bilinguals; and 3 tested Arabic–Hebrew bilinguals, representing 4% each. In the remaining 20 studies (38%), participants were bilingual in the following languages: Luxemburgish–French, German–French, Russian–Tatar, Pidgin–English, Japanese–English, Korean–English, Indonesian–English, Yoruba/Hausa–English, Swahili–English, Welsh–English, Irish–English, Italian–German, French–Dutch, Spanish–Catalan, Spanish–Basque, German–Turkish, Polish–English, German–Swedish, and German–English.

Since the first studies in the 1970s, research on mathematical performance in bilinguals has increased significantly, showing a growing interest in the topic, as shown in Figure 2.

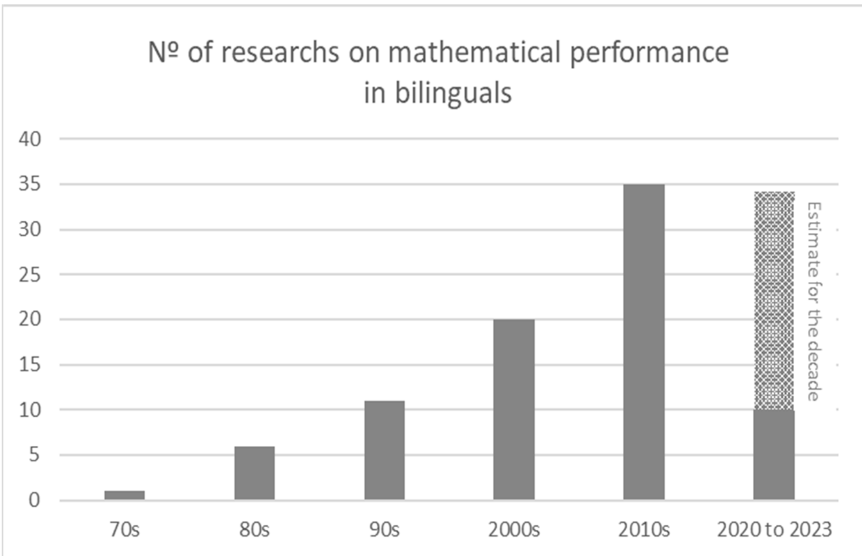

Figure 2. The number of studies on mathematical performance in bilinguals by decade.

The specific parameters of every reviewed study (sample size, age, task type, presentation, response, behavioral measures, neuroimaging techniques, language pairs, language of instruction, and language of application) can be found in Table 1.

Table 1. A summary of the studies.

Study	*N* = Sample Size	*N* = Bil	*N* = Mono	Age	BilOnset	Task:WP	Task:SG	Task: JudgC	Task: Solving	Pres	Res	Behavioral Measure	NI Tech	LPairs	LoI	LoA
Adetula (1990) [89]	48	48		<8–9>	<5/<8–9>	Yes	No	No	No	Vis	Wr	Accuracy	No	YoHa-En	L2	Both
Ardila et al. (2000) [90]	69	69		<18–49> (M = 30.28)	<0–35> (M = 10.5)	Yes	No	No	Ari. Word	Aud	Or	Accuracy/RT	No	Sp-En	L1	Both
Bernardo (2001)-exp. 1 [89]	21	21		N/A (High school students)	N/A	No	No	Ari. Num/Word	No	Vis	Wr	Accuracy/RT	No	Fi-En	L2	Both
Bernardo (2001)-exp. 2 [89]	59	59		N/A (High school students)	N/A	No	No	Ari. Num/Word	No	Vis	Wr	Accuracy/RT	No	Fi-En	L2	Both
Bernardo (2005) [91]	111	111		<5	<5	Yes	No	No	No	Vis	Wr	Accuracy	No	Fi-En	L2	Both
Bernardo and Calleja (2005) [92]	85	85		<5	<6–11>	Yes	No	No	No	Vis	Wr	Accuracy	No	Fi-En	L2	Both
Campbell and Dowd (2012) [93]	48	48		<18–30> (M = 32.1)	N/A	No	No	No	Ari. Num	Vis	Or	Accuracy/RT	No	Ch-En	L1	Both
Campbell and Epp (2004) [94]	26	26		N/A (Young adults)	N/A	No	No	Comparing_Num	Ari. Num/Transcoding	Vis	Or/Wr	Accuracy/RT	No	Ch-En	L1	Both
Campbell et al. (1999) [95]	26	26		20–39 (M = 28.4)	N/A	No	No	Comparing_Num	Ari. Num/Transcoding	Vis	Or/Wr	Accuracy/RT	No	Ch-En	L2	Both
Cardoza and Brown (2020) [96]	63	63		<8–10>	N/A	No	Yes	No	No	Vis	Wr	Accuracy	No	Sp-En	L1/L2*	L2
Cerda et al. (2019) [66]	28	28		<8–11>	<5	No	No	Ari. Word	No	Aud/Vis	Wr	Accuracy/RT	Yes (ERP)	Sp-En	L1	Both
Cerda et al. (2022) [67]	29	29		M = 21	N/A	No	No	Ari. Num/Word	No	Aud/Vis	Wr	Accuracy/RT	Yes (ERP)	Sp-En	L1/L2*	Both
Cho et al. (2020) [97]	368	368		<5–7>	<5	Yes	No	No	Ari. Num	Vis	Wr	Accuracy	No	Sp-En	L2	Both
Frenck-Mestre and Vaid (1993) 1.2. [98]	15	15		<19–22>	>12	No	No	Ari. Num	No	Vis	Wr	Accuracy/RT	No	En-Fr	L1	Both
Frenck-Mestre and Vaid (1993). 1.1 [98]	15	15		<19–22>	>12	No	No	Ari. Num	No	Vis	Wr	Accuracy/RT	No	En-Fr	L1	Both
Ganayim, D. and Ibrahim, R. (2014) exp. 1. [99]	18			(M = 23.9)	<6–11>	No	No	Comparing_Num	No	Vis	Wr	Accuracy/RT	No	Ara-Heb	L1	Both

Table 1. *Cont.*

Study	*N* = Sample Size	*N* = Bil	*N* = Mono	Age	BilOnset	Task:WP	Task:SG	Task: JudgC	Task: Solving	Pres	Res	Behavioral Measure	NI Tech	LPairs	LoI	LoA
Ganayim, D. and Ibrahim, R. (2014) exp. 2 [99]	18	18		(M = 23.8)	<6–11>	No	No	Comparing_Num	No	Vis	Wr	Accuracy/RT	No	Ara-Heb	L1	Both
Grabner et al. (2012) [68]	38	38		M = 23.45	<6–11>	No	No	No	Ari. Word	Vis	Wr	Accuracy	Yes (fMRI)	It-Ge	L1	Both
Guilllaume (2011) [100]	80	80		<18–40> (M = 20.31)	N/A	No	No	Ari. Num	Ari. Num/Transcoding	Vis	Or	Accuracy/RT	No	Sp-En	N/A	Both
Hahn et al. (2019) [101]	32	32		N/A (college students)	N/A	No	No	Ari. Num	No	Vis	Wr	Accuracy/RT	No	Ge-En	L1	Both
Klichowski and Króliczak (2017) exp. 1 [102]	29	29		<20–45>	>12	No	No	No	Ari. Num/Transcoding	Vis	Or	Accuracy/RT	No	Po-En	L1	Both
Klichowski and Króliczak (2017) exp. 2 [102]	29	29		<20–45>	>12	No	No	No	Ari. Num	Aud	Or	Accuracy/RT	No	Po-En	L1	Both
Kraut and Pixner (2020) [103]	101	101		<18–44> (M = 23.13)	N/A	No	No	Ari. Num	No	Vis	Wr	Accuracy/RT	No	Ge-Fr	L1	Both
Lachelin et al. (2022) [104]	99	99		(M = 10.69, 13.46, 16.48, 23.58)		No	No	Transcoding	No	Aud	Wr	Accuracy/RT	No	Ge-Fr	L1	Both
Lin et al. (2012) [105]	11	11		<20–30>	<7–13>	No	No	Ari. Num	No	Aud	Wr	Accuracy	Yes (fMRI)	Ch-En	L1	Both
Lin et al. (2019) [69]	22	22		<19–60> (M = 24)	>12	No	No	Ari. Word	No	Aud	Wr	Accuracy/RT	Yes (MEG)	Ch/Ja-En	L1	Both
Martinez-Lincoln et al. (2015) [70]	14	14		<27–48> (M = 37)	N/A	No	No	Ari. Word	No	Vis	Wr	Accuracy/RT	Yes (ERP)	Sp-En	L1	Both
McClain and Huang (1982) exp. 1 [84]	20	20		N/A (university students)	N/A	No	No	No	Ari. Word	Aud	Or	Accuracy/RT	No	Ch-En	L1	Both
McClain and Huang (1982) exp. 2 [84]	40	40		N/A (university students)	N/A	No	No	No	Ari. Word	Aud	Or	Accuracy/RT	No	Sp-En	L1	Both
Mondt et al. (2011) [63]	24	24		<7.8–11.4> (M = 9.6)	<5	No	No	No	Ari. Num	Vis	Wr	Accuracy	Yes (FMRI)	Fr-Du	L2	Both
Morales (1998) [106]	119	119		<7–11>	<11	Yes	No	No	No	Vis	Wr	Accuracy	No	Sp-En	L2	Both

Table 1. *Cont.*

Study	*N* = Sample Size	*N* = Bil	*N* = Mono	Age	BilOnset	Task:WP	Task:SG	Task: JudgC	Task: Solving	Pres	Res	Behavioral Measure	NI Tech	LPairs	LoI	LoA
Pifarré Turmo et al. (2003) [12]	483	483		<13–14>	N/A	No	Yes	No	No	Vis	Wr	Accuracy	No	Sp-Ca	L1/L2*	Both
Prior et al. (2015) [107]	63	63		(M = 22–26)	N/A	No	No	Ari. Num/Word	No	Aud/Vis	Wr	Accuracy/RT	No	Ara-Heb	N/A	Both
Salillas and Carreiras (2014) [71]	18	18		N/A	<5	No	No	No	Comparing_Num/Ari. Num	Vis	Wr	Accuracy/RT	Yes (EEG)	Sp-Ba	L1	Both
Salillas and Wicha (2012) exp. 1 [72]	11	11		<20–23> (M = 21.7);	>12	No	No	Ari. Num/Word	No	Vis	Wr	Accuracy/RT	No	Sp-En	L1	Both
Salillas and Wicha (2012) exp. 2 [72]	22	22		<19–32> (M = 23.5)	>12	No	No	Ari. Num	No	Vis	Wr	Accuracy/RT	Yes (EEG)	Sp-En	L1	Both
Spelke and Tsivkin (2001) exp. 1 [108]	8	8		<18–24> (M = 19.8)	>12	No	No	Ari. Word	No	Vis	Wr	Accuracy/RT	No	Ru-En	L1/L2*	Both
Spelke and Tsivkin (2001) exp. 2 [108]	8	8		<18–32> (M = 22.5)	>12	No	No	Ari. Word	No	Vis	Wr	Accuracy/RT	No	Ru-En	L1/L2*	Both
Spelke and Tsivkin (2001) exp. 3 [108]	8	8		<19–33> (M = 24)	>12	No	No	Ari. Word	No	Vis	Wr	Accuracy/RT	No	Ru-En	L1/L2*	Both
Stringer, A. P. (2000) [109]	32	32		(M = 21.7–21.9)	>12	No	No	No	Ari. Num/Word	Vis	Or	Accuracy/RT	No	En-Fr	L1	Both
Swanson et al. (2019) [110]	394	394		(M = 7.6) <6–8>	N/A	Yes	No	No	Comparing_Num/Ari. Num/Transcoding	Aud/Vis	Or/Wr	Accuracy	No	Sp-En	L1/L2	Both
Swanson et al. (2021) [111]	391	391		(M = 7.6) <6–8>	N/A	Yes	No	No	Comparing_Num/Ari. Num/Transcoding	Aud/Vis	Or/Wr	Accuracy	No	Sp-En	L1/L2	Both
Tamamaki (1993) [112]	32	32		<19–58>	N/A	Yes	No	No	Ari. Num	Aud	Or	Accuracy/RT	No	Ja-En	L1	Both
Vaid, J. (1985) [113]	10	10		<23–35> (M = 27.6)	>5	No	No	No	Comparing_Mix/Ari. Num/Word	Vis	Or	Accuracy/RT	No	En-Oth	N/A	N/A
Van Rinsveld et al. (2016a) [64]	193	193		(M = 12.2, 13.2, 15.5, 16.4, 22.4)	<7	No	No	No	Ari. Num	Vis	Or	Accuracy/RT	No	Ge-Fr	L1(+)-L2(−)	Both
Van Rinsveld et al. (2016b)	141	141		(M = 25.3, 12.6, 15.7)	<7	No	No	Comparing_Mix	No	Aud/Vis	Wr	Accuracy/RT	No	Ge-Fr	L1(+)-L2(−)	Both
Van Rinsveld et al. (2017) [73]	21	21		(M = 23.1)	<6–11>	No	No	Ari. Num	No	Aud	Wr	Accuracy/RT	Yes (FMRI)	Ge-Fr	L1(+)-L2(−)	Both
Venkatraman et al. (2006) [74]	20	20		N/A	<5	No	No	Ari. Num	No	Vis	Wr	Accuracy/RT	Yes (FMRI)	Ch-En	L1/L2	Both

Table 1. *Cont.*

Study	*N* = Sample Size	*N* = Bil	*N* = Mono	Age	BilOnset	Task:WP	Task:SG	Task: JudgC	Task: Solving	Pres	Res	Behavioral Measure	NI Tech	LPairs	LoI	LoA
Volmer, E. et al. (2018) [114]	58	58		<18–47> (M = 23)	N/A	Yes	No	No	Ari. Num	Aud	Or	Accuracy/RT	No	Ge-Fr	L1/L2*	Both
Wang et al. (2007) [75]	19	19		(M = 36)	>12	No	No	Ari. Num	No	Aud	Wr	Accuracy/RT	Yes (FMRI)	Ch-En	L1	Both
Wang et al. (2009) [76]	15	15		<19–23> (M = 20.5)	>12	No	No	No	Transcoding	Vis	Or	Accuracy/RT	Yes (FMRI)	Ch-En	N/A	Both
Zhang et al. (2015) [77]	16	16		(M = 21)	>12	No	No	No	Transcoding	Vis	Wr	Accuracy/RT	Yes (FMRI)	Ch-En	L1	Both
Abedi and Lord (2001) [83]	1174	372	802	<13–14>	N/A	Yes	No	No	No	Vis	Wr	Accuracy	No	En/Sp-Oth	L1	L2
Atagi & Sandhofer (2023) [79]	121	70	51	<8–11>	<5	No	No	No	Ari. Num	Vis	Wr	Accuracy/RT	No	En-Oth	L2	L2
Bamford and Mizokawa (1992) [85]	46	31	15	<6–11>	N/A	Yes	No	No	Ari. Num/Transcoding	Vis	Wr	Accuracy	No	En-Sp	L2	L2
Choi et al. (2018) [86]	825	350	475	4	<5	Yes	No	No	Ari. Num/Word/Trascoding	N/A	N/A	Accuracy	No	Sp-En	L1	L2
Clarkson (1992) [60]	301	232	69	<11–12>	<6–11>	No	No	No	Ari. Word	Vis	Wr	Accuracy	No	Pi-En	L2	Both
Daubert and Ramani (2019) [59]	74	37	37	<4–5>	<5	No	No	No	Ari. Sym/Ari. Num	Vis	Wr	Accuracy	No	Oth-En	L2	L2
Fleckenstein et al. (2019) [115]	590	590	N/A	M = 6	<6–11>	No	Yes	No	No	N/A	N/A	Accuracy	No	Ge-En	L2	L1
Garret (2010) [116]	22,000	22,000	N/A	<9–10>	<5	No	Yes	No	No	N/A	N/A	Accuracy	No	Oth-En	L2	N/A
Geary et al. (1993) exp. 1 [61]	35	26	9	N/A (University students)	N/A	No	No	Ari. Num	No	Vis	Wr	RT	No	En/En-Fr	L1	L2
Geary et al. (1993) exp. 2 [61]	84	56	28	N/A (University students)	N/A	No	No	Ari. Num	No	Vis	Wr	RT	No	En/En-Sp	L1	L2
Han (2012) [117]	16,380	4100	12,280	<5–10>	<5/<6–11>	No	Yes	No	No	N/A	N/A	Accuracy	No	En-Oth	N/A	L2
Hartanto et al. (2018) [80]	44,230	6171	38,059	<4–5>	<5	No	No	No	Ari. Sym/Ari. Num	Aud/Vis	Wr	Accuracy	No	Sp-En	L2	L2
Kempert et al. (2011) [87]	78	44	34	M = 8.5	<5	Yes	No	No	Ari. Num	Aud/Vis	Wr	Accuracy	No	Ge-Tu	L1	Both

Table 1. *Cont.*

Study	*N* = Sample Size	*N* = Bil	*N* = Mono	Age	BilOnset	Task:WP	Task:SG	Task: JudgC	Task: Solving	Pres	Res	Behavioral Measure	NI Tech	LPairs	LoI	LoA
Mägiste, E. (1980) [78]	46	32	14	<14–19>	<0–12>	No	No	No	Ari. Num	Vis	Wr	Accuracy/RT	No	Ge-Swe	L1	Both
McClain and Huang (1982)-2.2 [84]	60	40	20	N/A (University students)	N/A	No	No	No	Ari. Word	Aud	Or	Accuracy/RT	No	Sp-En/En	L1	Both
Mielicki et al. (2017) exp. 1 [88]	61	29	32	<18–35>	>7	No	No	No	Ari. Num/Word	Vis	Or/Wr	Accuracy	No	En-Oth	L1	N/A
Mielicki et al. (2017) exp. 2 [88]	105	64	41	<18–26>	>7	No	No	No	Ari. Num/Word	Vis	Wr	Accuracy/RT	No	En-Oth	L1	N/A
Ní Ríordáin and O'Donoghue (2009) [82]	107	52	55	<4–18>	<5	Yes	No	No	No	Vis	Wr	Accuracy	No	Ir-En	N/A	Both
Nishat, T. (2015) [118]	164	64	100	<18–34> (M = 23.08)	N/A	No	No	No	Ari. Num/Word	Vis	Wr	Accuracy/RT	No	En-Sp	L1	Both
Marsh & Maki (1976) [81]	40	20	20	N/A (College students)	N/A	No	No	No	Ari. Num	Vis	Or	Accuracy/RT	No	En-Sp	L1	Both
Piper et al. (2018) [119]	1800	900	900	<6–8>	<5	Yes	No	No	Ari. Num	Vis	Or/Wr	Accuracy/RT	No	Sw-En	L1/L2*	Both
Poncin et al. (2020) [68]	83	29	54	(M = 24)	6	No	No	Transcoding	No	Aud/Vis	Wr	Accuracy/RT	No	Ger-Fr	L1(+)-L2(−)	Both
Powell et al. (2020) [120]	1258	743	515	<8–9>	<5	Yes	No	No	Ari. Num	Vis	Wr	Accuracy	No	Oth-En	L1	Both
Salekhova and Tuktamishov (2020) [57]	62	29	33	<18–20>	<5	No	No	No	Ari. Sym	Vis	Wr	Accuracy	No	Ru-Oth	L1	N/A
Secada (1991) [58]	45	45	88	<6–7>	<5/<6–11>	Yes	No	No	No	Vis	Wr	Accuracy	No	Sp-En	L2	Both
Turnbull et al. (2000) [121]	97,340	8863	88,477	<8–9>	<6–7>	No	Yes	No	No	Vis	Wr	Accuracy	No	En-Fr	L2	L1
Turnbull et al. (2003) [122]	114,064	8865	105,199	<11–12>	<6–7>	No	Yes	No	No	Vis	Wr	Accuracy	No	En-Fr	L2	L1

Table 1. *Cont.*

Study	N = Sample Size	N = Bil	N = Mono	Age	BilOnset	Task:WP	Task:SG	Task: JudgC	Task: Solving	Pres	Res	Behavioral Measure	NI Tech	LPairs	LoI	LoA
Van Rinsveld et al. (2016b) [123]	111	41	70	(M = 25.3, 23.3, 19.7)	<7	No	No	No	Ari. Num/Word	Aud/Vis	Wr	Accuracy/RT	No	Ge-Fr	L1(+)-L2(−)	Both
Williams (2002) exp. 1 [124]	96	82	14	<11–12>	<5	No	Yes	No	No	Vis	Wr	Accuracy	No	We-En	L1(+)-L2(−)	L1
Williams (2002) exp. 2 [124]	88	76	12	<14–16>	<5	No	Yes	No	No	Vis	Wr	Accuracy	No	We-En	L1(+)-L2(−)	L1

KEYS: N = sample size, of which N = bilingual subjects and N = monolingual subjects. Profile = subjects' profile: Bil-MN = bilinguals–monolinguals. Bil = bilinguals. Age = age of participants as written in the studies. (<X, younger than, <X<, age between, >X, older than, M = mean, N/A, not indicated). BilOnset = bilingual onset; the age of bilingual exposure (<X, before age, <X<, between ages, >X, after age, N/A, not indicated). Task = refers to the type of math task: (1) WP: word problems; (2) SG = data from school grades or other institutional sources; (3) JudgC: judgment of correctness of arithmetical operations; (a) Arabic numbers (Ari. Num); (b) Language: number words, oral or written = Ari. Word; (c) Other mathematical symbols (Ari. Sym); (d) Comparing: What number is bigger than the other? There are two options: comparing_Num = using Arabic numbers and Comparing_Mix = using both Arabic numbers and words; (e) Transcoding = word to number/number to word; (4) Solving—giving the result of a number calculation using the following: (a) Arabic numbers (Ari. Num); (b) Language: number words, oral or written = Ari. Word; (c) Other mathematical symbols (Ari. Sym); (d) Comparing: What number is bigger than the other? There are two options: comparing_Num = using Arabic numbers and Comparing_Mix = using both Arabic numbers and words; (e) Transcoding = word to number/number to word; Pres = presentation of the tasks: Aud = auditorial; Vis = visual; Aud/Vis = both auditorial and visual; N/A: not indicated. Res = the task's responses: Or = oral; Wr = written; Or/Wr = oral and written. N/A: not indicated. Behavioral measure = accuracy/response time (RT). NI Tech = stimuli were measured through neuroimaging and brain-scanning techniques (EEG, ERP, MEG, or fMRI): yes/no/type. LPairs = language pairs assessed in the study. The first one written in the pair is L1: Ba = Basque, Ca = Catalan, Ch = Chinese (Mandarin or Cantonese), Du = Dutch, En = English, Fi = Filipino, Fr = French, Ge = German, Heb = Hebrew, In = Indonesian, Ir = Irish (or Gaeilge), It = Italian, Ja = Japanese, Ko = Korean, Lux = Luxemburgish, Oth = Other native language, Pi = Pidgin, Po = Polish, Ru = Russian, Sp = Spanish, Sw = Swahili, Swe = Swedish, Ta = Tatar, Tu = Turkish, We = Welsh, YoHa = Yoruba/Hausa. LoI = language of instruction (bilingual participants): L1; L2; L1/L2; L1/L2* (two groups of bilinguals. For one group, LoI = L1, for the other group, LoI ≠ L1); L1(+)-L2(−) (two different LoI. Luxembourg case: first LoI German and second LoI English); N/A (not indicated). LoA = language of application. Language used in the test: L1; L2; Both L1 and L2 (two tests); N/A (not mentioned).

3.2. Bilinguals Versus Monolinguals

A total of 30 out of 82 studies (36.6%) analyzed bilinguals' mathematics performance compared to monolinguals.

For this set of studies, a total of 16 studies (53%) showed that generally, bilinguals performed better than monolinguals, 11 studies (37%) concluded that they performed equally, and 3 studies (10%) indicated that bilinguals performed worse than monolinguals.

Within those, six studies (20%) requested that students answer non-language dependent tasks, presenting problems and operations only with Arabic numbers or symbols [57,59,78–81], and compared the results of those tests between bilingual and monolingual subjects. The outcome showed divided results. The more recent studies showed that bilinguals obtained similar [79] or better results [57,59,80] than monolinguals in strictly nonverbal activities, such as analytical reasoning abilities (enhanced working memory), fluency in complex math task-solving, abstract thinking, attentional focus, applying new procedures, and flexible selection. Earlier studies, such as that by Mägiste [78], showed that high-proficiency bilinguals performed more slowly and less accurately in simple arithmetic. Marsh and Maki [81] show that bilinguals are slower in responding to solving problems. Nevertheless, the difference was significant only in the trials (1) where bilinguals had to respond using their non-preferred language (not LoI) or (2) they had to change between their two languages.

Two other studies (6.7%) judged the correctness of arithmetical operations using exclusively Arabic numbers in those cases. Both studies are included in the same article by Geary et al. [61] concluded that there is no significant difference between bilingual and monolingual subjects. However, bilinguals were slightly slower in executing operations when solving complex problems.

Six studies (20%) focused on tasks only, including word-type problems (word problems, the judgment of correctness with transcoding, and solving with arithmetic words). All studies indicated that bilinguals performed better than monolinguals [58,60,62,82] or performed similarly [83,84]. This good performance is also shown in general math results [58,60,82] or concrete activities such as those with sequential conditions [62]. Nevertheless, the positive results for bilinguals in word-type problems only apply to subjects with high-proficiency in both languages. Students with low proficiency in L2 obtained worse results than highly proficient bilinguals and monolinguals [58,60,62,82,83]. Moreover, bilinguals' performance decreased substantially when the LoA was not the same as their LoI [62,84], even when mathematical education took place in a second language at a later age. As a good example, the study by Poncin et al. [62] in the Luxembourgish context showed how subjects that had German as a LoI in primary school and French in secondary school demonstrated no difference compared to German monolinguals but were slower and made more errors than their monolingual French peers.

We found nine studies (30%) that used both arithmetic or symbol tasks and word tasks in different mixed ways. Six stated that bilinguals performed better than monolinguals [85–88,119], and two studies [64,118] indicated that bilinguals and monolinguals performed equally. Only Powell et al.'s [120] results showed that English Learners (Els) scored lower than non-ELs across all groups, but the group of Els showed low proficiency in the LoA of the test. Indeed, longitudinal studies in bilingual schools demonstrated that math achievement seems to develop with the level of bilingualism. In a study by Choi et al. [86], the bilingual group started kindergarten with lower baseline math skills than monolingual children but outperformed them only 1.5 years later. Similarly, Bamford and Mizokawa [85] showed in a four-year longitudinal study that bilingual development correlated with mathematical performance, especially in enhancing higher-order mathematical skills. This advantage in tasks requiring abstract or symbolic problem solving is also highlighted in Mielicki et al. [88]. In this study, bilinguals performed the same as monolinguals in basic math but demonstrated a clear advantage on more challenging items within the Symbol Math task. This advantage persisted even when controlling socioeconomic status, what seems to indicate that bilingualism enhances abstract and symbolic thought processes crucial for complex mathematical reasoning.

In line with this, Kempert et al. [87] also indicated a better performance of highly proficient bilinguals in problems with distractors that especially required attentional control skills. Additionally, it is worth noting that highly proficient bilinguals obtained better results in math problems in German (their LoI) than in Turkish, reflecting the cognitive costs of switching between the LoI and LoA. Nevertheless, high-proficiency bilinguals scored higher than low-proficiency bilinguals in both German and Turkish. This advantage for high-proficiency bilinguals, even when the LoI does not coincide with LoA, was also found in work by Piper et al. [119] in the context of Kenya. In this study, high-proficiency bilinguals with English as an LoI outperformed low-proficiency bilinguals who studied in Kiswahili on math tests that had Kiswahili as an LoA. Interestingly, this advantage persisted even when controlling for socioeconomic status (SES).

The last seven studies (23.3%) only used the data from school grades or other institutional sources as criteria, and all showed better results for bilinguals versus monolinguals [115,116,122] or equal results [117,121,124]. The studies showed that bilingual (immersion) students performed better than monolingual (conventional program) students. Immersion students outperformed conventionally schooled students with respect to initial math skills, and their performance continued to improve with increased proficiency. Bilingual children showed a faster rate of growth in math skills, which was positively associated with the amount of non-English language spoken at home. Immersion students performed equally to regular students in grade 3 but significantly better by grade 6, showing no disadvantage in studying in either language.

The results are presented below as the number of studies according to the proposed categorizations. It is important to note that for this set of studies, no stimuli were measured through neuroimaging or brain-scanning techniques (Bil > Mono means that bilinguals performed better than monolinguals, Bil = Mono means they performed equally, and Bil < Mono means monolinguals performed better).

Figure 3 compares task categories that either include or exclude word problems. Figure 4 provides a comparison of task presentations across different modalities, while Figure 5 focuses on the comparison of task responses across these modalities. Figure 6 presents the comparisons of task performance using behavioral measures. Additionally, Figure 7 shows comparisons based on the language of instruction, including L1/L2 and L1(+)-L2(−) distinctions. Lastly, Figure 8 highlights comparisons of performance based on the language of application.

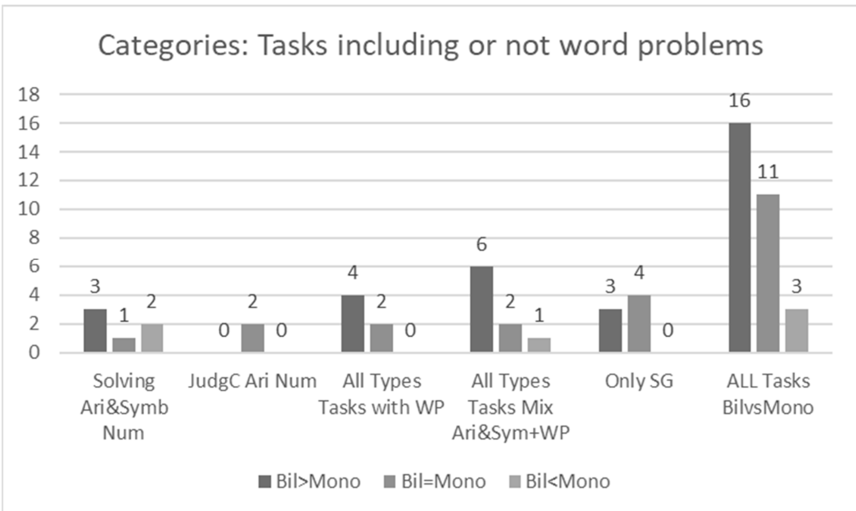

Figure 3. A comparison of task categories including or excluding WP.

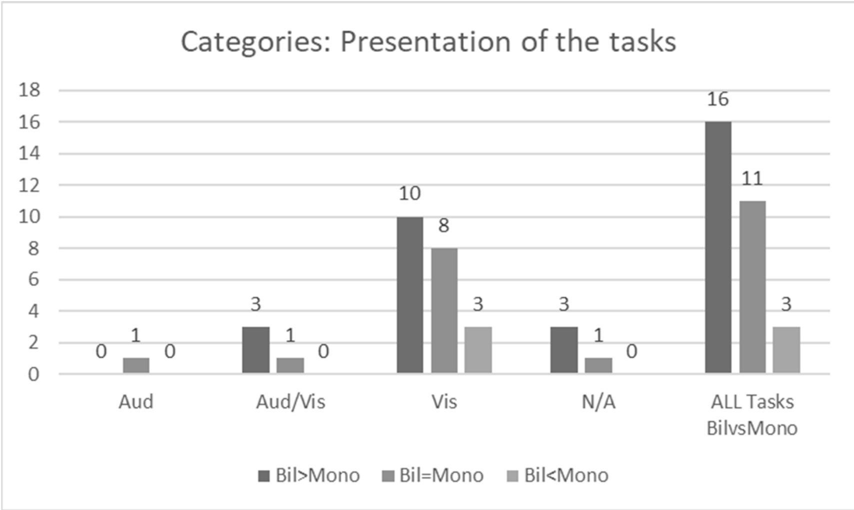

Figure 4. A comparison of task presentations across different modalities.

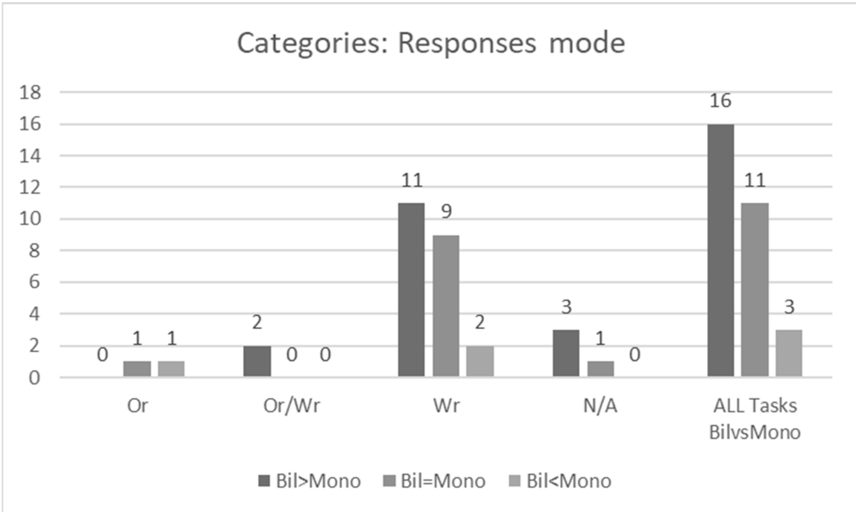

Figure 5. A comparison of tasks responses across different modalities.

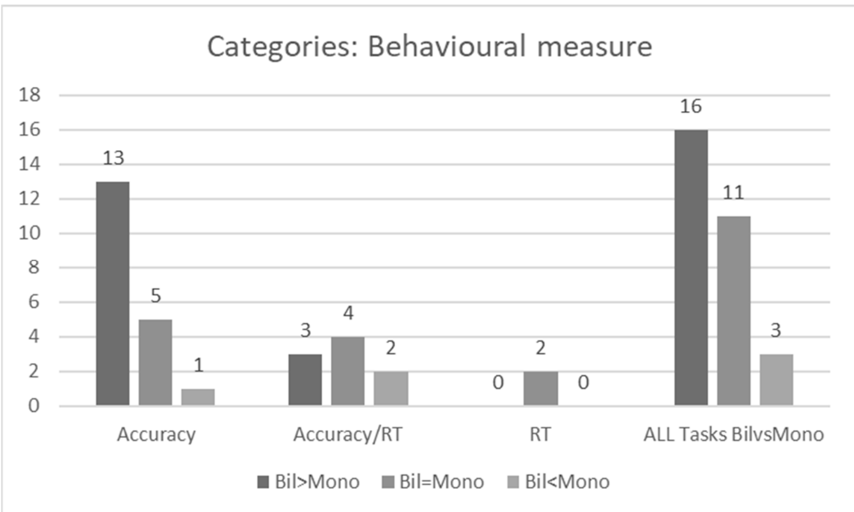

Figure 6. A comparison of task performance in behavioral measures.

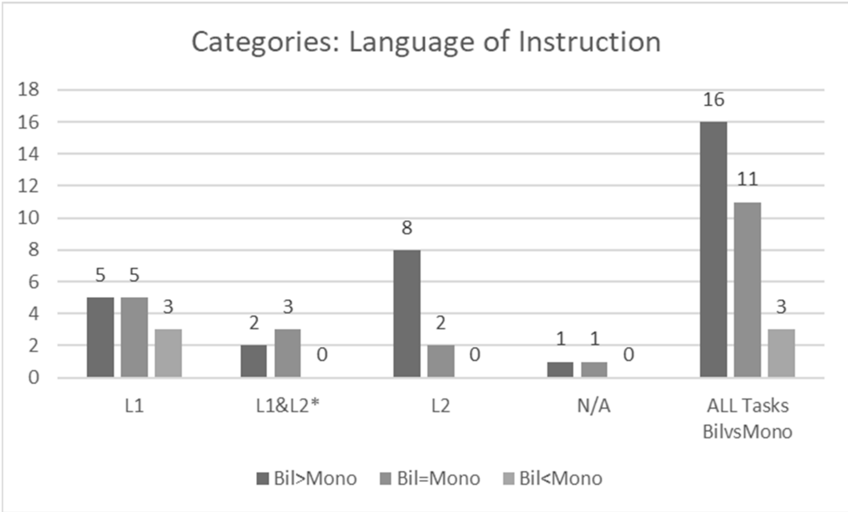

Figure 7. A comparison based on the language of instruction. * includes L1/L2* and L1(+)-L2(−).

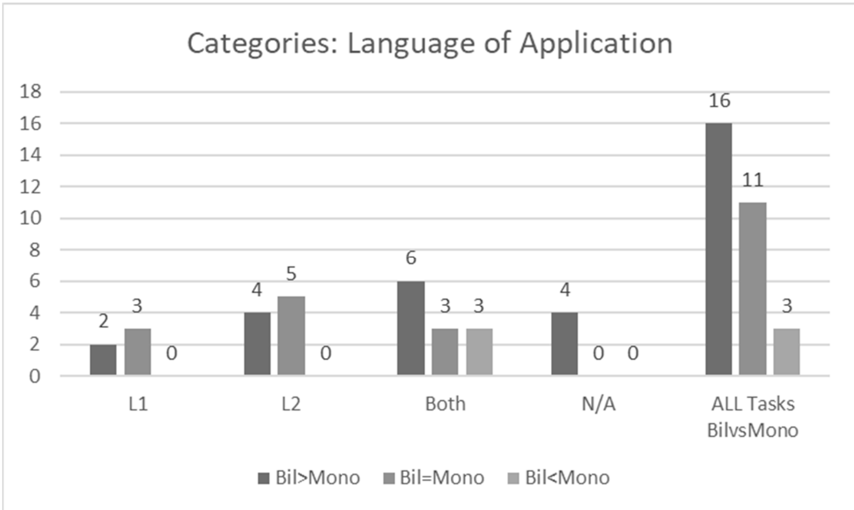

Figure 8. A comparison of performance based on the language of application.

3.3. Bilinguals

The second set of studies is composed of the remaining 52 studies out of a total of 82 (63.4%), which focused exclusively on bilingual subjects.

In this set, in 25 studies (48.1%), the subjects performed better in their L1. In 22 of the studies (42.3%), the L1 was the language of instruction [L1 = LoI], and in 3 studies (5.8%), the L1 was not the language of instruction [L1 ≠ LoI]. In a total of 18 studies (34.6%), the subjects performed better in their L2; in 17 of the studies (32.7%), L2 was the language of instruction [L2 = LoI], and in 1 study (1.9%), L2 was not the language of instruction [L1 ≠ LoI]. In the remaining nine studies (17.3%), there was no significant difference in the performance between L1 and L2 [NoDif].

Within these, five studies (9.6%) requested students answer non-language dependent tasks, present problems and operations, and only compare with Arabic numbers [63,64,71,93,102]. The outcome showed divided results. Campbell and Dowd [93] and Klichowski and Króliczak [102] both showed similar results [L1 = LoI]. Bilinguals performed better in their L1, which was also their LoI, but had lower accuracy and longer response times in English because it is their L2, and not their language of study. Van Rinsveld et al. [64] and Salillas and Carreiras [71] showed an L2 = LoI result. In Rinsveld et al. [64], students performed better in German, which was their language of instruction (LoI), compared to French. In Salillas and Carreiras [71], two groups of Castilian Spanish and Basque bilinguals were created in based of their language of instruction (one group, Castilian Spanish; the other, Basque). Each group showed better performance in their language of instruction when determining if one number was larger than another. This effect was particularly pronounced among high-proficiency bilinguals. The findings indicate a significant influence of the language of instruction on basic numerical tasks. Mondt et al. [63] showed a [NoDif] result where all groups scored high on accuracy, which refers to the percentage of correct responses during the two arithmetic tasks.

Eleven studies (21.2%) used the judgment of correctness of arithmetical operations and compared numbers using exclusively Arabic numbers. Seven studies indicated an L1 = LoI result [72–75,98,99,101,103,105]. Subjects were always faster with numbers in their first language (L1) compared to their second language (L2), and they performed better and faster in L1, which matched their language of instruction (LoI). They were slower and less accurate in L2 for both addition and multiplication. No differences in response time between Arabic and Hebrew bilinguals were found for digits. The mean response times for two-digit number words were lower in L1 than L2, which indicated semantic and syntactic processing differences. Performance was better in the LoI, even if it was not the first language. Exact arithmetic processing showed greater neural activation for L2 in the left inferior frontal area, with a negative correlation between brain activation and performance in the left inferior parietal area. Participants responded faster and had greater neural reactions in the LoI. Complex additions showed more activation and required more resources in L2. Highly proficient bilinguals used different activation patterns for solving problems, which indicated varied solving procedures. Calculation in L2 resulted in more errors and longer response times, and involved additional neural activation compared to L1.

Four studies showed L2 = LoI results [72–74,101,103,105]. Bilinguals trained in mathematical operations performed better in the language of instruction (LoI), even if it was not their first language (L1). In single-digit multiplication tests similar to Spelker's [108], they were faster in L1, even when only trained in L2, as these operations were memorized from childhood. Bilinguals excelled in L1, their language of study (Chinese). Language differences showed greater activation in the left inferior frontal area regarding exact addition for L2, and a negative correlation between brain activation and performance in the left inferior parietal area. English–Spanish bilinguals responded faster and had greater neural reactions in the LoI, even if it was no longer dominant. They were faster and made fewer errors in German (LoI) than in French for complex additions, with similar results for simpler problems. Activation patterns were higher in complex problems and more pronounced in French than German, requiring more resources. Highly proficient bilinguals used different activation patterns for simple and complex additions in each language, which indicated different solving procedures. LoI response time data showed faster results for trained problems, as expected. Exact arithmetic processing relied on verbal and language-related networks, while approximate arithmetic (calculations that are too complex to easily give the exact answer) processing engaged parietal circuits involved in magnitude-related processing. Seventeen studies (32.7%) focused on tasks including only word-type problems (word problems, judgment of correctness with transcoding or arithmetic words, and solving with transcoding or arithmetic words).

Six studies showed L1 = LoI results [69,76,77,84,90]. In Ardila [90], bilinguals performed better in their first language (L1) when it was also their language of instruction (LoI), with a strong interaction of age of acquisition, which ranged from 0 to 30 years; Lin et al. [69] showed that bilinguals had lower accuracy in L2 compared to L1, having studied in L1 and acquired L2 later in life. In Zhang et al. [77], behavioral results indicated worse response times (RT) in L2 and significant switching costs. it is worth to notice that free language switching showed reduced switching costs compared to forced language switching. Those switching costs were also found in McClain and Huang [84] through two experiments and Spanish–English bilinguals. In the first experiment, with Chinese-English bilinguals, subjects were faster in their LoI, which coincided with L1, especially when switching between languages. Subjects were 0.225 s faster in their preferred language

(2.285 s) than their nonpreferred language (2.510 s). In the second experiment that replicated the first one with Spanish–English bilinguals, subjects took longer to respond exclusively in L2 compared to L1. Performance did not significantly differ when using one language per session, but a significant difference of 0.229 s was found when both languages were used in one session with preferred (2.343 s) and nonpreferred (2.572 s) languages.

Two studies stated L1 $\neq$ LoI results [92,125]. Adetula [125] showed that bilinguals perform better in their native language, with significant differences observed in those from public schools, as they had just started studying in English that year. By their side, Bernardo and Calleja [92], also found bilingual students to show a better performance in their L1, but admit that teachers occasionally use L1, instead of L2, in class, as students had a low level in L2. The use of L2 as LoI does not look as detrimental as authors underlined that students show language comprehension deficiencies but not in mathematical concepts.

Five studies showed L2 = LoI results [66,68,108]. These studies seem to indicate that the language of instruction (LoI) significantly influences learning outcomes, particularly in behavioral tests related to mathematical solutions. Interestingly, as we can see in Cerda et al. [66]. highly bilingual students showed consistent N400 responses regardless of whether they learned mathematics in English or Spanish. This suggests that while LoI can enhance proficiency in a specific language, it may not affect certain cognitive processes uniformly across languages.

Four studies showed [NoDif] results [70,91,104,106]. The findings suggest that the proficiency level in a language plays a crucial role in cognitive processes and behavioral outcomes. As shown in Martinez-Lincoln et al. [70], bilingual teachers teaching either in their first language (L1) or non-native language (L2) showed distinct patterns: those teaching in their L1 exhibited delayed N400 congruency effects for their L2, while those teaching in their L2 showed consistent effects in both languages. These results as the ones of Lachelin et al. [104] highlight that while initial encoding may be language-specific, proficiency can mitigate these differences, allowing for comparable development across languages. Additionally, in Morales [106], high-proficiency bilinguals demonstrate similar high accuracy scores in both Spanish and English, whereas low-proficiency bilinguals showed lower accuracy in both languages, underscoring the influence of language proficiency on task performance.

A total of 17 studies (32.7%) featured assignments that used both arithmetic or symbol tasks and word tasks in different mixed ways. Five studies showed L1 = LoI results [94,95,100,102,107]. In Campbell and Epp [94] and Campbell et al. [95], bilinguals whose first language (L1) is Chinese experienced slower response times when processing in their second language (L2), English. In Guillaume [100], bilinguals showed faster digit naming in L1 and size effects in addition problems, presented in both L1 and, to a lesser extent, in L2, especially in unbalanced proficiency scenarios. Challenges arose when verifying results written in L2, reflecting difficulties transitioning from Arabic numerals to words in L2. (English, which they did not study in. In Prior et al. [107], Arabic-Hebrew bilinguals demonstrated more flexibility, particularly in arithmetic operations, where they showed no significant preference for the order of operations, unlike Hebrew monolinguals, who were faster but made more errors with inverted operation orders.

One study showed L1 $\neq$ LoI results [97]. Students from first year of a bilingual school performed bet ter in their L1 Spanish than in their LoI English. Regarding the comparison between bilingual subjects, low-proficiency bilinguals perform worse than high-proficiency bilinguals in L2.

Six studies showed L2 = LoI results [64,67,72,91,114]. In Bernardo [91], participants showed a better performance in digits operations in English, their LoI, despite Filipino being their first language. Similarly, in Van Rinsveld et al. [64] and Volmer at al, [114], German-French bilinguals performed better in their LoI, German despite having similar proficiency levels in both languages For instance, participants trained in German and tested in French showed significantly slower reaction times compared to those trained and tested in French. Participants who switched from German to French experienced language switch costs (LSC), while the reverse switch did not result in LSC. The importance of the LoI can be seen in studies using neuroimaging and brain-scanning techniques. In Salillas and Wicha [72], bilingual English–Spanish speakers responded faster and showed greater neural activity in their LoI, even if it is no longer their dominant language. The. In Cerda et al. [67] bilinguals exhibited similar P300 effects as monolinguals, if their L2 was their LoI. In both studies, results were influenced by their language proficiency levels.

One study showed L2 $\neq$ LoI results [113]. Bilinguals were faster in L2 because writing differs in L1, Hindi, and L2, English, being words shorter in English. Four studies showed [NoDif] results [109–112]. The French group, highly proficient in English (French L1 but US residents), performs similarly in French and English. The English group performs better in English but has lower proficiency overall. Similarly, Tamamaki [112] showed that long-term residents show identical results in English and Japanese, with reaction times decreasing with longer residence (higher English proficiency). By his side, Swanson et al. [110], shows that students learning mathematics in two languages show no significant differences in performance in L1 or L2, indicating interactions with executive function development rather than language alone.

The last two studies (2.8%) [12,96] only used the data from school grades or other institutional sources as criteria, and both showed L1 = LoI results, claiming that bilingual students performed best when their language of instruction matches their home language. Research [126] comparing students taught primarily in Spanish versus English showed that those instructed in their first language (L1) generally achieved better results. This trend was evident among English Language Learner (ELL) newcomers in the US, where academic success varied based on language proficiency and instructional language. Similarly, as shown by Pifarré Turmo et al. [12] students from Catalan-speaking families excelled in mathematical proficiency compared to those from bilingual or Castilian-speaking backgrounds. These findings underscore the importance of linguistic alignment between educational settings and students' linguistic backgrounds for optimizing academic achievement.

The results are presented below as a number of studies according to the different categorizations proposed: Figure 9 compares performance across various tasks, both with and without word problem inclusion. Figure 10 compares task performance across different presentation formats, such as auditory, auditory/visual, and visual. In Figure 11, task responses are compared based on different instruction languages and response types. Figure 12 compares behavioral measures, includi2ng accuracy and response time, across various language instruction groups. Additionally, Figure 13 examines stimuli comparisons measured through different neuroimaging techniques within these groups. Figure 14 continues with task performance comparisons, specifically distinguishing between L1/L2 and L1(+)-L2(−) instruction groups, while Figure 15 concludes with further performance comparisons across these language groups.

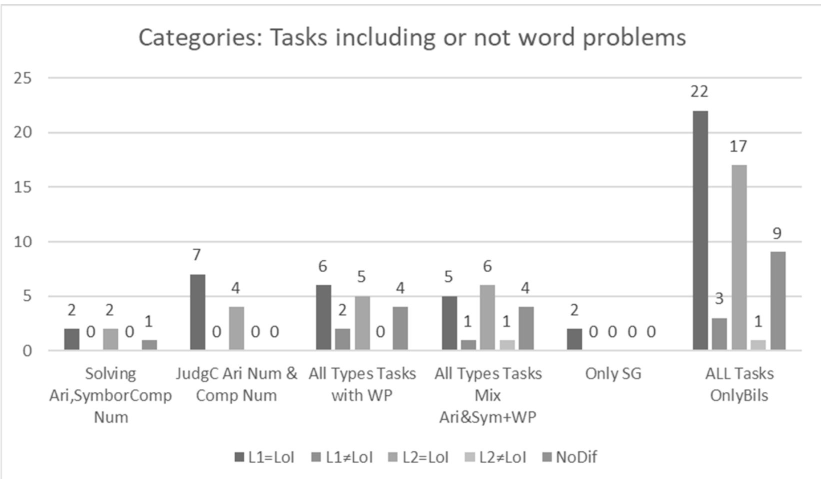

Figure 9. A comparison of performance on various tasks, including or not including word problems.

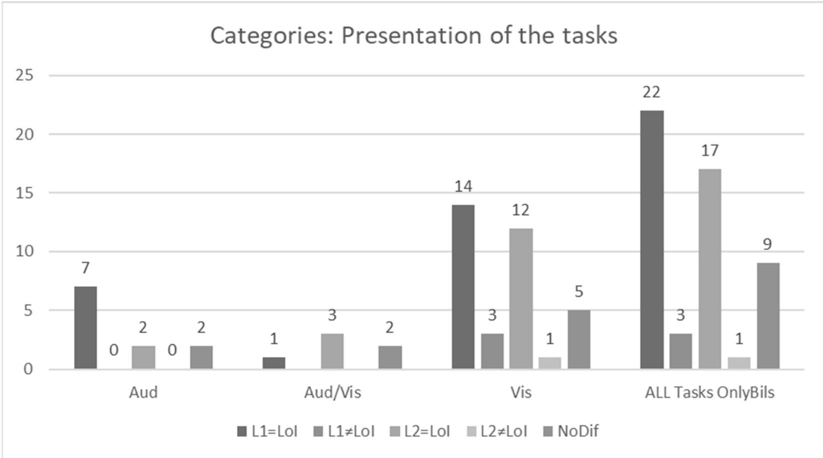

Figure 10. A comparison of task performance based on the presentation format (auditory, auditory/visual, and visual).

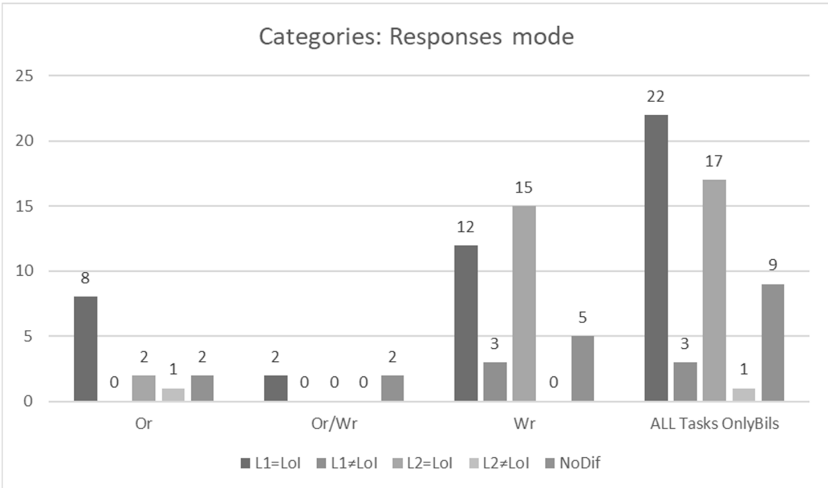

Figure 11. A comparison of task responses categorized by different instruction languages and response types.

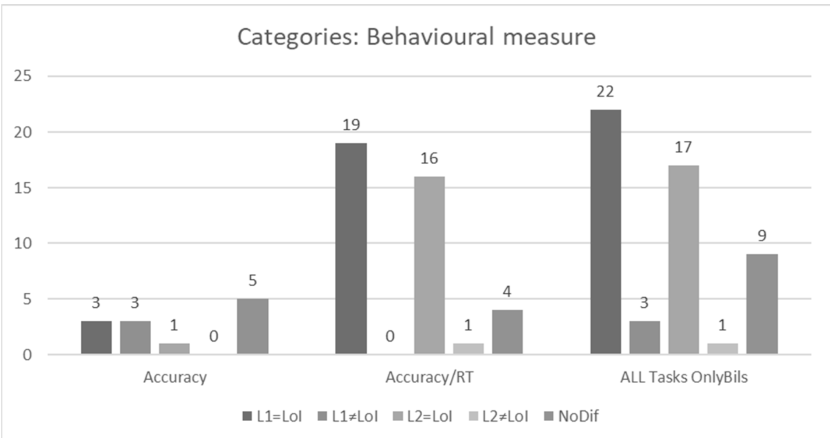

Figure 12. A comparison of behavioral measures, such as accuracy and response time, across different language instruction groups.

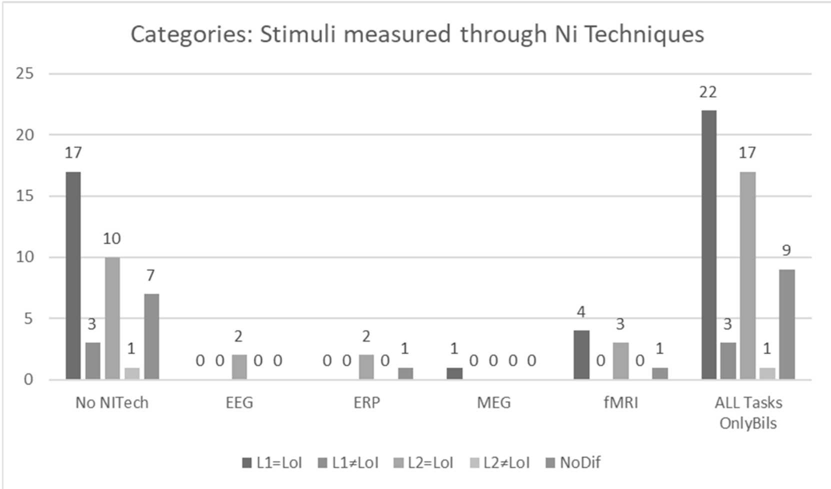

Figure 13. A comparison of stimuli measured using different neuroimaging techniques across various language instruction groups.

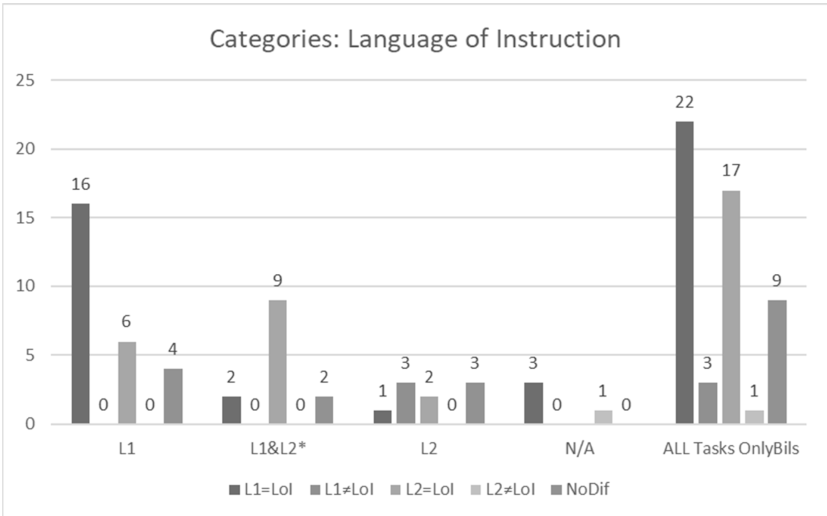

Figure 14. A comparison of task performance across different language instruction groups. * includes L1/L2* and L1(+)-L2(−).

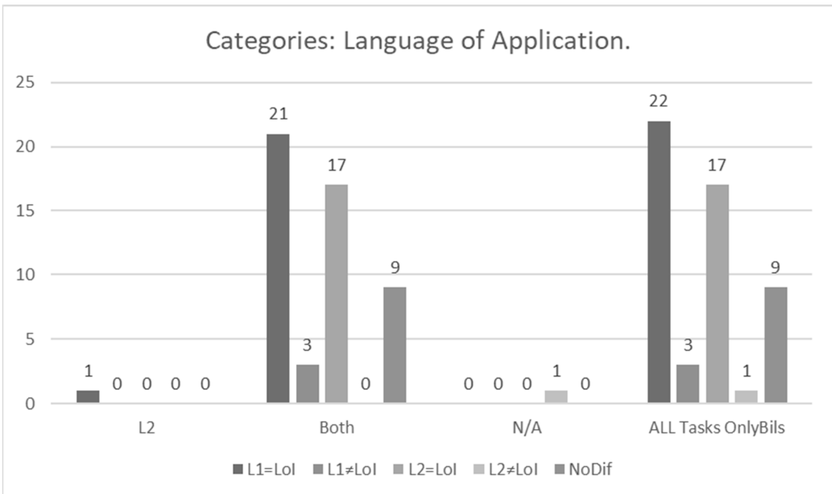

Figure 15. A comparison of task performance across different language application groups.

4. Discussion

Other than facilitating communication in a globalized world, bilingualism has been said to enhance cognition through an increase in executive functions, creativity, metalinguistic awareness, or even general IQ [52]. In mathematics, the previous literature seems to offer controversial results, as we found that bilinguals obtain the same, better, or worse results than monolinguals [57,79,81]. Moreover, the results are also inconsistent when testing if there is any difference in performance when bilinguals use their L1 or L2 to solve math tasks. A systematic review of this study offers a good picture of the four factors modulating the heterogeneous results:

- Proficiency in the language of instruction;
- Language used in the test (L1/L2/LoI);
- Test typology: Proficiency measures and mathematical task;
- The matching between the language of application (LoA) and the language of instruction (LoI).

4.1. Proficiency in the Language of Instruction

Language proficiency has a direct impact on mathematical results, as it is the medium used to acquire and perform mathematics. Through language, we learn from basic arithmetic (reading numbers and memorizing simple calculations) to problem solving and complex algebra. Thus, our capacity to first acquire and then use mathematics is obviously influenced by various linguistic skills from early age to adulthood [12,58,64,126]. According to the authors of [98], the way arithmetic facts are obtained and how the activation of the network of numerical facts is spread are very likely sensitive to, if not dependent on, linguistic competence.

According to Frenck-Mestre and Vaid [12], the students' performance in mathematics depends on the mastery and use of the vehicular language of teaching. Furthermore, in addition to the close relationship between language and mathematics performance, Salillas and Wicha [72] suggest that it may have a decisive influence on addressing difficulties in further mathematics studies if they have mid–low levels of competency in the language. Secada [58] argues that the centrality of mathematical reasoning (explaining, making questions, and giving evidence) is language, which indicates not only that language is crucial to follow a math lesson but that there is also a need to master the language of instruction for students to obtain better grades in mathematics. Similarly, Clarkson [60], in his study on students in Papua New Guinea, tested bilinguals and monolinguals and found out that, in bilingual schools, those students who were proficient in their two languages obtained significantly higher results in mathematics compared to their peers who had low competence in both, and that those with high competence in both languages performed better than monolinguals, with the latter having better educational resources. In this specific case, it should be borne in mind that in Papua New Guinea, bilingual schools usually follow international language immersion programs in English, avoiding the use of the official language (New Guinea Pidgin), even though it is the most widely spoken language in the country (it is spoken significantly more than English).

Regarding mastering the language of instruction, some studies found significant differences when the language of instruction was also used at home (the home environment). In this sense, students using that language at home obtain better educational outcomes than those speaking another language. This was the case with students living in bilingual regions such as Ireland, Cataluña, or the Basque Country [12,70,81].

The findings on the crucial role of the language of mathematics instruction provide evidence that a high level of proficiency in the language of early instruction significantly improves the students' results and defines adults' transcoding [62,71,72]. For example, this was exemplified in a study conducted by Cardoza and Brown [96], where English Language Learners (ELLs) who had moved to the US and had the opportunity to continue learning in their first language (Spanish) showed greater gains compared to those Spanish-speaking EELs who had started receiving math instruction in English, a language they did not understand at first.

In general, individual and longitudinal studies comparing the performance of bilingual and monolingual students along K12 education show that bilingual students ended up equating [64,80,117,119,121,122] or outperforming their monolingual peers [12,58,63,70,87,115,117,123]. Of those, twelve of the studies revised give support to Cummins Threshold Hypothesis [9,28], which claims that sufficient proficiency in L1 and L2 is the determinant factor for cognitive advantage (in mathematics and other areas) in bilinguals [68,82,83,114,115,120,127]. This bilingual advantage has also been reported by different studies [57,59,80,88,117] comparing the results of bilingually schooled students and their peers educated monolingually.

4.2. Language Used in the Test (L1/L2/LoI)

As previously stated, a good performance in mathematics is highly modulated by language proficiency, as low-proficiency bilinguals experience more challenges when using their second language as the medium to acquire and use knowledge. High-proficiency bilinguals have been proven to show better results than low-proficiency bilinguals and monolinguals when using their favorite language, and they lose this advantage when using their non-favorite language. Moreover, they showed different reaction times and accuracy when their mathematical skills were tested in both languages. Notably, studies show that bilinguals' favorite language for performing mathematics is their language of instruction, whether or not this has been their L1 or L2. This finding seems to be supported by neuroimaging studies reporting on stronger overall activation for arithmetic concepts in bilinguals performing mathematics instruction, number word calculations [63,68,69,73,74,102], and correctness judgment tasks [66,71,72,75].

As Bernardo [89] affirms, when performing calculations, the most reliable verbal code is not always the bilinguals' first language. Instead, it is the language they learned arithmetic tasks such as multiplications, as found by Salillas and Wicha [72]. An example of this was found by the authors of [125], who compared the mathematics performance of young students in their two languages in Papua New Guinea and found that children enrolled in international schools using English as the vehicular language performed math better in English than in their native language. Regarding Tamamaki's findings [112], Wang et al. [75] suggest that in the given tests, their participants may have translated the incoming English (L2) questions into Chinese (L1, and also their language of mathematics instruction) to perform the task, as calculation integrates verbal joints of the numerical lexicon and syntax they acquired through L1, concluding that "bilinguals access addition and multiplication problems through the language that they first studied mathematics in" (p. 12). Lin et al. [69] employed MEG brain imaging during mental addition to show spatiotemporal dynamics in bilingual adults and found lower accuracy in number–word operations when presented in bilinguals' non-instructional language.

In summary, several of the studies reviewed indicated the language of the test as the main factor modulating the performance results due to the better outcomes of bilinguals when performing the task in the language in which they were first taught mathematics [63,64]. To explain this statement, Salillas and Carreiras [71] suggest that "quantity representation may have verbal traces inherited from early learning" (p. 1). Similarly, Poncin et al. [62] also support that the language of math acquisition modulates transcoding in adulthood, evidencing the crucial role of language in numerical cognition.

Tamamaki [112] studied groups of bilingual adults with Japanese as L1 and English as L2 residing in the US. All participants were born in Japan, and Japanese was their first language and the language in which they learned arithmetic. It was found that, for short-term residents, Japanese was still their dominant language when performing arithmetic calculations and that the response times in English were much longer. Participants claimed that, when hearing the problems in English, they had to first turn to Japanese and translate the digits rather than directly picturing them. However, this study found that these differences in response times disappeared as the level of proficiency in English and residence time in the US increased. In the long-term residents' group, the results in both languages were virtually identical. Similarly, in a study by Martínez-Lincon et al. [70], the mathematical obstacles of bilingual adults who performed in their second language were caused by resorting to the language in which they received mathematics in childhood.

Learning is therefore coded in a concrete language (not only in math but in every content area), and switching from one language to another could cause worse results in reaction times and accuracy. In McClain and Huang's study [84], the results show that the solution time averaged 0.227 s faster in the preferred language and was an increasing linear function of the number of addition operations required. Those language-switching costs were clearly identified in studies on bilingual subjects tested in their two languages, and although bilingual proficiency has proved to decrease the negative effects of code-switching, some studies state that they would not disappear completely, even in the most proficient groups [64].

4.3. Test Typology: Proficiency Measures and Mathematical Task

Different methods used to measure mathematical proficiency in bilinguals have been proven to produce different results [61].

In tasks where only accuracy is measured, high-proficiency bilinguals show similar or even better results than monolinguals [59,124]. Nonetheless, bilinguals may show worse results than monolinguals when reaction times are measured [84]. As previously established, this disadvantage could be due to switching effects if the language of the test does not coincide with the language of instruction. Knowledge such as the word for an Arabic number (2 = two) or simple multiplications (i.e., two*two = four) would be coded in the concrete language of learning and activated in the linguistic loop as any other memorized form of knowledge (i.e., naming an object shown in a picture). Therefore, bilinguals show longer reaction times naming objects and numbers or even memorizing results from simple calculations if not tested in their language of learning. Moreover, even when tested in their language of instructions, high-proficiency bilinguals also show worse reaction times because of competition effects, namely, that two full-blown languages are available that engage in constant competition in mapping numbers (as well as other symbols or objects) onto words [65].

Notably, these competition/code-switching effects seem to only apply to exact mathematics tasks and not approximate calculations. In the test performed by Spelke and Tsivkin [108], bilingual students who learned new concepts about approximate calculations in one language —in this case, logarithm and cube root problems—use those facts with equal efficacy in their two languages, suggesting that this kind of approximate learning seems to rely on representations that are language-independent. On the contrary, when the same students learn new concepts about exact numbers in one language, they make use of those concepts more efficiently in the language of instruction than in the untrained language. In this study, despite all the students preferring to perform elementary arithmetic in their L1 (Russian), they outperformed in English (their L2) when solving new problems taught in this language. These findings reveal that exact number concepts are represented at least partially in a language-specific form, while approximate calculations appear to be language-independent.

This differentiation between language-dependent and -independent tasks seems to explain the different results when comparing monolingual/bilingual performance in symbolic math tasks versus simple arithmetic. As can be seen, monolinguals usually outperform the reaction times of bilinguals in number identification and basic calculation. However, bilinguals outperform monolinguals in symbolic math tasks such as analytical reasoning abilities (enhanced working memory), inhibitory control, fluid intelligence, mental flexibility, and selective attention [57,97,116,128]. Moreover, bilinguals obtained better results than monolinguals in only three studies [57,59,80] exclusively testing numerical abilities without the use of language.

In a nutshell, the findings in these studies seem to point to a positive impact of bilingualism on mathematics in non-language-dependent tasks. Regarding language-dependent tests, the results depend on the testing measure: if only accuracy is considered, there is no difference between bilinguals and monolinguals; if not only accuracy but also reaction time is measured, monolinguals perform better than their bilingual peers.

4.4. The Matching Between Language of Application (LoA) and the Language of Instruction (LoI)

Bilinguals perform better when the LoA is their LoI [59,60,80,85–87,116], if the LoA is L1 [88,115,122], or if the level in both languages is reported as being the same [57].

When math instructions are in two languages [58,62,82,119], bilinguals may perform worse than monolinguals in the second LoI [62] but perform the same or better than monolinguals in their favorite language [57].

In addition to better performance in math tasks, bilinguals may show other cognitive developments that support those positive results, namely, better adaptation to novel tasks [57] and better abstract or symbolic thought processes [88] and working memory [59].

5. Conclusions

This literature review summarizes the most relevant research results on bilingualism and mathematics performance over the last 40 years.

The findings provide evidence that mathematics achievement in bilingual subjects is highly dependent on three related factors: (1) language proficiency, (2) language used in the test, and (3) test typology (proficiency measures and mathematical task).

As with any other knowledge, correct language proficiency is essential to acquiring mathematics and understanding and correctly performing tests measuring proficiency in the area. The revised studies show strong evidence that mathematical performance develops with bilingualism and that, in general, high-proficiency bilinguals perform better than low-proficiency ones.

Compared with monolinguals, high-proficiency bilinguals perform similarly to monolinguals in language-dependent tasks when only accuracy is measured. If reaction time is considered, bilinguals perform slightly worse than monolinguals, especially if the language of the test is not the same as the language of instruction. This shows the early coding of concrete mathematical knowledge (number–word transcoding/identification and simple arithmetic) in the language of learning, causing switching costs when the language of tests varies. On the other hand, bilinguals seem to outperform monolinguals in language-independent tasks (using only Arabic numbers) and in language-dependent tasks that require the enhanced use of working memory, inhibitory control, mental flexibility, or selective attention.

In a nutshell, bilingualism does not seem to affect mathematical performance that is language-dependent if bilinguals are highly proficient. This type of bilingual may only be affected by lower reaction times depending on the testing language. On the other hand, low language proficiency has a negative impact on mathematical performance. Lastly, bilingualism enhances mathematical encoding and processes in non-language-related tasks. These findings seem to indicate that future research should focus on designing tests that remove language from the equation so as to clearly establish if bilingualism develops mathematical cognition.

Regarding the implications for education, L1–L2 bilingual and L2 immersion programs seem to enhance not only L2 language but also general cognition, including mathematical skills. Nonetheless, students need a time window of L2 instruction to acquire these advantages, as mathematical skills develop with bilingualism. In line with this, students enroll in bilingual or immersion programs since kindergarten education would take the most of this type of education, as they have the time of acquiring a proficiency in language adequate to face mathematical knowledge in a L2 during primary education. On the other hand, older students that join later this kind of programs (for example, emigrants) seem to benefit of instruction in their L1 as they develop their L2 skills.

This review presents a wide state of the art in bilingualism and mathematical performance to disentangle the different results in the literature. It is necessary to consider that the studies reviewed include subjects with different ages and social backgrounds. Therefore, further studies narrowing the research to different variables, such as subjects' age, language proficiency, or age of L2 acquisition, could provide more understanding of the relationship between bilingualism and mathematical skills.

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