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Mathematical skills in heritage bilingual children with and without developmental dyscalculia: A comparative study

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ABSTRACT

This study examined how basic numeracy skills relevant for identifying developmental dyscalculia (DD) differ between heritage bilingual (HB) children and monolingual peers, given the well-established links between language experience and numerical cognition. We compared sociolinguistic background, cognitive abilities, and mathematical performance in 311 primary school children, divided into four groups: HBs with a Specific Learning Disorder in mathematics (SLD-DD; n = 72), HBs with typical development (TD; n = 86), monolinguals with SLD-DD (n = 56), and monolinguals with TD (n = 97). Parents provided detailed language-history information, and children completed standardized assessments of nonverbal IQ, working memory, processing speed, and mathematical skills across numerical knowledge, calculation, and number sense. Controlling for socioeconomic status (SES) and listening comprehension as a proxy for L2 proficiency, results showed that HB children with SLD-DD exhibited numeracy difficulties comparable to monolinguals with SLD-DD but performed better in number-sense tasks, particularly in the triplets task, suggesting a possible bilingual advantage in this domain. HB children with SLD-DD also displayed greater dominance in Italian than typically developing HBs, who showed a more balanced bilingual profile. Among typically developing children, HBs underperformed monolingual peers on linguistically demanding tasks but performed similarly on tasks with limited verbal load. SES was related only to nonverbal cognitive functioning, whereas listening comprehension significantly covaried with all verbally mediated tasks. Overall, the findings underscore the importance of considering both SES and L2 language skills when assessing

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mathematical performance in bilingual learners and highlight the need for targeted support in language-heavy mathematical contexts.

1. Introduction

As more children learn mathematics in a language different from the one spoken at home, it is crucial to understand how multilingual exposure shapes their mathematical skills and how math-related difficulties manifest in multilingual learners, in order to ensure fair assessment and equal learning opportunities. In Italy, where this research was conducted, students with a migrant background represent approximately 11.2 % of the school population (MIM, 2024). Bilingualism is a multifaceted phenomenon, and the literature offers various terms to capture the diversity of bilingual experiences (Surrain & Luk, 2019). To reflect the linguistic background of children in multilingual families and avoid negative connotations, this study adopts the term *heritage bilinguals* (HBs), referring to children who grow up in homes where a language other than the dominant societal language—Italian, in this case—is spoken (Paradis, 2023; Polinsky & Scontras, 2020; Valdés, 2000).

Previous research has shown that speaking two languages in everyday life can lead to cognitive advantages in executive functions, working memory (WM), and anticipation skills (Calvo & Bialystok, 2014; Desideri & Bonifacci, 2018; Monnier et al., 2022), which may support problem-solving and analytical abilities relevant for mathematics (Marian et al., 2013). However, other evidence indicates that HBs may show reduced vocabulary breadth in their L2 compared to monolingual peers (Bialystok et al., 2010), even though they demonstrate comparable conceptual vocabulary when both languages are considered (Ehl et al., 2020). In the literacy domain, HBs generally perform similarly to monolingual children in word and nonword reading, while they may require more time to consolidate text comprehension (Bonifacci & Tobia, 2016; Melby-Lervåg and Lervåg, 2014) and spelling accuracy (Affranti et al., 2024), particularly during the primary school years. These L2 linguistic vulnerabilities may also affect aspects of mathematical performance, including number-word comprehension, the interpretation of problem-solving texts, and the writing of complex numbers (Bonifacci et al., 2025).

Although fewer studies have examined mathematical skills in HBs, the available findings, summarized in the next section, are mixed and vary according to task characteristics. Overall, they suggest that HBs may face greater challenges than monolingual peers in some math-related tasks (e.g., Bar & Shaul, 2021).

Some potential disadvantages, however, may not stem from managing multiple languages at a time but from environmental factors such as language exposure, proficiency, and socio-economic status (Saenz & Huer, 2003). Socioeconomic status (SES) is known to influence cognitive, language, and literacy outcomes (Bonifacci et al., 2022; Calvo & Bialystok, 2014) as well as mathematical performance (Demir-Lira et al., 2016; Coley et al., 2020; Lee & Borgonovi, 2022), placing children with low SES at greater risk for academic difficulties (Kieffer, 2010). SES may also affect parents' participation in home numeracy practices (Bonifacci et al., 2021; Mutaf-Yıldız et al., 2020), which support the acquisition of math skills (Ribeiro et al., 2023).

Importantly, SES is closely related to children's proficiency in the school language (L2). Lower-SES backgrounds often entail reduced exposure to linguistically rich environments and fewer opportunities to develop advanced oral language skills, including listening comprehension, which plays a crucial role in verbally mediated mathematical tasks requiring the processing of instructions or number-word information (Cerda & Wicha, 2024; Peng et al., 2020). Thus, differences attributed to language background may in some cases reflect SES-related disparities. Migrant families who speak a minority language at home, and whose children are HBs, often have lower SES compared to monolingual families. In Italy, for instance, the incidence of absolute poverty is 41.4 % among families with non-Italian citizenship (34.1 % when only one parent has a migrant background), compared to 8.2 % among families with two Italian parents (ISTAT, 2024).

Finally, some HB children, like their monolingual peers, may experience difficulties in math due to a Specific Learning Disorder (SLD) in math (i.e., developmental dyscalculia). SLDs are understood to arise from multiple interacting factors (McGrath et al., 2020) in the absence of intellectual disability, sensory or neurological problems, or inadequate educational experiences (APA, 2013).

1.1. *Numerical cognition, language and bilingualism*

The triple code model (Dehaene, 1997) proposes that numbers are represented through three codes that support counting and numerosity processing. The first is a verbal code linked to the linguistic system and used for arithmetic facts, counting, and multiplication tables. The second is a visual code that spatially represents and manipulates Arabic numerals. The third is the analogue magnitude code, which maps quantities onto a mental number line, commonly referred to as the Approximate Number System (ANS), and supports approximate computation and non-symbolic comparison tasks. From a developmental perspective, Von Aster and Shalev's (2007) four-stage model suggests that numerical skills emerge from a core magnitude system (Stage 1), followed by the association of quantities with verbal labels (Stage 2) and then with Arabic symbols (Stage 3). The development of the mental number line (Stage 4) enables more advanced arithmetic thinking. According to this model, from Stage 2 onward, numerical development is closely intertwined with language and WM skills. Difficulties in ANS-related tasks have been identified as specific markers of dyscalculia (Libertus et al., 2011; Piazza et al., 2010).

At the same time, extensive evidence shows that language is tightly linked to mathematical abilities (Peng et al., 2020), including more advanced mathematics (Kleemans et al., 2018). Systematic reviews have also demonstrated stronger associations between symbolic and mathematical skills than between non-symbolic skills and mathematics (De Smedt et al., 2013; Goffin & Ansari, 2019).

Regarding heritage language speakers, the notion that bilingualism is unrelated to mathematical achievement has been dismissed, although it may persist in some educational contexts. A first line of evidence highlights how the structure of the native language shapes children's numerical understanding. For instance, Sarnecka et al. (2007) showed that children learn the meanings of basic number words through grammatical constructions in their language, indicating that linguistic structure contributes to conceptual development. Children's ability to express numerical relationships improves as they master these grammatical structures (Wiese, 2003). Likewise, cross-linguistic studies have shown that features such as numerical morphology can facilitate the acquisition of number words (Geary et al., 1996). For example, the Chinese number system transparently reflects its base-10 structure, whereas English and Italian include more irregular number words, especially for the teens and up to 100 (Ngan Ng & Rao, 2010). French adds complexity by requiring internal calculations (e.g., quatre-vingt-seize for 96). Seron and Fayol (1994) reported that French second graders made more errors in transcoding tasks than Walloon peers exposed to more regular number-word structures. These linguistic differences contribute to cross-cultural variability in numerical development (Krinzinger et al., 2011; Macizo et al., 2011). Van Rinsveld et al. (2016) also demonstrated language effects in magnitude judgment tasks, particularly when presented verbally.

A second line of research shows that bilingual adults (Garcia et al., 2021) and children (Cerda & Wicha, 2024) tend to process numerical information more efficiently in the language in which they first learned mathematics. In that language, they retrieve arithmetic facts more easily and are more accurate and faster when solving complex operations (Van Rinsveld et al., 2015; Van Rinsveld et al., 2016). The cognitive costs of bilingualism in math development have been documented by Saalbach et al. (2013), particularly when students must navigate between the instructional and application languages.

Language proficiency is therefore central to mathematical performance: students who struggle with the language of instruction may face greater cognitive demands when solving complex tasks (Kempert et al., 2011). Peng et al. (2020) found that the relation between language and mathematics was stronger for native speakers than for L2 learners, although this difference disappeared once WM and intelligence were controlled for.

1.2. *Math skills and math impairments in heritage bilingual children*

Research comparing the math skills of HB and their monolingual peers shows mixed findings, often depending on the linguistic demands of specific tasks and learners' cognitive profiles. In preschool settings, Bar and Shaul (2021) found that bilingual children outperformed monolinguals only on language-dependent tasks such as number naming and counting, while no differences emerged on non-linguistic tasks like quantity comparison or simple arithmetic. In contrast, Daubert and Ramani (2019) reported that bilinguals outperformed monolinguals on WM tasks and showed better performance on addition and number identification, with WM predicting most math outcomes. Similarly, Bonifacci et al. (2016) found that bilingual preschoolers performed worse on verbally loaded tasks such as digit naming, seriation, and number line estimation, but performed similarly to monolinguals on non-symbolic quantity comparison and counting.

At the primary school level, Kleemans et al. (2014) showed that L2 learners in second grade underperformed in phonological awareness, grammar, and basic arithmetic compared to monolinguals, despite similar non-verbal intelligence and WM scores; for both groups, arithmetic performance was predicted by language skills, WM, and non-verbal intelligence. A longitudinal study by Bonifacci et al. (2025) reported an advantage for HBs in approximate calculation but lower performance in problem-solving, multiplication tables, and mental calculations, with more HBs scoring below average on number line, mental calculation, and multiplication tasks.

In more advanced mathematics, bilingual students often face additional challenges. Biernacki et al. (2022) found that long-term English learners were disproportionately placed in lower-level math tracks. Martin et al. (2012) reported that HB underperformed relative to monolinguals, whereas Vukovic and Lesaux (2013) found no significant differences. Kleemans and Segers (2020) observed that L2 students in 5th and 6th grade struggled particularly with geometry and fractions. Their results indicated that basic language skills supported advanced math growth indirectly via arithmetic, while higher-level language abilities directly predicted gains in geometry and fractions. Bilingual children at risk showed weaker computation and problem-solving performance (Swanson et al., 2020). Domain-general cognitive skills, especially short-term and WM, have also been linked to math outcomes in bilinguals, particularly those at risk for learning difficulties (Swanson et al., 2018, 2019, 2022).

Evidence on HBs with developmental dyscalculia is scarce. Salillas and Martínez (2018) found that bilingual children with dyscalculia showed different neural patterns in quantity processing depending on the language in which they first learned math, suggesting that language-specific numerical frameworks may interact with cognitive vulnerabilities. Conversely, Opitz and Schindler (2021) reported that only math-specific factors predicted learning progress in HBs with and without dyscalculia, concluding that language abilities and background characteristics affected both groups similarly.

1.3. *The present study*

In this study, we examined differences between heritage bilingual (HB) and monolingual children in basic numeracy skills relevant for the identification of developmental dyscalculia (DD), controlling for SES and L2 linguistic skills, given their strong associations with mathematical development. Because the goal of the project was to evaluate classification practices used in real diagnostic contexts, we employed the BDE-2, a standardized battery widely used in Italian clinical assessments, rather than experimental tasks that are less representative of routine practice. The study included students aged 7–13; this broad age range was treated as exploratory and was statistically controlled, also considering that BDE-2 scores are age-standardized.

Given the established relationship between bilingualism, language proficiency, and numerical cognition, it is important to clarify whether the numeracy profiles of HB children differ from those of monolingual peers and whether these differences may affect clinical identification. Moreover, language history is rarely examined in clinical samples, and little evidence is available on the numerical and cognitive characteristics of children diagnosed with a Specific Learning Disorder in mathematics (SLD-DD).

Considering concerns about potential over- or underdiagnosis in multilingual learners (Terry et al., 2023), it is essential to evaluate diagnostic processes while taking into account confounding factors such as SES (Lai et al., 2025). The study is part of the broader ADLAB multicenter project conducted in collaboration with public health centers in Northern Italy; in the present study, seven centres participated.

The present study has two main aims, each accompanied by explicit hypotheses.

Research Question 1 (RQ1). Do HBs with SLD-DD differ from TD-HB and monolingual peers in sociolinguistic background, and are they more exposed to potential diagnostic biases?

This question is exploratory, as evidence is limited. We do not expect substantial differences in linguistic history between TD and SLD-DD groups. However, previous research suggests a risk of under- or overdiagnosis in HBs (Terry et al., 2023) and a tendency toward lower school-based evaluations for HB children (Morita-Mullaney et al., 2020). We therefore hypothesize a potentially higher rate of false positives (i.e., DD diagnoses in children without severe math difficulties) among HBs.

Research Question 2 (RQ2). How do math-skills profiles differ between DD and TD groups across HB and monolingual children when SES and L2 language skills are controlled?

Based on previous findings, we expect HB children with TD to perform similarly to monolingual peers on tasks with low linguistic load, but to show disadvantages on tasks with higher linguistic demands (Bonifacci et al., 2025; Kleemans et al., 2014). Because L2 oral linguistic skills, particularly listening comprehension, support the processing of instructions, number words, and verbally mediated procedures, we expect listening comprehension to emerge as a significant covariate influencing performance on language-heavy tasks. At the same time, some studies indicate potential bilingual advantages in non-verbal components of numerical cognition, such as approximate number processing (Bonifacci et al., 2025). We therefore expect HBs to show relatively stronger performance on tasks relying more heavily on the ANS and involving limited linguistic load. Finally, because SES is strongly associated with linguistic and mathematical outcomes, we expect that differences attributed to bilingualism may become more nuanced once SES is included as a covariate (Lee & Borgonovi, 2022; Coley et al., 2020).

2. Method

2.1. Participants

The sample included 311 children aged 7.75–13.75 years old (mean age = 9.84 ± 1.24 years old; 58.2 % females) and attending from the 3rd to the 8th grade in primary and middle schools in Northern Italy. Around half of the sample (n = 158; 57.6 % females; mean age = 9.74 ± 1.22 years old) were HB children, of these 86 were TD and 72 had received a diagnosis of SLD-DD (see below for inclusion criteria). The common inclusion criterion was a nonverbal intelligence quotient (NVIQ) greater than 70 and the absence of sensory and neurological impairments. Children were considered HB if their parents reported speaking at least one language other than Italian in the family context. There was variability in the languages spoken at home: Arabic 24.7 %, Albanian 15.2 %, Chinese, Romanian, Spanish 7.6 %; Urdu 7 %, Punjabi 6.3 %, Hindi 3.8 %; Pidgin English, Tagalog 3.2 %, Russian 2.5 %, Other 11.3 % (less than 2 % each: Wolof, Bengali, Igbo, Polish, Twi, Turkish, etc.). 90.5 % of the parents were both born abroad, 7.6 % of the couples had one parent born abroad (1.9 % were missing data). Regarding children, 81.0 % was born in Italy, with similar percentage for the SLD-DD and TD group (81.4 % and 80.6 % respectively; χ^2 (1) = .018, p = .893). More information on language exposure and language use for the HB group is presented in Table 1.

The remaining proportion of the sample (n = 153) included children born in Italy from parent(s) that uniquely speak Italian at

Table 1
Descriptive statistics (mean, SD and valid cases) for linguistic history variables in HBs group.

	HB-TD Mean	SD	N	HB-SLD Mean	SD	N
First words in Italian*	27.38	20.47	61	29.14	25.05	106
Age of arrival (Italy)*	7.94	21.29	86	7.74	20.2	72
Age of First Exposure L2*	22.14	28.2	86	31.54	27.4	72
Total Length of Exposure*	91.4419	27.93	86	93.0139	25.8	72
First words HL*	15.58	10.064	76	13.49	10.79	72
L2 Proficiency (mother)	3.33	1.202	86	3.1	1.16	71
L2 Proficiency (father)	3.71	1.071	82	3.36	1.09	70
Exposure HL *minus* L2 (mother)	0.3372	1.766	86	0.3889	1.85	72
Exposure HL minus L2 (father)	0.4167	1.845	84	0.2857	2.17	70
Exposure HL minus L2 (siblings)	-0.6753	1.601	77	-1.7969	1.49	64
Exposure HL minus L2 (TV-media)	-1.2093	1.674	86	-2.2676	1.17	71
Mothers, years in Italy	15.5176	8.044	85	15.6197	6.91	71
Fathers, years in Italy	18.4684	7.197	79	19.2239	6.71	67

*Months

home (i.e., monolinguals; 58.8 % females; mean age = 9.94 ± 1.25 years old). Within the monolingual group, 97 participants were in the TD group, and 56 in the SLD-DD group.

Participants in the SLD-DD group were recruited and assessed in seven public health centers (developmental neuropsychiatric units) participating in the ADLAB research project. Only children diagnosed with SLD-DD were included. Some of these children also had a comorbid reading/spelling disorder (25.4 %), but children with only reading/spelling disorders were not included in the sample. The diagnosis of SLD-DD was given based on a full neuropsychological assessment according to the Italian guidelines outlined in the Consensus Conference, (2010), (2022) documents and the International Classification of Diseases (ICD-10 code: F.81.2 or F81.3) (World Health Organization, 2016). To control for the risk of assessment bias (false positives) and the presence of cases with clearly compromised profiles in the control sample (false negatives), we considered participants with scores below at least −1.5 sd according to the parameters of the national standards in less than 50 % of the tasks as false positives. For the TD group, participants with more than 50 % of math tasks below −1.5 sd were considered false negatives.

2.2. Instruments

Socio-economic status: Parents completed the Hollingshead Four Factor Index of Social Status (Hollingshead, 1975). To obtain a composite score for each child's SES, information on both parents' education and occupation was scored from 1 to 7 for education and 1–9 for occupation. The SES scores for each parent were then calculated using the formula (education level*3 + occupation*5), and the mean of the parents' SES was used as the child's SES. In the case of single parents, their unique score was used. The minimum and maximum scores ranged from 8 to 66. Scores between 8 and 29 are considered low-moderate SES, scores between 30 and 39 are defined as moderate SES, and scores above 40 are considered medium-high SES.

Linguistic history: For the purposes of this study, we developed a parental interview administered by the researchers in Italian or, when needed, with the support of language mediators. The first section gathered anamnestic information about the child (e.g., place and date of birth, age of arrival in Italy if born abroad, languages spoken at home, age of first exposure [AFE] to the Heritage Language [HL] and to Italian, age of first words in each language). The Total Length of Exposure (TLE) was calculated as the difference between chronological age and AFE. The second section focused on parental language proficiency, collecting information about parents' age, place of birth, year of arrival in Italy (if applicable), as well as self-ratings of their proficiency in the HL and in Italian, each assessed through a single 5-point Likert-scale question. The third section assessed family language exposure and children's language dominance. Parents rated, on a 4-point Likert scale, the frequency of the child's exposure to HL and Italian across interlocutors (mother, father, siblings) and media use (TV/video). An exposure index was computed as the difference between HL and Italian (negative = greater exposure to Italian; positive = greater exposure to HL). In addition, parents rated the child's dominant language (1 = HL, 2 = Italian, 3 = both) for comprehension, production, and preferred language use.

Non-verbal IQ: Matrix subtest of the Kaufman Brief Intelligence Test-2 (K-BIT2; Kaufman & Kaufman, 2004; Bonifacci & Nori 2016). The child is asked to select one picture from a set of six that best fits the matrix presented. A score of 1 is given for each correct answer, and standard scores are calculated from the norms in the test manual. The number of items is 46, but there are starting points and cut-off criteria that make the number of items administered variable. The split-half reliability coefficient was 0.86.

Working Memory: Working memory index of the Wechsler Intelligence Scale for Children (WISC-IV, Wechsler, 2003). The working memory index involves two subtests. In the memory span the examiner read aloud numerical strings of increasing lengths, and the child is asked to repeat each in the correct order (forward condition) or in the reversed order (backward condition). In the letter-number sequencing the examiner asks the child to repeat aloud the string he/she reads, processing it in a specific order: first the numbers and then the letters, in ascending, alphabetical order. Raw scores were converted into standard scores according to the test manual.

Speed of processing: Processing Speed Index of the Wechsler Intelligence Scale for Children (WISC-IV, Wechsler, 2003). The index consists of two subtests. In the Coding subtest, children are asked to match numbers with the corresponding symbol shown in a table at the top of the paper. The raw score is given by the total number of correct symbols reported. In the Symbol Search, the child must indicate whether at least one of the symbols on the left is present in the group on the right by checking the "yes" or "no" box. The time limit for both tests is two minutes. Raw scores were converted to standard scores according to the test manual.

Listening comprehension: Assessment Lettura Comprensione età Evolutiva (ALCE) Battery (Bonifacci et al., 2014). Participants listened to a narrative passage read aloud by the examiner and then answered 10 oral comprehension questions without access to the text. A grade-appropriate passage was used for each school grade. Each question was scored 0, 1, or 2 according to fixed criteria in the test manual, producing a total score ranging from 0 to 20. Raw scores were converted into z-scores based on normative data. Internal consistency was adequate, with Cronbach's alphas between.72 and.80.

Math skills*:* Children completed a standardized numeracy battery, used in Italy for the clinical assessment of DD, designed for children from the third year of primary school to the third year of middle school (Batteria Discalculia Evolutiva [BDE-2]; Biancardi et al., 2016). According to the diagnostic battery structure, the following tasks were administered across three math-related domains:

Numerical area: 1) Counting forward and backward (from 80 to 140 and back): In this task, the experimenter asks the child to count aloud from 80 to 140 and records the time. The experimenter then asks the child to count backwards from 140. The time given is the time it took the child to count forward. The score is the total number of numbers that the child correctly said backwards within the allotted time; 2) Number reading: In the number reading task children have 1 min to read aloud a list of numbers of increasing difficulty (three to six digits). The score is the total number of digits they read correctly; 3) Dictation of numbers: There are 18 numbers, among which there are numbers with the 0 (e.g., 5010) and numbers with 4, 5, and 6 digits (e.g., 346879). A score of 1 is given for each number that the child writes correctly. The maximum score is 18.

Calculation skills: 1) Mental calculation: the examiner reads 18 operations (nine additions and nine subtractions), and children have 30 s to answer each operation with the correct result. The score is the total of answers they give correctly. The maximum score is 18; 2) Multiplications: the examiner reads 18 items in random order (e.g., 3 × 4, 7 × 9). Children have 3 s to give an answer to each operation. The score is the total number of answers they give correctly within 3 s. The maximum score is 18.

Number sense: 1) Triplets of numbers: children have 2 min to indicate, on a paper record form, the largest number in 18 sets of three numbers (e.g., 30100, 31000, and 30009). The score is the total number of answers they give correctly in 2 min. The maximum score is 18: 2) Insertions of Arabic digits on a number line: children have 2 min to place a target number at the correct place in a series of three numbers arranged in ascending order. For example, they have to sign on a paper record form the number 10 in the correct position between the numbers 5, 8, and 15. The score is the total number of correct items done in 2 min. The maximum score is 18.

The manual reports, for the whole scale, test-retest reliability of about .60. Data were converted into z-scores according to the test manual.

2.3. *Procedure*

Parents signed an informed consent form to participate in the study. The matrix subtest was administered collectively in class (for TD groups) or individually for SLD groups. All other tasks were administered individually in Italian, in a pseudo-random order, by trained experimenters who had access to participants' group status. The battery took approximately 1.5 h to complete. The study was approved by the Ethics Committees of each site participating in the multicenter study (632-2021-OSS-AUSLBO; 900/2021/Oss/AUSLF; 734-2021-OSS-AUSLIM; 840/2021/OSS/AUSLMO; 848/2021/OSS/AUSLPR; 8540/2021/I.5/228/Cerom; 869/2021/OSS/AUSLRE).

2.4. *Data analysis*

Preliminary analyses were conducted through ANOVAs and *t*-tests on sample demographic characteristics and HB language history (see Table 1). To examine the association between language background (bilingual vs. monolingual) and diagnostic accuracy and assess whether language background influenced the likelihood of misclassification (RQ1), a chi-square test for independence was performed. Specifically, the analysis focused on two types of classification errors: false negatives and false positives. False negatives refer to cases in which children who exhibit difficulties in mathematical abilities are not identified as such, leading to a missed diagnosis. Conversely, false positives occur when children with adequate mathematical skills are incorrectly diagnosed as having difficulties.

In order to investigate the second research question, a series of ANOVAs and MANOVAs were performed on domain-general (i.e., non-verbal IQ, working memory, speed of processing) and domain-specific (i.e., tasks in the numerical, calculation, and number sense areas) dependent variables, testing the effect of Language Background (monolingual vs. HB) and Diagnosis (SLD-DD vs TD) as between-subject factors. Then, SES and listening comprehension were included as covariate. Age was not included as a covariate because scores were corrected for age according to the norms reported in the test manuals. All assumptions underlying the multivariate analyses were examined. Univariate distributions and scatterplots did not indicate substantial departures from normality or linearity, and no influential multivariate outliers were detected. The predictors showed no problematic multicollinearity, and the homogeneity of variance–covariance matrices was considered acceptable for the robustness of the MANOVA models. Taken together, the assumptions were adequately met for the analyses reported. Additional checks to evaluate the internal structure of the BDE-2 battery were performed, given concerns about potential overlap among mathematical subdomains. A Confirmatory Factor Analysis testing the three-factor structure proposed in the validation manual (Numerical Knowledge, Calculation, Number Sense) showed excellent fit (CFI =.987, TLI =.974, RMSEA =.064, SRMR =.028), with all subtests loading significantly onto their expected factors.

3. Results

3.1. *RQ1: Do HBs with SLD-DD differ in linguistic history from monolingual peers, and are they more exposed to potential diagnostic biases?*

Gender was balanced across groups χ^2 (1) = 1.108, $p = .293$. For age, there was an effect of language background $F(1, 311) = 6.85$, $p < .01$, $\eta^2 = .022$ and diagnosis $F(1, 311) = 71.159$, $p < .001$, $\eta^2 = .188$; with a tendency for an interaction effect $F(1, 311) = 3.3421$, $p = .065$, $\eta^2 = .011$. Children in the diagnostic group, especially monolinguals, were slightly older than children in the TD group, but there were no differences between monolinguals and HBs in the TD groups. For SES, the ANOVA revealed a main effect of language background $F(1, 311) = 110.661$, $p < .001$, $\eta^2 = .265$ and a main effect of diagnosis $F(1, 311) = 9.175$, $p < .01$, $\eta^2 = .029$; in the absence of interaction effects. HB children had lower SES compared to monolinguals, and children with SLD-DD had lower SES compared to the TD groups.

Regarding the language history of the HB group, descriptive statistics are reported in Table 1. It was found that the SLD-DD group had a slightly later age of first exposure to Italian $t(156) = -2.115$, $p < .05$, but there were no differences in the total length of exposure $t(156) = -.365$, $p = .716$, nor in the mean age of arrival in Italy ($t < 1$). The two groups also did not differ in age of first words in HL, $t(146) = 1.221$, $p = .224$, nor in Italian, $t(147) = -.606$, $p = .546$. Regarding parents' competence in the L2 (Italian), there were no differences for mothers $t(155) = 1.196$, $p = .234$, but fathers of children in the TD group had slightly higher competence than those in the SLD group $t(150) = 1.992$ $p = .048$. The two groups did not differ in the number of years the parents had lived in Italy (all $t < 1$).

Further, HB children with SLD were more dominant in Italian than in HL in terms of language comprehension χ^2 (2) = 22.782, $p < .001$, expressive language χ^2 (2) = 25.696, $p < .001$, and prevalence of language use χ^2 (2) = 34.462, $p < .001$ compared to HB-TD, who showed a more balanced profile of bilingualism (Fig. 1). Finally, there were no differences in language of exposure with mothers and fathers (t < 1), but children in the SLD-DD group were more exposed to Italian, compared to the TD group, in communication with siblings, $t(139) = 4.269$, $p < .001$, and in media/television exposure $t(155) = 4.495$, $p < .001$.

The chi-square test for independence investigating the relationship between language background (bilingual vs. monolingual) and diagnostic accuracy (false negatives, false positives, true negatives, true positives) revealed a significant association between these variables, χ^2 (3) = 311.0, $p < .001$. Adjusted residuals indicated a similar percentage of false positive in HBs and monolinguals (respectively, 3.2 %; 3.3 %). However, in the TD group 10.8 % of the HBs resulted to be "false negatives" compared to 1.3 % in the monolingual group.

3.2. RQ2: How do math-skills profiles differ between DD and TD groups across HB and monolingual children when SES and L2 language skills are controlled?

The scores of the four groups in the math tasks are presented in Table 2.

The MANOVA run on the tasks of the numerical area revealed a significant effect of Diagnosis, F(3, 303) = 63.315, $p < .001$, $\eta^2 = .385$, with univariate analysis revealing lower scores in children with DD for counting, F(1, 305) = 56.200, $p < .001$, $\eta^2 = .156$, number reading, F(1, 305) = 161.364, $p < .001$, $\eta^2 = .346$, and number writing, F(1, 305) = 107.305, $p < .001$, $\eta^2 = .260$. The effect of Language Background was non-significant, F(3, 303) = .905, p = .439, $\eta^2 = .009$, as well as the covariate SES, F(3, 303) = .719, p = .541, $\eta^2 = .007$. Listening comprehension was significant, F(3, 303) = 3.458, p = .017, $\eta^2 = .033$. Further, there was a significant interaction Diagnosis × Language Background, F(3, 303) = 3.528, p = .015, $\eta^2 = .034$, which showed (see Fig. 2) that bilingual children with typical development underperformed compared to their monolingual peers in counting (p = .016), number reading (p = .009), and number writing (p = .004), while no differences emerged within the groups with SLD-DD.

The MANOVA run on the tasks assessing the calculation skills also showed a significant effect of Diagnosis, F(2, 304) = 160.764, $p < .001$, $\eta^2 = .514$**,** with univariate analysis revealing lower scores in children with SLD-DD for both mental calculation, F(1, 305) = 130.002, $p < .001$, $\eta^2 = .299$**,** and multiplications, F(1, 305) = 294.247, $p < .001$, $\eta^2 = .491$. The effect of Language Background was non-significant, F(2, 304) = 0.134, p = .874, $\eta^2 = .001$, nor that of SES, F(2, 304) = 1.062, p = .347, $\eta^2 = .007$**,** whereas listening comprehension was significant, F(2, 304) = 10.643, $p < .001$, $\eta^2 = .065$. Further, there was a significant interaction Diagnosis*Language Background, F(2, 304) = 4.834, p = .009, $\eta^2 = .031$. Also in this case, only HB with TD underperformed compared to TD monolingual peers in mental calculation (p = .043**)**, in absence of differences in SLD-DD groups and in multiplications (see Fig. 3).

Finally, the MANOVA run on the number sense area revealed a significant effect of Diagnosis, F(2, 289) = 47.864, $p < .001$, η^2

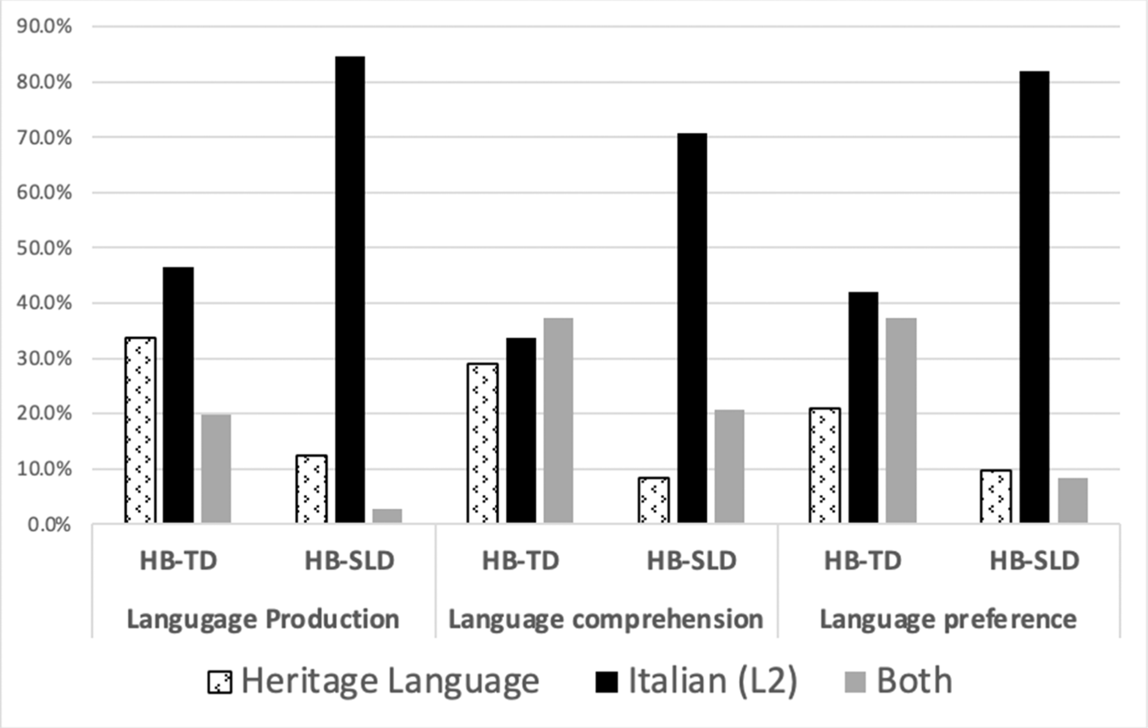

Fig. 1. Distribution (%) of language use and preference in HB with TD or SLD.

Table 2
Descriptive statistics (mean, SD) for each group and main effects of ANOVAs and ANCOVAs with SES as a covariate.

		No diagnosis		Developmental dyscalculia	
		Monolinguals	Bilinguals	Monolinguals	Bilinguals
Math skills	Counting	-0.28 (0.93)	-0.76 (1.05)	-1.63 (1.27)	-1.59 (1.18)
	Number reading	-0.33 (0.94)	-1.03 (1.71)	-2.85 (1.27)	-2.79 (1.10)
	Dictation of numbers	0.14 (0.89)	-0.54 (1.54)	-1.94 (1.24)	-1.99 (1.37)
	Mental calculations	0.13 (0.86	-0.27 (1.08)	-2.69 (1.29	-2.48 (1.37)
	Multiplications	0.17 (0.94)	-0.27 (0.97)	-1.62 (1.08)	-1.54 (0.99)
	Triplets	0.15 (1.03)	-0.32 (1.56)	-2.11 (2.03)	-1.63 (1.90)
	Insertions	0.30 (1.03)	-0.17 (1.30)	-1.67 (1.80)	-1.81 (2.12)
Domain general skills	Non-verbal IQ	109.18 (14.53)	101.49 (17.16)	102.23 (13.91)	102.61 (11.54)
	Working memory index	99.29 (13.71)	89.27 (13.44)	82.00 (11.50)	81.54 (11.57)
	Speed of processing index	100.27 (15.65)	96.91 (15.78)	91.05 (13.33)	91.25 (17.22)

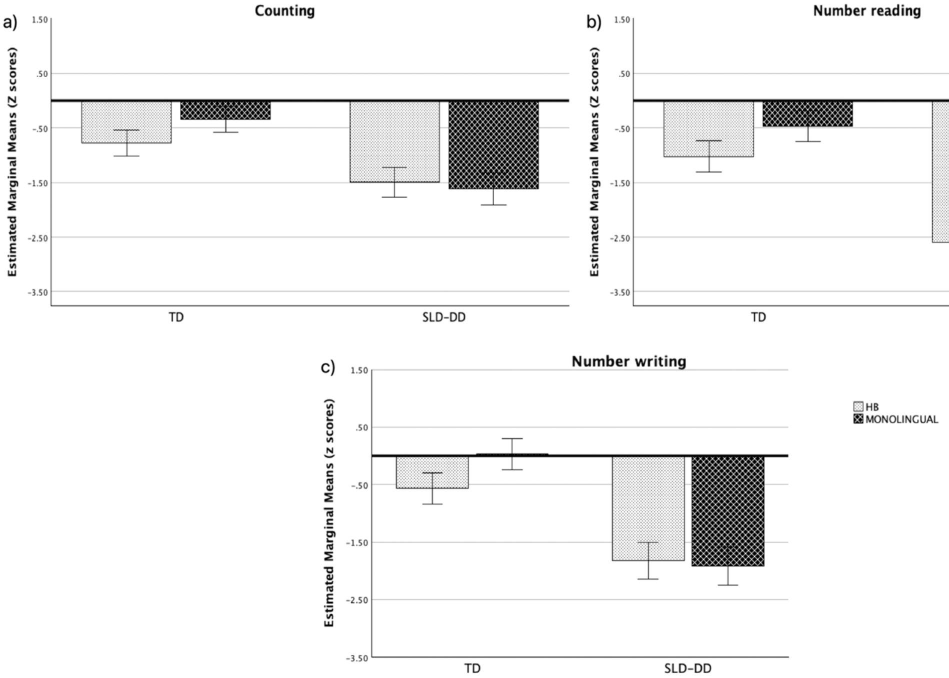

Fig. 2. Estimated means of group comparisons in numerical knowledge tasks. Notes: Covariates appearing in the model are evaluated at the following values: SES = 27.816, Listening comprehension = .02; Error bars: 95 % CI.

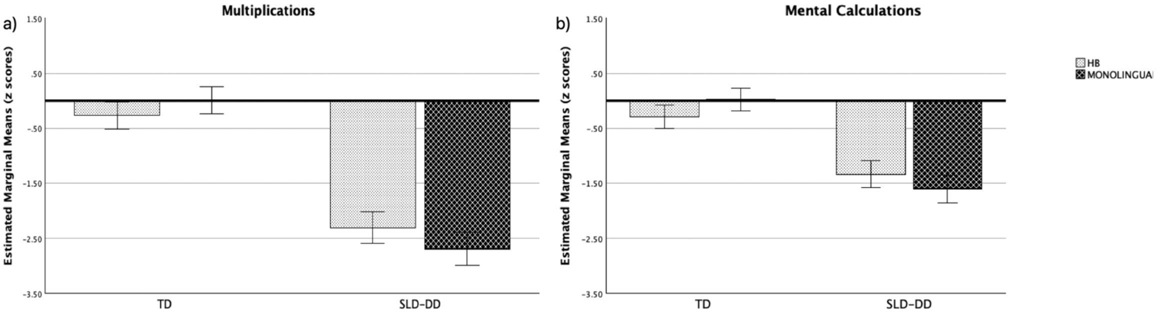

Fig. 3. Estimated means of group comparisons in calculation tasks Notes: Covariates appearing in the model are evaluated at the following values: SES = 27.816, Listening comprehension = .02; Error bars: 95 % CI.

$= .249$. Univariate results showed lower scores of children with SLD-DD both in triplets, $F(1, 290) = 56.632$, $p < .001$, $\eta^2 = .163$, and insertions, $F(1, 290) = 87.741$, $p < .001$, $\eta^2 = .232$. Language Background and SES were non-significant, $F(2, 289) = 0.453$, $p = .636$, $\eta^2 = .003$, and $F(2, 289) = 0.886$, $p = .413$, $\eta^2 = .006$, respectively. Listening comprehension showed a significant multivariate effect, $F(2, 289) = 4.125$, $p = .017$, $\eta^2 = .028$, with a univariate effect on triplets, $F(1, 290) = 7.089$, $p = .008$, $\eta^2 = .024$, but not on insertions, $F(1, 290) = 0.289$, $p = .591$, $\eta^2 = .001$. The interaction Diagnosis*Language Background was significant, $F(2, 289) = 3.112$, $p = .046$, $\eta^2 = .021$. In the triplet task HBs with SLD-DD had better scores compared to the monolingual group with SLD-DD (see Fig. 4).

The ANOVA run on the non-verbal IQ revealed no significant main effects of Diagnosis, $F(1, 305) = 0.279$, $p = .598$, $\eta^2 = .001$, nor of Language Background, $F(1, 305) = 0.073$, $p = .788$, $\eta^2 = .000$. In contrast, both covariates were significant, with SES showing an effect, $F(1, 305) = 6.514$, $p = .011$, $\eta^2 = .021$, and listening comprehension also contributing to the model, $F(1, 305) = 4.837$, $p = .029$, $\eta^2 = .016$. A significant Diagnosis × Language Background interaction was found, $F(1, 305) = 6.689$, $p = .010$, $\eta^2 = .021$. Inspection of estimated means showed that monolingual children without a diagnosis scored higher than the other three groups, which all obtained comparable scores, fully within the average range.

The MANOVA run on the WISC-IV processing indices, namely working memory and speed of processing, revealed a significant multivariate effect of Diagnosis, $F(2, 304) = 29.352$, $p < .001$, $\eta^2 = .162$, with higher scores for children with no diagnosis for both working memory, $F(1, 305) = 50.991$, $p < .001$, $\eta^2 = .143$, and speed of processing, $F(1, 305) = 13.147$, $p < .001$, $\eta^2 = .041$. The effect of Language Background was not significant at the multivariate level, $F(2, 304) = 2.648$, $p = .072$, $\eta^2 = .017$, although univariate tests showed a small effect on working memory, $F(1, 305) = 5.248$, $p = .023$, $\eta^2 = .017$, but not on speed of processing, $F(1, 305) = 0.272$, $p = .603$, $\eta^2 = .001$. SES was non-significant, $F(2, 304) = 0.350$, $p = .705$, $\eta^2 = .002$, whereas listening comprehension showed a significant multivariate effect, $F(2, 304) = 4.441$, $p = .013$, $\eta^2 = .028$, driven by working memory, $F(1, 305) = 8.889$, $p = .003$, $\eta^2 = .028$, and not by processing speed, $F(1, 305) = 0.040$, $p = .841$, $\eta^2 = .000$. A significant multivariate Diagnosis*Language Background interaction was found, $F(2, 304) = 6.142$, $p = .002$, $\eta^2 = .039$, with monolingual children without a diagnosis showing higher working memory scores than their bilingual peers ($p < .001$), while bilingual and monolingual children with SLD-DD scored similarly. Consistent with this, the interaction was significant for working memory, $F(1, 305) = 12.183$, $p < .001$, $\eta^2 = .038$, but not for the speed of processing measure, $F(1, 305) = 0.611$, $p = .435$, $\eta^2 = .002$.

4. Discussion

The main aim of the present study (RQ2) was to assess the basic mathematical skills of heritage bilingual children identified as having a specific learning disorder in mathematics (developmental dyscalculia) or typically developing. The study also included monolingual peers with and without SLD-DD to provide a cross-group comparison of the phenotypic characteristics of DD in monolingual and HB populations. However, as a preliminary investigation, the first research question (RQ1) aimed to understand the sociolinguistic background of HBs with and without SLD-DD in order to assess the risk of bias in the assessment. To this end, an estimate of diagnostic bias was also made.

4.1. Research question 1: do HBs with SLD-DD differ in sociolinguistic background from monolingual peers, and are they more exposed to potential diagnostic biases?

Regarding socioeconomic status (SES), the findings mirrored national statistics (ISTAT, 2024): heritage bilinguals (HBs) had lower SES than monolingual peers. A second, less expected pattern also emerged: children in the clinical groups showed lower SES than those in the TD groups. Although SLDs have a neurobiological basis (McGrath et al., 2020), some authors suggest a cycle in which parents' learning difficulties limit educational and occupational opportunities, resulting in lower SES for their children (Scarr, 1992). Prior studies often reported no SES differences between families of children with and without SLD (Bonifacci et al., 2013; Dilnot et al., 2017), whereas larger cohort studies show that SES can predict SLD diagnoses, indicating that non-clinical factors may influence identification (Knight & Crick, 2021). Although the present study is not a cohort analysis, it includes a large sample of children accessing public health services and shows that SLD diagnoses are more frequently associated with lower SES in both HB and monolingual

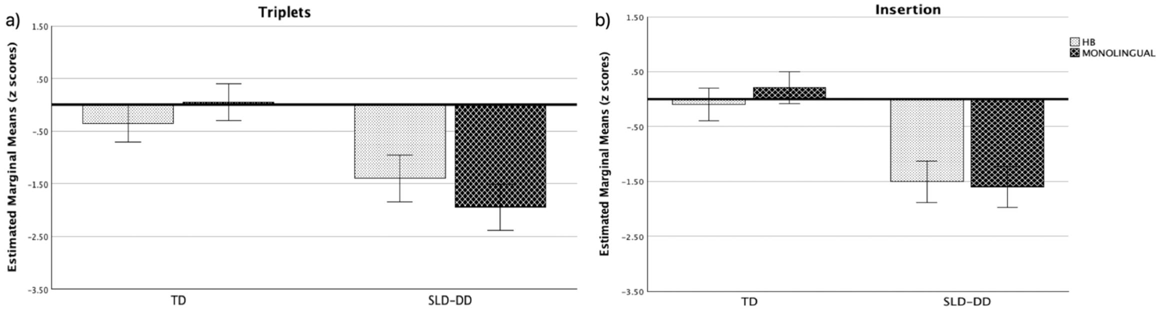

Fig. 4. Estimated means of group comparisons in number sense task Notes: Covariates appearing in the model are evaluated at the following values: SES = 27.816, Listening comprehension = .02; Error bars: 95 % CI.

groups.

HBs with and without SLD-DD did not differ in parents' reports of age of first words in Italian or in the HL, nor in migratory background variables such as time spent in Italy or language use with mothers and fathers. This supports the idea that diagnostic identification was not biased by differing migration histories or exposure patterns. However, parents reported greater Italian dominance in the SLD-DD group than in the TD group. As shown in Fig. 1, fewer than 10 % of parents of children with SLD-DD selected "both" for the question "Which language does the child mainly use?", compared to about 40 % in the TD group. Children with SLD-DD also used Italian more frequently with siblings and during media exposure.

Although the study did not directly examine how language exposure relates to math achievement, the observed differences between SLD-DD and TD groups suggest that children with SLD-DD often show signs of heritage-language (HL) erosion. This pattern was associated with lower SES and lower parental proficiency in Italian. Two interpretations emerge: maintaining bilingualism may support learning, whereas in the presence of a learning disorder, families may increasingly shift toward the dominant language, contributing to a HL decline. Previous research shows that families of children with neurodevelopmental disorders often rely more on the dominant language (Kay-Raining Bird et al., 2016), sometimes influenced by recommendations from educators or clinicians (Borghetti et al., 2025). This phenomenon has been rarely examined in the context of SLD and represents a novel finding consistent with results in the literacy domain.

Finally, the rate of false positives was low in both HB and monolingual groups (around 3 %). However, a larger proportion of HBs (10.8 %) compared to monolinguals (1.35 %) in the TD group met regulatory cut-offs in at least 50 % of math tests. These cases cannot be considered true false negatives, as participants were school-recruited and did not undergo full diagnostic evaluation. Nonetheless, this trend may reflect a tendency toward underdiagnosis in HBs, as suggested by previous work (Vender et al., 2021). It also highlights the need to move beyond monolingual assessment practices by including HL evaluation when possible. Moreover, contextual factors such as SES interact with bilingualism and may influence both language development and performance on school-based learning tasks.

4.2. Research question 2: how do math-skills profiles differ between SLD-DD and TD groups across HB and monolingual children when SES and L2 language skills are controlled?

The study made comparisons between bilinguals and monolinguals with and without SLD-DD by including SES and Listening comprehension as covariates, as a discrepancy was observed between the groups. SES was not significant on math tasks, nor on processing measures of WM and processing speed, but it was significant on nonverbal IQ.

This trend appears to be at odds with previous research reporting a significant relationship between SES and math skills (De Florio & Beliakoff, 2015). However, previous research on the relationship between SES and math skills has also yielded mixed results. For example, the study by Jordan et al. (2006) found that while low-income kindergarten children initially scored lower on mathematical tasks, their rate of growth in mathematical skills was comparable to that of middle-income peers when nonverbal representations were used. Other authors have reported that the effect of SES may be mediated by the home learning environment (Elliott & Bachman, 2018; Bonifacci et al., 2021). This implies that socioeconomic disadvantage may manifest as lower baseline skills but does not necessarily dictate the ability to grow in mathematical understanding.

Since the present study was conducted on children from grade 3 to grade 8, the role of SES may have been nuanced compared to studies conducted in preschool or early elementary school, due to the influence of extra-familial stimuli, such as those encountered within the school context. Finally, the weight of SES may have been reduced considering that about half of the sample has SLD-DD, so their performance on arithmetic tests is due to neurobiological factors rather than environmental ones. However, these results are inconsistent with those observed for language and literacy, which report significant relationships between SES and literacy (Hoff, 2006; Bonifacci et al., 2022). However, SES was found to play a role in higher-order nonverbal cognitive functioning (Dolean & Călugăr, 2020) which may, in turn, have an influence on numerical reasoning.

Moreover, listening comprehension emerged as a consistent covariate for all tasks with a verbal component, confirming that L2 oral language skills substantially shape mathematical processing in heritage bilingual learners, as widely documented in the literature (Cerda & Wicha, 2024; Peng et al., 2020). The only exceptions were the insertion task and the speed-of-processing measure, both of which rely minimally on linguistic input. Notably, listening comprehension also correlated with verbal working memory and nonverbal IQ, suggesting that language proficiency may support broader cognitive processes involved in maintaining, integrating, and manipulating information during mathematical reasoning. This pattern is compatible with the view that linguistic comprehension scaffolds access to symbolic representations and task instructions (Peng et al., 2020) and that weaker L2 proficiency can inflate the cognitive load required to perform language-heavy mathematical tasks (Cerda & Wicha, 2024). Together, these findings reinforce the importance of considering L2 oral language skills when interpreting HB children's math performance, particularly in assessments conducted exclusively in the societal language.

When comparing between groups, as expected, children in the SLD-DD groups performed significantly worse than the TD groups. Considering the effects of language background, the main effects were all nonsignificant, but a number of interactions between language background and diagnostic group emerged. Specifically, in number knowledge and mental arithmetic, TD HB children underperformed compared to monolingual peers, but there were no differences between HB and monolinguals in the SLD-DD group. However, on number sense tasks, HB with TD were on par with monolinguals and, importantly, HB children with SLD-DD were less impaired than monolinguals on the triplet task, i.e., recognizing the largest numbers in a set of three.

This pattern suggests that the main profile of HB children with SLD-DD is substantially similar to that of monolingual peers with the same diagnosis in terms of difficulties in lexical components and mental calculation skills, but with a relative advantage of HBs in the number sense component. Although all the tasks in the present study involved a symbolic component, those in the number sense area were less verbally demanding, in the way that only instructions were given verbally, but no verbal response was required. In other terms, math difficulties in HBs seem to be more dependent on the verbal and visual codes (Dehaene, 1997) and less on the analogic code. In line with previous literature, one possible explanation is that approximation tasks may rely on mechanisms related to cognitive flexibility, a domain in which bilinguals have sometimes been reported to show advantages (Marzecová et al., 2013). However, this interpretation should be considered a hypothesis rather than a confirmed mechanism, as the present study did not include direct executive-function measures (e.g., inhibition or task-switching) capable of capturing this dimension.

To the best of our knowledge, no previous studies directly investigated these aspects in HBs with SLD-DD, but the results are in line with previous evidence that suggested an advantage in approximate calculation in HBs with typical development (Bonifacci et al., 2025). In the present study, however, the same advantage was not found in the TD group, where no differences emerged compared to monolinguals, differently from the discrepancy found in verbal-related tasks (numerical knowledge and mental calculation). Future studies including direct assessments of executive-function components will be crucial to clarify whether bilingual advantages in cognitive flexibility truly contribute to HB children's performance in number-sense tasks.

Regarding the cognitive profile, in line with previous studies (Riva et al., 2016), no differences were found between HB and monolinguals in non-verbal reasoning and processing speed (nonverbal task in any case), whereas differences emerged in WM that included verbal stimuli (letters and numbers). In contrast, the differences between clinical and nonclinical groups were always significant except for non-verbal IQ. This is in line with previous evidence on monolinguals (Giofrè et al., 2017), and on HBs (Swanson et al., 2022), but the study adds that these differences remain stable even when SES and L2 proficiency are considered, in HB children with SLD-DD.

5. Limitations and future directions

Before considering the impact of the study with respect to previous knowledge and potential implications, some limitations of the present study need to be considered. First, all assessments were administered in Italian, the participants' second language. This may have introduced language-related bias, particularly for heritage bilingual children with varying levels of L2 proficiency, and represents a general constraint given that best practices recommend assessing bilingual students in both languages (Cerda & Wicha, 2024). The absence of direct measures of heritage-language proficiency limits the interpretation of bilingualism effects. This was difficult to address, as most heritage bilingual children were dominant in Italian and received all schooling in this language, while standardized and clinically validated assessments in their heritage languages are often difficult to identify, access, or apply consistently.

Second, the cross-sectional design and relatively wide age range prevent a clear understanding of age-related developmental variation, which should be addressed in future longitudinal research. In addition, the considerable linguistic heterogeneity within the bilingual group, combined with relatively small subgroup sizes, limits the generalizability of the findings. These factors also made it impossible to examine whether typological properties of the heritage languages (e.g., Romance vs. non-Romance structures, number-word transparency) modulate numerical performance; future studies with larger and more balanced subgroups will be needed to clarify these effects.

Finally, the study relied on standardized tools commonly used in Italy for diagnosing DD. Although the BDE-2 showed encouraging results in confirmatory factor analyses, future research should incorporate theory-driven experimental measures, such as tasks targeting the ANS, to enable more fine-grained examination of numerical processes across groups.

Despite these limitations, the present study provides new highlights on the mathematical profile of HBs with SLD-DD, a topic relatively understudied in previous literature (Lai et al., 2025). The main findings of the study can be summarized in four main points: 1) HBs with SLD-DD have numerical and counting deficits similar to their monolingual peers with SLD-DD, but perform better on number sense tasks, suggesting a bilingual advantage. Their linguistic background is characterized by a greater dominance of Italian than in the TD group, which maintains a more balanced bilingual profile; 2) Typical HBs underperform compared to monolingual peers in numerical knowledge and mental arithmetic when assessed in the social language (L2), even when SES and L2 skills are controlled, but they perform similarly in numerical tasks with less verbal load; 3) SES does not appear to play a primary role in explaining variation in math ability, but it does play a role in higher order cognitive functioning (nonverbal IQ), which in turn may influence math ability. Future studies should better address, possibly longitudinally, more complex patterns of relationships between environmental and cognitive variables in math acquisition in HB children.

This study offers important strengths that enhance its contribution to the field. By examining heritage bilingual children, an understudied population, and using standardized cognitive and mathematical assessments while rigorously controlling for SES, L2 language skills, and including additional cognitive measures (nonverbal reasoning and working memory), the findings rest on a strong methodological foundation. The results also highlight potential risks of underdiagnosis in bilingual learners, emphasizing the need for more culturally and linguistically sensitive assessment practices. This work therefore represents a meaningful step toward more equitable identification and support of bilingual children in educational settings. Future research could advance this line of inquiry by employing analytic approaches such as ROC curves or sensitivity/specificity indices, which would allow a more rigorous evaluation of diagnostic accuracy and potential classification biases in identifying SLD-DD among heritage bilingual learners. The lack of direct assessments of heritage-language proficiency, due to the limited availability of standardized tools, remains an important consideration. This constraint tempers conclusions about language dominance and possible transfer effects, which future studies should examine through bilingual assessments in both languages.

6. Conclusions and implications

The study also suggests several implications for educational and clinical contexts. First, HB with typical development may lag behind their peers in math tasks with high verbal load and they may benefit from specific interventions in the school context, as also suggested by Arizmendi et al. (2021). There might also be a risk of underdiagnosis of math difficulties in HBs, but in the clinical context it is important to adopt adequate assessment measures which prioritize tasks with low verbal load. In other words, the evaluation of math disorders in HBs requires moving beyond monolingual-like approaches in assessment and diagnosis. This shift involves adopting culturally relevant frameworks, refining assessment tools to include bilingual norms, and acknowledging the social and familial contexts surrounding bilingual development.

CRediT authorship contribution statement

Simona Chiodo: Supervision, Conceptualization. **Valentina Tobia:** Methodology, Formal analysis. **Michela Muccinelli:** Investigation, Conceptualization. **Chiara Nanni:** Investigation, Conceptualization. **Marina Porrelli:** Investigation, Conceptualization. **Paola Bonifacci:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Chiara Gelmini:** Investigation, Conceptualization. **Carlotta Facini:** Investigation, Conceptualization. **Anna Gallani:** Investigation, Conceptualization. **Alessia Rapino:** Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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