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To what extent do home numeracy practices and parental number talk relate to children's math skills? A pre-registered study in 5-year-old children

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ABSTRACT

A growing number of studies suggest a relation between young children's math skills and their home numeracy environment (HNE), typically assessed through home numeracy practices and parental number talk. However, studies are characterized by heterogeneity in methods, analytic strategies, and results. Here we tested prevalent models of the HNE via a pre-registered study to reduce analytic flexibility and distinguish between confirmatory and exploratory findings. A wide range of mathematical skills was measured in 128 5-year-old children, while their HNE was assessed via a parental questionnaire evaluating the frequency of home numeracy practices and a direct measure of parental number talk during a free-play session in the lab. Contrary to our hypotheses, we did not find any predicted relation between children's mathematical skills and parental number talk or frequency of informal practices at home. However, as predicted, we confirmed a relation between formal advanced numeracy practices and symbolic mathematical skills.

Educational relevance statement

There are large disparities in young children's mathematical skills, and these disparities persist beyond the first years of schooling. Therefore, it is important to understand how the home numeracy environment may contribute to differences in early math skills among children. In this pre-registered study, we show how the relation between home mathematic practices and math skills is specific to certain types of practices and certain types of skills. We also show the reciprocity of number talk exchanges between parents and children.

1. Introduction

Technological advances in our society are making numeracy skills all the more critical for the personal and professional development of individuals. However, there are significant disparities in math skills in the population (Mullis et al., 2020; Peña-López, 2019). Critically, these disparities can be traced back (to some extent) to individual differences as early as in kindergarten (Duncan et al., 2007; Watts et al., 2014). Indeed, some children may start formal schooling more prepared than others for mathematical learning, possibly because they benefit from a more favorable home environment with respect to math learning (the so-called "Home Numeracy Environment" or HNE). For example, some families might engage children in more frequent activities involving math than others, or might talk more about numbers than others (Daucourt et al., 2021; Elliott & Bachman, 2018; Mutaf-Yıldız et al., 2020). Over the past decades, it has increasingly been argued that such favorable environments might boost math school readiness and have positive consequences for future abilities (Lehrl et al., 2020), consistent with the view that math learning is cumulative and involves skill building (Watts et al., 2018).

1.1. HNE measured with activities and number talk

The HNE has been mainly studied from two different angles. On the one hand, in keeping with research on the Home Literacy Environment (Sénéchal, 2006), most studies have relied on parental reports to measure the frequency of activities involving math at home (Mutaf-Yıldız

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et al., 2020). Results of such studies, however, are relatively inconsistent. The majority of them have shown that the frequency of home numeracy activities is positively related to young children's mathematical skills (e.g., Benavides-Varela et al., 2016; Cheung et al., 2020; Dearing et al., 2012; LeFevre et al., 2010; Mutaf-Yıldız, Sasanguie, De Smedt, Reynvoet, 2018a; Napoli & Purpura, 2017; Niklas & Schneider, 2014; Vasilyeva et al., 2018). However, a number of studies have also failed to find any significant relation between home numeracy activities and children's math skills (e.g., Cheung et al., 2018; Ciping et al., 2015; De Keyser et al., 2020; Lehrl et al., 2020; Missall et al., 2015), and some have even found evidence for a negative relation (Huang et al., 2017; Silinskas et al., 2020).

On the other hand, because questionnaires have a number of shortcomings (e.g., parents are asked about a limited range of home numerical activities, some activities might be easier to remember than others; Hornburg et al., 2021; Napoli & Purpura, 2017), a smaller number of studies have also started to directly label and quantify linguistic inputs that children receive from their parents (Mutaf-Yıldız et al., 2020). Such measures, which typically focus on the effective use of number words between parents and children (e.g., "*one*", "*two*" or "*three*"; Thippana et al., 2020), have been defined as *number talk*. For example, Susperreguy and Davis-Kean (2016) recorded exchanges during mealtimes at home among 40 families. Results showed that children who heard more instances of number talk (e.g., "*Do you want two slices of bread*?") were those with enhanced math skills one year later (Susperreguy & Davis-Kean, 2016). Other studies focused on more specific types of math talk (e.g., DePascale et al., 2021; Elliott et al., 2017; Gunderson & Levine, 2011; Ramani et al., 2015). For instance, using a semi-standardized laboratory situation (10 min of free play session, with many objects and toys available), Elliott et al. (2017) found that children's math skills were specifically related to the occurrence of "large" number words provided by their parent (i.e., number words bigger than ten). Gunderson and Levine (2011) further characterized the type of number talk related to children's math skills by identifying parental number talk involving counting or labeling sets of present and visible objects. However, much like with questionnaires, not all studies identified a significant relation between parental instances of number talk and children's numerical skills (DePascale et al., 2021; Douglas et al., 2019; Silver et al., 2021; Zippert et al., 2020), and some even found a negative relation (Mutaf-Yıldız, Sasanguie, De Smedt, Reynvoet, 2018b).

1.2. Variability in HNE measurement

Perhaps the greatest source of complexity in interpreting the literature on the HNE stems from differences in analytical choices made by researchers across studies. These notably concern the way both the HNE and math skills are measured, as well as the variables that are controlled for. The heterogeneity in HNE measurement concerns questionnaires and direct observations. In questionnaires, for instance, while some studies have used a global frequency score of activities reported (e.g., Cheung et al., 2020; Napoli & Purpura, 2017; Thippana et al., 2020; Wei et al., 2020), others have focused on specific scores for activities that could be categorized as formal (Lehrl et al., 2020; Manolitsis et al., 2013; Silinskas et al., 2020) or informal (De Keyser et al., 2020; Ramani et al., 2015). The distinction comes from a model of the HNE proposed by LeFevre et al. (2009). Formal activities are defined as activities in which parents explicitly intent to teach math concepts (e.g., counting objects, solving simple sums). In contrast, informal activities are everyday activities that parents engage in without obvious explicit teaching purpose but that may carry implicit mathematical content (e.g., cooking, playing a board game). Within formal activities, some (but not all) studies have also made the distinction between activities that are relatively basic and might not challenge children (e.g., counting up to 5 for a preschooler) and activities that are more advanced and therefore more demanding (e.g., reading numbers up to 20 for a preschooler) (del Río et al., 2017; Skwarchuk et al., 2014; Susperreguy et al., 2021; Susperreguy, Burr, et al., 2020; Susperreguy, Douglas, et al., 2020).

Finally, there is no consensus on the number of items that should be used to assess different numerical activities in questionnaires (from 1 to 36 items, e.g., Benavides-Varela et al., 2016; Cheung et al., 2020; De Keyser et al., 2020; Girard et al., 2021; Missall et al., 2015) or on whether classifications of math activities should come from theoretical assumptions (e.g., Silver et al., 2021; Susperreguy & Davis-Kean, 2016) or from data-driven statistical analyses (e.g., Hart et al., 2016; Mutaf-Yıldız, Sasanguie, De Smedt, Reynvoet, 2018b; Napoli & Purpura, 2017). Therefore, there can be considerable variation regarding activities that are considered formal, informal, basic or advanced between studies that rely on questionnaires. Interestingly, Cahoon et al. (2021) recently suggested that to reliably assess preschoolers' experiences, questionnaire items should be developed deductively through qualitative interviews with caregivers.

Measurement variability is also apparent in studies of number talk. For example, number words have been classified differently depending on their "size" (e.g., DePascale et al., 2021; Elliott et al., 2017), their purpose (such as counting objects and naming cardinal values of objects; Gunderson & Levine, 2011; Susperreguy & Davis-Kean, 2016) or the context of the interaction (e.g., playing Lego or reading books; Mutaf-Yıldız, Sasanguie, De Smedt, Reynvoet, 2018b; Thippana et al., 2020). Studies have also examined number talk in different contexts, such as laboratories where play material is typically provided (e.g., Casey et al., 2018; DePascale et al., 2021; Elliott et al., 2017; Lombardi & Dearing, 2020), home where material is already available (e.g., Gunderson & Levine, 2011; Levine et al., 2010; Silver et al., 2021; Susperreguy & Davis-Kean, 2016) or even school (Ramani et al., 2015; Zhou et al., 2006; Zippert et al., 2020). Context might play an important role here, as number talk that occurs in semi-structured situations (e.g., in the lab) might capture a different process than when children are with familiar toys (e.g., at home; Thippana et al., 2020). Finally, the duration of the interactions also varied greatly between studies (from 10 to 90 min; Elliott et al., 2017; Gunderson & Levine, 2011; Mutaf-Yıldız, Sasanguie, De Smedt, Reynvoet, 2018b). Altogether, it is clear that there are large differences in the way the HNE is measured between studies, whether they use questionnaires or measure number talk. Critically, a recent meta-analysis shows that such variability may largely influence the size of the relation between the HNE and children's math achievement (with effect size estimates ranging from 0.02 to 0.22; Daucourt et al., 2021).

1.3. Variability in assessment of math skills

Another shortcoming in the HNE literature is that children's math skills are assessed in a variety of ways. For example, most studies have used a single composite numerical score encompassing both symbolic and non-symbolic numerical skills (e.g., Cheung et al., 2018; Napoli & Purpura, 2017; Thippana et al., 2020; Thompson et al., 2017). Others have exclusively focused on symbolic skills or have made the distinction between symbolic and non-symbolic math skills (Girard et al., 2021; Susperreguy, Burr, et al., 2020; Susperreguy, Douglas, et al., 2020). This is because symbolic and non-symbolic skills have been proposed to relate to different aspects of home numeracy activities: while symbolic skills may be bolstered by formal activities, non-symbolic skills may be more likely influenced by informal activities (Skwarchuk et al., 2014). Critically, the way math skills are defined may greatly influence the size of the relation between the HNE and children's math achievement (Daucourt et al., 2021).

1.4. Variability in control variables

Finally, the relation between HNE and children's math skills is likely to be confounded by a number of factors that need to be considered in the analyses. These include cognitive and linguistic skills, socio-economic status, and family genetics. Yet, studies greatly vary in the extent to which they control for these variables. For example, some studies have controlled for cognitive (e.g., Bernabini et al., 2020; Kleemans et al., 2018; Niklas & Schneider, 2014) or language skills (e.g., Cheung et al., 2018; Kleemans et al., 2012; LeFevre et al., 2009; Napoli & Purpura, 2017) while others have not (Susperreguy, Burr, et al., 2020; Susperreguy, Douglas, et al., 2020). Socio-economic status (SES), which critically affects number talk (Dearing et al., 2022), is sometimes not measured (e.g., Huang et al., 2017; Vasilyeva et al., 2018) or suggest a non-diverse sample (e.g., Kleemans et al., 2012; Ramani et al., 2015). Only few studies have also attempted to control for family genetics, notably by controlling for parental math skills when investigating the relation between HNE and children's math skills (Cheung et al., 2020; Girard et al., 2021; Silver et al., 2021). Finally, it is possible that parents adapt their activities to their child's interest and skill rather than the other way around (Zippert & Ramani, 2016). To some extent, this could be controlled by asking parents to give a subjective estimate of their child's math skill. However, only a few studies have used such a measure as covariate when assessing the relation between children's math skills and HNE (Girard et al., 2021; Hart et al., 2016; Zippert et al., 2020; Zippert & Ramani, 2016).

Overall, the substantial heterogeneity in measures and analyses raises the question of analytic flexibility in the HNE literature. Given the quasi-systematic absence of pre-registration of hypotheses and methods across studies (with the exception of DePascale et al., 2021, who focused on spontaneous focus on numbers), it is difficult to distinguish exploratory from confirmatory findings (Munafò et al., 2017; Wagenmakers et al., 2012). This is because studies typically use a large number of measurements and, without preregistration, a subset of the results might be reported conditionally on statistical significance (Strømland, 2019). Not only would this increase false positive error rates in probability tests when examining a hypothesis (Simmons et al., 2011), it would also cast doubt on the exact size of the relation between HNE and children's math skills (which may be inflated, Bakker et al., 2020; Nosek et al., 2015). By requiring to specify, prior to any analysis, which data will be used and how they will be analyzed, pre-registration allows one to "confront a prediction with the possibility of being wrong" (Nosek et al., 2018, p. 2605).

1.5. Current study

The present study aimed to measure the relation between the HNE and children's math skills while (i) gathering comprehensive measures of math skills, HNE, and confounding variables, and (ii) pre-registering hypotheses and analytic strategy to distinguish confirmatory from exploratory findings. Specifically, children were tested on both symbolic and non-numerical skills, as well as IQ. Parents not only completed an extensive questionnaire on the home learning environment (in which informal, formal basic, and formal advanced activities could be distinguished), but were also asked to engage in free play session with their child in the lab, allowing for a measure of number talk. Finally, we collected from parents measures of parental income and education levels (SES), parental math skills, and subjective estimate of children's math skills.

We made 6 pre-registered hypotheses. First, based on LeFevre et al. (2009), we predicted that informal numeracy activities (as measured by the questionnaire) would be specifically related to non-symbolic skills (*H1*). Second, also based on LeFevre et al. (2009), we predicted that formal numeracy activities would be specifically related to symbolic skills (*H2*). Third, consistent with Skwarchuk et al. (2014), we expected the latter relation to be stronger for advanced HNE than basic HNE (*H3*). Fourth, we anticipated that number talk (as measured in the free play session) would positively relate to children's math skills (*H4*). Fifth, in line with Gunderson and Levine (2011), we predicted that this relation would be stronger for number talk involving counting and labeling large sets of present objects than other number talk (*H5*). Sixth, if the relations above are uniquely driven by HNE, they should hold even when controlling for parental education, parental income, children's IQ, parental math skills, and subjective estimates of children's skills (*H6*).

2. Material and methods

2.1. Participants

One hundred and thirty-three young children of approximately 5 years of age and one of their parents were recruited for the experiment in the Lyon area in France. Participants were contacted through advertisements on social media. Participants were involved in a larger project involving MRI scanning. Four parent-child dyads were excluded from further analyses because children did not complete the behavioral testing ($n = 3$) or had an overall cognitive functioning (IQ score) lower than 70 ($n = 1$). One additional dyad was excluded because the parent did not complete the questionnaire ($n = 1$). Therefore, 128 typically developing 5- to 6-year-olds ($M = 5.66$, min = 5.00, max = 6.74, 42 % girls) within the typical range were included in the final analyses. Out of the 128 children, 2 were in their last month of their pre-kindergarten year, 118 were in kindergarten and 8 were at the beginning of first grade (within the four first months of the school year).

All children and parents included in the study were French speakers. Eighty-six percent of the parents whose children were included in the analyses were mothers. Parents completed a questionnaire evaluating their SES via household income and education levels (9 families were single parents). Household income ranged from less than €12,000 to more than €160,000 per year ($M = 50,459$, SD = 23,985). In France the median household income was €30,260 euros in 2018 (Insee Références, 2021). Twenty-six percent of parents reported to only have a secondary degree (including 3 parents with only a primary degree), 40 % reported having an undergraduate degree, and 34 % a master's degree or higher. Therefore, SES ranged from low to high. Parents gave written informed consent and children gave their assent to participate in the study. The study was approved by the local ethics committee (Comité pour la Protection des Personnes Sud-Ouest et Outre-Mer 4, n°CPP18-050 / 2018-A01229-46). Families were paid 40 euros for their participation in the testing session.

2.2. Pre-registration and justification of sample size

Material and planned analyses were preregistered via the Open Science Framework (https://osf.io/yjzqn). We a priori planned to recruit a sample of 120 participants, based on a frequentist power analysis assuming a medium to large effect size observed in a meta-analysis of the relation between home numeracy practices and children's math skills (Dunst et al., 2017). At the time of the pre-registration, we considered the smallest estimate of that meta-analysis ($r = 0.31$). G*Power 3.1 (Faul et al., 2007) indicated that our final sample ($n = 128$) would provide an achieved power of 98 % to detect a similar positive association in a linear regression at $\alpha = 0.05$ (one tailed).

Note, however, that an updated meta-analysis of the relations between children's math skills and various dimensions of the home math environment has now estimated the size of these correlations between $r = 0.20$ to $r = 0.22$, with the smallest effect for numerical practices and the largest for parental academic expectations (see Fig. 2 in Daucourt et al., 2021). Updating our power estimation with the smallest estimate of that range ($r = 0.20$), G*Power 3.1 (Faul et al., 2007) indicated that our final sample ($n = 128$) would still provide an achieved power of 74 % to detect a positive association at $\alpha = 0.05$ (one tailed).

Three changes were made to the preregistered methods and analyses. First, Bayesian analyses are presented in addition to the preregistered frequentist statistics to facilitate the interpretation of null results. Second, because our sample included children who scored in the superior range on the IQ measure, we also included children whose standardized IQ was below the 25th percentile not to bias the sample towards high IQ children (only one child who scored below the 3rd percentile was excluded). Third, although we initially planned to only analyze the number talk as a function of the size of numbers used by parents, exploratory analyses also focused on the type of activities in which numbers were used.

2.3. Child measures

Children's math skills were assessed using the TEDI-MATH battery (Van Nieuwenhoven et al., 2001). This comprehensive battery includes 26 subtests assessing a range of numeracy skills. Non-symbolic skills are estimated using two subtests involving non-symbolic comparison of quantity. Symbolic skills are estimated using the 24 remaining subtests. Internal consistency of these measures is good (Cronbach's alpha can be found in Table 1). Knowledge of the verbal numerical sequence is measured using four subtests ("counting as far as possible", "counting with an upper limit", "counting with a lower limit", "counting with both an upper and a lower limit", 2 items each, 1 point per item). According to the test manual (Van Nieuwenhoven et al., 2001), these four subtests are merged to form a composite score with a maximum of 8 points. Counting is assessed using two subtests involving different patterns of elements to count (2 linear items for a maximum of 2 points each, 2 nonlinear items for a maximum of 3 points each) and one subtest measuring essential counting concepts (abstraction and cardinality, 3 points max). According to the rating standards of the TEDI-MATH battery (Van Nieuwenhoven et al., 2001), counting subtest is designed to be scored using a single value. Knowledge of the written number system and knowledge of the oral number system are each assessed using different subtests involving numerical decision (8 items for written system, 12 items for oral system, 1 point max each), comparison (8 items for written system, 10 items for oral system, 1 point max each), estimation (12 items for written system, 1 point max each), and judgment of grammaticality (6 items for oral system, 1 point max each). Transcoding is estimated using two subtests involving writing and reading Arabic numbers (6 items for writing, 6 items for reading, 1 point max each). Calculation is assessed using eight different subtests in which children solve different types of arithmetic problems (addition, subtraction, multiplication) with and without visual support. In detail, there are 6 items for calculation with visual support, 32 items for calculation with written statement, 8 items for calculation with verbal statements and 6 items for additive decomposition (1 point max each). Finally, the battery also includes logical operations (classification, seriation, inclusion), which are not considered here as they go beyond basic mathematical skills. To avoid a ceiling effect, we administrated subtests items beyond clinical recommendations. For this reason, we used raw scores associated with each numeracy skill, as well as the composite raw score for the entire battery. We also asked parents to provide a subjective estimate of their child's math skills using a point rating scale from −2 to 2 (i.e., Not sure or no opinion was coded 0, Severe difficulty was coded −2, Difficulty was coded −1, Average skills was coded 0.5, Good skills was coded 1 and Excellent skills was coded 2).

Table 1
Children's raw subscores and composite score of the TEDI-MATH.

Subtest	Mean (SD)	Min	Max	Number of items	Alpha Cronbach
Non-symbolic					
Non-symbolic skills (/10)	7.55 (1.63)	3	10	10	0.95
Non symbolic estimation (/6)	5.84 (0.59)	3	6	6	
Non-symbolic comparison (/4)	1.71 (1.44)	0	4	4	
Symbolic					
Knowledge of the verbal numerical chain (/8)	5.55 (2.17)	0	8	8	0.86
Counting (/13)	10.93 (1.54)	3	13	7	0.78
Written number system (/28)	23.07 (4.11)	10	28	28	0.94
Written numerical decision (/8)	7.88 (0.69)	1	8	8	
Written numerical comparison (/8)	6.85 (1.53)	1	8	8	
Written numerical estimation (/12)	8.34 (2.93)	1	12	12	
Oral number system (/28)	24.55 (3.43)	11	28	28	
Oral numerical decision (/12)	11.34 (1.10)	7	12	12	0.98
Oral numerical comparison (/10)	8.33 (2.03)	0	10	10	
Judgment of grammaticality (/6)	4.87 (1.28)	1	6	6	
Transcoding (/12)	7.95 (3.05)	0	12	12	0.99
Arabic number writing (/6)	3.04 (2.00)	0	6	6	
Arabic number reading (/6)	4.91 (1.46)	0	6	6	
Calculation (/52)	16.97 (10.75)	2	49	52	
Calculation with visual support (/6)	4.73 (1.38)	0	6	6	0.70
Calculation with written statement (/32)	7.34 (6.76)	0	29	32	0.97
Calculation with verbal statement (/8)	3.31 (2.29)	0	8	8	0.77
Additive decomposition (/6)	1.59 (1.94)	0	6	6	0.94
Total score (/151)	96.53 (20.29)	55	148		

Parental arithmetic skills as measured by the Math Fluency subtest of the WJ-III ranged from low to high normal (M = 97.12, SD = 9.97, range = 69–120). Reading skills of parents measured by the Alouette test were considered normal (reading efficiency, M = 524.08, SD = 96.10, range = 313.2–857.45), except for 9 parents who did meet the cut-off criteria for low reading skills in adults according to Cavalli et al. (2018) (i.e., their reading efficiency score was below 403).

In addition to math skills, the NEMI-2 standardized intelligence test (Cognet, 2006) was administered to estimate children's overall cognitive functioning. A full-scale IQ was calculated by using subtests of verbal intelligence and matrix reasoning. Verbal intelligence subtests included general knowledge (up to 29 items, Cronbach's $\alpha = 0.88$) vocabulary (up to 27 points, Cronbach's $\alpha = 0.89$) and comparison (up to 27 items, Cronbach's $\alpha = 0.94$). Matrix reasoning was estimated using Raven's matrices (up to 27 items, Cronbach's $\alpha = 0.89$).

2.4. Measures of parent's arithmetic skills

Arithmetic skills of parents were assessed with the Math Fluency subtest of the Woodcock-Johnson-III Tests of Achievement (WJ-III, Woodcock et al., 2001). Within a 3-minute time limit, participants were asked to solve simple addition, subtraction, and multiplication problems. Published median reliability of this Fluency subtest is 0.90 (Schrank et al., 2001).

2.5. Questionnaire on home numeracy practices

Parents were asked to rate the frequency of 60 home learning activities via an electronic questionnaire that was self-administered on a tablet. Thirty-sevene of these activities involved math, while the others involved topics such as reading, history, and music (these were introduced to disguise the goal of the study). For each activity, parents rated via a six-point rating scale the frequency with which they were engaged in that activity with their child at home during the past month. Thirteen items were directly translated from English to French from the questionnaire used in LeFevre et al. (2009) (translations were verified for accuracy by a French-English bilingual speaker) and 24 were directly adapted from our previous study in older children (Girard et al., 2021,

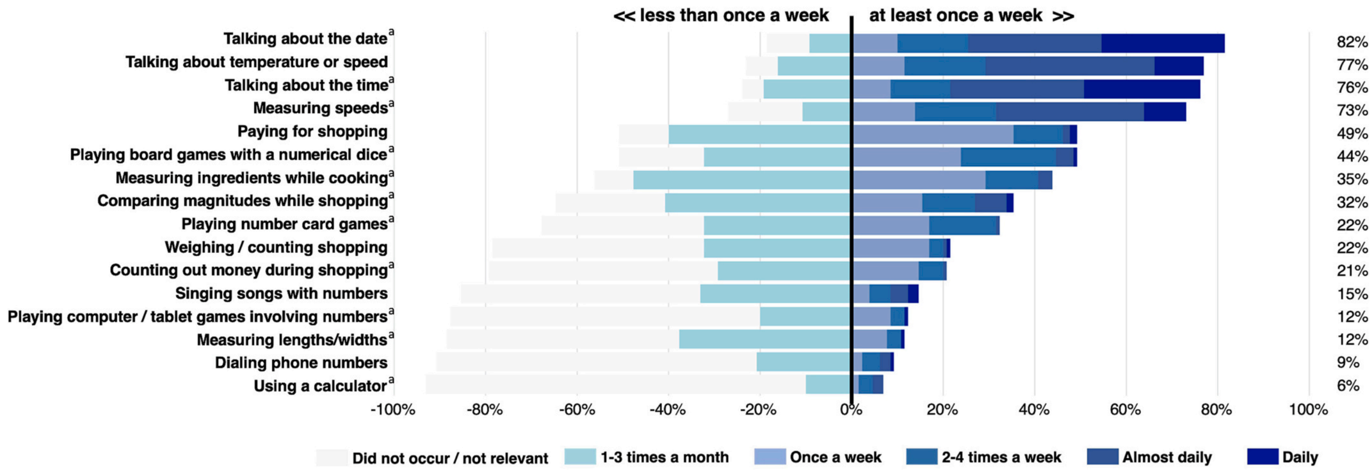

Fig. 1. Stacked bar chart showing the frequencies of informal home numeracy practices. Percentages on the right indicate the proportion of parents who engage in each activity at least once a week. [a]Items directly translated from LeFevre et al.'s questionnaire. All the remaining items are adapted from our previous questionnaire (Girard et al., 2021, 2022) with older French school children.

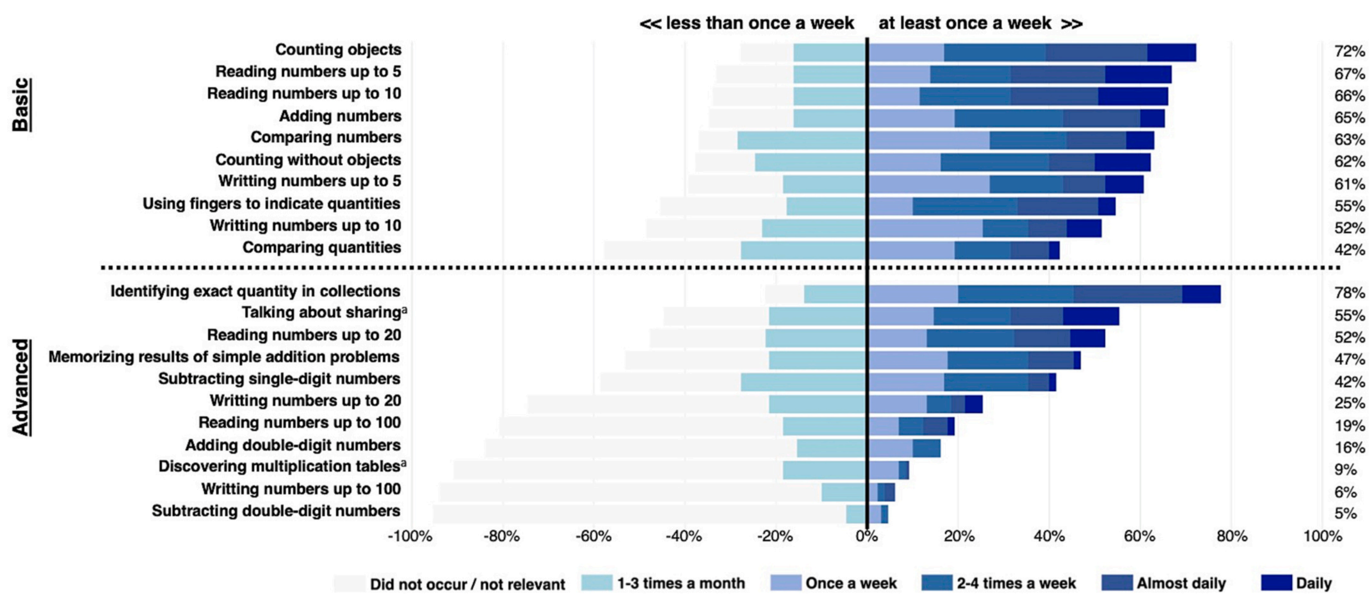

Fig. 2. Stacked bar chart showing the frequencies of formal basic and advanced home numeracy practices. Percentages on the right indicate the proportion of parents who engage in each activity at least once a week. [a]Items directly translated from LeFevre et al.'s questionnaire. All the remaining items are adapted from our previous questionnaire [masked for review] with older French school children.

2022) (see Fig. 1 and Fig. 2 for details). We followed prior recommendations about using a priori classifications of the HNE (see Elliott & Bachman, 2018; Vasilyeva et al., 2018) as well as our previous study (Girard et al., 2021, 2022) to define 16 activities as *informal* (see list in Fig. 1) and 21 as *formal* (see list in Fig. 2) with good internal consistency (for informal, Cronbach's alpha = 0.74; for formal, Cronbach's alpha = 0.90). Following Skwarchuk et al. (2014) and our previous study (Girard et al., 2021, 2022), the level of complexity for each math activity was determined based on the French curriculum. Specifically, ten formal activities were considered basic because they are in line with expectations from kindergarten, while 11 activities were considered advanced because they are in line with expectations from 1st grade.

2.6. Measure of parental number talk

Parents were asked to play with their child in a separate room of the lab, while their interactions were video-recorded during 10 min. The room was filled with a variety of objects and toys, including picture books, play food and dishes, a cash register with pretend money, paper and colored pencils, puppets, a building game, and a set of toy vehicles. The choice of these objects and toys was based on a previous study that used a similar setup to investigate the number talk between parents and children in the lab (Elliott et al., 2017). Due to technical issues, four interactions could not be recorded, such that there were only 124 dyads with available video recordings. All 10-min videos were manually transcribed by trained research assistants. A random sample of 22 % of the transcripts of these videos were checked for accuracy by another trained research assistant, indicating an agreement rate above 95 %. These transcriptions were then coded for number talk at the word level. A subsample of 25 % of these codings ($n = 31$) was double-coded. This showed excellent inter-coding reliability (over 98 %).

Parental number talk corresponded to parental uses of all numbers during the 10 min of the free play session (Elliott et al., 2017; Levine et al., 2010). As indicated in the preregistration, we calculated for each dyad an overall score capturing all instances of number words (including zero), as well as different scores for small (0–5), medium (6–10) and large (>10) numbers. Finally, we also quantified the total number of non-number words spoken by the parent during the whole recording.

Exploratory analyses also focused on the specific scores for different types of parental number talk. Following Gunderson and Levine (2011), we coded whether parents were using number words while labeling cardinal values of sets and whether objects were present or not when parents used number words. Finally, following Thippana et al. (2020), we also coded the different activities in which parents and children engaged. This enabled us to calculate utterance of number talk for each activity, for example reading, playing construction games or dominos. Because the word "one" ("un") has a particular status in French (i.e., it may correspond to either an indefinite article or a cardinal value), we created a control variable to quantify its specific occurrence and regress it out from additional analyses. Finally, we also coded children's math talk for exploratory analysis.

2.7. Analyses

Following our preregistered analysis plan, we tested our a priori hypotheses by using a series of one-tailed Pearson correlations assessing whether children's scores on subtests of the TEDI-MATH battery increased with the frequency of informal or formal (basic and advanced) home numeracy practices, as well as with different aspects of parental number talk. Children's math scores that were correlated with home numeracy practices or parental number talk were then used as outcomes of multiple regression analyses that included as predictors (1) parental income and education (2) children's overall cognitive functioning, (3) parental math skills, and (4) parental subjective estimate of children's numerical skills, in addition to home numeracy practices or parental number talk. This allowed us to test the specificity of the relations between children's math skills and either home numeracy practices or parental number talk, controlling for a range of potentially confounding factors.

Data were analyzed in Jamovi version 1.6.3. using standard frequentist statistics and Bayesian statistics. This allowed us to provide quantifiable evidence in support of a lack of positive association between practices or number talk and math skills (null hypothesis) as well as in support of a positive association between practices or number talk and math skills (alternative hypothesis). Bayesian analysis was conducted using the Jamovi Bayesian Methods package, with default priors (stretched beta prior width = 1). Following Jeffreys (1961), a $BF < 3$ was considered anecdotal evidence, a $3 < BF < 10$ was considered substantial evidence, a $10 < BF < 30$ was considered strong evidence, a $30 < BF < 100$ was considered very strong evidence, and a $BF > 100$ was considered extreme evidence that our data are more likely under the alternate than the null hypothesis (i.e., BF_{+0}) or under the null hypothesis than the alternate hypothesis (i.e., BF_{0+}). The use of both frequentist and Bayesian statistics allowed us to decide on whether to reject or not the null hypothesis, but also to quantify the level of evidence either in favor of the null or the alternative.

3. Results

3.1. Cognitive scores

The raw composite score of children on the TEDI-MATH battery was 96.53 (SD = 20.29; range = 55–148). Scores for each subtest are shown in Table 1. As expected, parental subjective estimate of their child's math skills was positively related to the composite math score ($r = 0.52$, $p < .001$, $BF_{0+} > 100$), as well as to each subscore (all $rs(126) > 0.30$, all $ps < 0.001$, all $BF_{0+s} > 60$), with the exception of non-symbolic skills ($r(126) = 0.11$, $p = .20$; $BF_{0+} = 0.45$). Children's full-scale IQ ranged from 71 to 146 ($M = 105.6$, $SD = 13.4$).

3.2. Do children's math skills increase with the frequency of home numeracy practices?

Frequencies of home numeracy activities (as reported by parents) are shown in Fig. 1 and Fig. 2. On average, informal activities occurred less frequently than formal activities ($t(127) = 2.48$, $p = .01$, $BF = 1.86$). The most frequent informal math activities were "talking about the date" and "talking about temperature or speed". The less frequent were "measuring lengths/widths" and "dialing phone numbers" (see Fig. 1). Within formal activities, basic activities occurred more often than advanced activities ($t(127) = 14.83$, $p < .001$, $BF > 100$). The most frequent formal basic activities were "counting objects" and "reading numbers up to 5", while the most frequent advanced activities were "identifying the exact quantity in a collection" and "talking about sharing". We did not observe any evidence for an effect of the child's gender on the frequency of any mathematical activities reported by parents (all $rs < 0.12$, all $ps > 0.19$, BFs <0.26).

Table 2 reports the bivariate correlations between children's math skills and the frequencies of home numeracy practices. We made four pre-registered predictions concerning the relation between children's math skills and home numeracy practices.

First, we predicted that informal practices would be positively related to non-symbolic math skills (*H1*). In contrast to that hypothesis, frequentist statistics indicated no significant positive association between informal practices and non-symbolic math skills. In fact, as indicated in Table 2, Bayesian statistics indicated substantial evidence for a lack of positive association between informal numeracy practices and non-symbolic numerical skills.

Second, we predicted that formal practices would be positively related to symbolic skills (*H2*), and that this relation would be stronger for advanced formal practices than basic formal practices (*H3*). We found that knowledge of the verbal numerical sequence, transcoding and calculation skills increased with the frequency of formal advanced numeracy practices, but not with the frequency of formal basic numeracy practices. As indicated in Table 2, frequentist statistics suggested significant relations for all of these subtests, though only relations with transcoding and calculation skills remained significant after Bonferroni correction for multiple comparison (critical value of $p_{corr} < 0.0024$ for 21 tests). Bayesian statistics indicated extreme evidence for a relation between formal advanced practices and transcoding skills, as well as strong evidence for a relation between formal advanced practices and calculation skills, but only anecdotal evidence for a relation between formal advanced practices and knowledge of the verbal numerical sequence.

In contrast to the findings above, frequentist analysis indicated no significant relation between formal basic numeracy practices and symbolic skills. In fact, Bayesian statistics indicated substantial evidence for a lack of relation between formal basic numeracy practices and both transcoding and calculation skills. Therefore, *H2* and *H3* were supported as far as transcoding, calculation and (to a lower degree) knowledge of the verbal numerical sequence were concerned. However, we found no significant positive relation between either formal basic or formal advanced numeracy practices and other math skills (i.e., non-symbolic skills, counting skills, written and oral number system skills). In addition, there was even substantial evidence for an absence of positive relation between formal practices and those other skills.

Third, we predicted that the relations observed between home numeracy practices and math skills would be observed over and above effects of parental income and education levels, children's IQ, parental math skills, and parental subjective estimate of their child's math skills (*H6*). As can be seen in Table 3, regression analyses confirmed that both transcoding and calculation skills (but not knowledge of the verbal numerical sequence) increased with the frequency of formal advanced numeracy practices, even after controlling for a range of variables (i.e., parental income and education, children's overall cognitive functioning, parental math skills, and parental subjective estimate of children's

Table 2
Pearson correlation coefficients between home numeracy practices and children's math skills across all participants.

	1.			2.			3.			4.			5.			6.			7.			8.			9.		
	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}
Home numeracy practices																											
1. Informal	-																										
2. Formal basic	**0.54*****	**>150**	0.00	-																							
3. Formal advanced	**0.55*****	**>150**	0.00	**0.70*****	**>150**	0.00	-																				
TEDI-math																											
4. Non-symbolic skills	0.01	0.12	**8.61**	-0.03	0.09	**11.27**	0.01	0.12	**8.12**	-																	
5. Verbal numerical sequence	0.07	0.24	**4.24**	-0.06	0.07	**13.87**	**0.17***	1.28	0.78	0.11	0.45	2.23	-														
6. Counting	0.10	0.37	**2.71**	-0.02	0.09	**10.88**	0.11	0.44	2.26	0.06	0.20	**4.92**	**0.43*****	**>150**	0.00	-											
7. Written number system	-0.02	0.09	**10.70**	-0.22	0.03	**31.91**	-0.01	0.10	**9.61**	**0.15***	0.85	1.17	**0.47*****	**>150**	0.00	**0.26****	**18.80**	0.05	-								
8. Oral number system	0.07	0.24	**4.23**	-0.18	0.04	**26.44**	0.04	0.17	**5.91**	**0.25****	**12.89**	0.08	**0.50*****	**>150**	0.00	**0.29*****	**49.20**	0.02	**0.55*****	**>150**	0.00	-	-	-	-	-	-
9. Transcoding	0.13	0.55	1.80	0.00	0.11	**8.89**	**0.33*****	**>150**	0.00	0.10	0.38	2.62	**0.51*****	**>150**	0.00	**0.37*****	**>150**	0.00	**0.38*****	**>150**	0.00	**0.54*****	**>150**	0.00			
10. Calculation	**0.18***	1.76	0.57	-0.08	0.06	**16.64**	**0.27*****	**27.07**	0.04	**0.40*****	**>150**	0.00	**0.56*****	**>150**	0.00	**0.40*****	**>150**	0.00	**0.46*****	**>150**	0.00	**0.55*****	**>150**	0.00	**0.55*****	**>150**	0.00

Note. Frequentist statistics: ***, $p < .001$; **, $p < .01$; *, $p < .05$. *P* values are one-tailed (testing for a positive association). Significant results are in bold. Bayesian statistics: BFs > 3 are indicated in bold. BF_{+0} indicates the strength of the evidence in favor of a positive relation between home numeracy practices and math skills. BF_{0+} values (in grey columns) indicate the strength of the evidence in favor of a lack of positive relation between home numeracy practices and math skills.

Table 3
Effect sizes and t-values associated with regression analyses of numeracy practices on math subtests controlling for covariables across all participants.

Numeracy practices	Transcoding			Calculation			Verbal numerical sequence		
	η^2p	t	$BF_{inclusion}$	η^2p	t	$BF_{inclusion}$	η^2p	t	$BF_{inclusion}$
Home numeracy practices									
Informal	0.002	−0.492	0.322	0.006	0.826	0.288	0.003	−0.550	0.335
Formal basic	**0.044**	**−2.328**	**6.624**	**0.079**	**−3.196**	**23.485**	0.013	−1.266	0.577
Formal advanced	**0.122**	**4.067**	**152.92**	**0.100**	**3.634**	**77.975**	0.031	1.946	1.027
Control variables									
Child's IQ	**0.035**	**2.077**	**3.320**	**0.100**	**3.639**	**435.08**	**0.049**	**2.485**	**12.943**
Parental math skills	0.000	0.076	0.293	0.009	1.037	0.490	0.004	0.664	0.465
Parental subjective estimate of their child's math skills	**0.046**	**2.402**	**7.261**	**0.066**	**2.891**	**13.873**	**0.035**	**2.081**	**4.626**
Parental education	0.004	0.651	0.552	0.006	0.828	0.672	0.003	0.594	0.372
Parental income	0.003	0.575	0.437	0.009	1.032	0.628	0.004	−0.707	0.313
R^2	0.328			0.464			0.216		

Note. Significant results are in bold (Frequentist statistics: $p < .05$. Bayesian statistics: BFs > 3). BFinclusion indicates the strength of the evidence in favor of a positive relation.

numerical skills). Specifically, after controlling for these factors, frequentist statistics still indicated a positive significant relation between these children's math skills and the frequency of formal advanced numeracy practices. Moreover, Bayesian evidence for the relation with transcoding skills remained extreme while evidence for the relation with calculation skills was very strong. Therefore, *H6* was supported as far as transcoding and calculation skills were concerned.

3.3. Do children's math skills increase with the frequency of parental math talk?

The total verbal input provided by parents during the 10-min free play session greatly differed among families, ranging from 132 to 1332 words ($M = 804$, $SD = 248.39$). We counted an average of 31.6 instances of number talk across families, also with a large variability ($SD = 25.88$, range = 0–142). Table 4 shows the instances of overall number talk, as well as that number talk broken down by number size, by whether numbers were used to describe cardinality, whether numbers were used in the presence of objects, and by whether numbers were used in specific activities.

First, we predicted that number talk instances would be positively related to children math skills (*H4*). Table 5 reports the bivariate correlations between children's math skills and parental math talk. We made three pre-registered predictions. In contrast to that hypothesis, frequentists statistics did not indicate any significant positive association between overall number talk and math skills. As can be seen in Table 5, Bayesian statistics indicated substantial to strong evidence for a lack of positive association between parental number talk and children's numerical skills.

Second, we predicted that number talk involving large sets, especially when labeling large sets of present objects, would be positively related to numerical skills (*H5)*. In contrast to that hypothesis, we did not observe any positive association between this specific type of math talk and math skills and frequentist analysis did not allow us to reject the

Table 4

Instances of number talk ($n = 124$) broken down by number size, use of number to describe cardinality, presence of objects, and activities.

Type of number talk	Mean (SD)	Min	Max
Number "one" (total)	13.77 (8.27)	0	35
Small numbers (total)	23.35 (16.66)	0	82
Medium numbers (total)	4.46 (6.32)	0	29
Large numbers (total)	4.81 (7.61)	0	39
Large numbers (only cardinality)	0.58 (2.27)	0	18
Large numbers (only cardinality with object present)	0.24 (1.69)	0	18
Overall number talk (total)	31.6 (25.88)	0	142
Overall number talk (only cardinality)	16.25 (10.65)	0	67
Overall number talk (abacus)	0.41 (1.61)	0	10
Overall number talk (construction game)	1.86 (5.29)	0	32
Overall number talk (play tea parties – play shop)	17.84 (24.63)	0	118
Overall number talk (domino)	3.66 (11.93)	0	68
Overall number talk (drawing)	1.73 (4.83)	0	30
Overall number talk (reading)	1.99 (8.18)	0	72
Overall number talk (general discussion)	1.52 (2.49)	0	10

Table 5

Pearson Correlation Coefficients Between Parental Math Talk and Children's Math Skills (n = 124).

	1.			2.			3.			4.			5.			6.			7.			8.			9.			10.		
	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}	r	BF_{+0}	BF_{0+}
Parental math talk																														
1. Overall	-																													
2. Talking about *large* sets of objects	**0.64*****	**>150**	0.00																											
Parental math talk on cardinality																														
3. Labeling large sets of objects	**0.30*****	**56.43**	0.02	**0.40*****	**>150**	0.00																								
4. Labeling large sets of present objects	**0.30*****	**65.46**	0.02	**0.30*****	**54.94**	0.00	**0.74*****	**>150**	0.00																					
TEDI-math																														
4. Non-symbolic skills	-0.03	0.09	**11.20**	-0.06	0.07	**13.99**	0.07	0.23	**4.37**	<0.01	0.11	**8.84**	-																	
5. Verbal numerical chain	-0.12	0.05	**20.72**	-0.20	0.04	**27.78**	-0.15	0.04	**22.57**	-0.11	0.05	**18.87**	0.11	0.45	2.23	-														
6. Counting	0.02	0.13	**7.74**	0.05	0.19	**5.29**	-0.03	0.09	**11.07**	-0.11	0.05	**19.16**	0.06	0.20	**4.92**	**0.43*****	**>150**	0.00	-											
7. Written number system	-0.16	0.04	**24.19**	-0.13	0.05	**20.65**	-0.07	0.00	**14.54**	-0.13	0.05	**20.86**	**0.15***	0.85	1.17	**0.47*****	**>150**	0.00	**0.26****	**18.80**	0.05	-								
8. Oral number system	0.03	0.24	**7.15**	0.06	0.05	**5.13**	0.01	0.12	**8.56**	-0.03	0.09	**10.95**	**0.25****	**12.89**	0.08	**0.50*****	**>150**	0.00	**0.29*****	**49.20**	0.02	**0.55*****	**>150**	0.00	-	-	-	-	-	-
9. Transcoding	0.07	0.55	**4.55**	0.05	0.18	**5.48**	<0.01	0.11	**8.81**	-0.04	0.08	**12.52**	0.10	0.38	2.62	**0.51*****	**>150**	0.00	**0.37*****	**>150**	0.00	**0.38*****	**>150**	0.00	**0.54*****	**>150**	0.00			
10. Calculation	-0.02	1.76	**10.24**	-0.03	0.09	**11.08**	0.03	0.15	**6.83**	-0.04	0.08	**12.53**	**0.40*****	**>150**	0.00	**0.56*****	**>150**	0.00	**0.40*****	**>150**	0.00	**0.46*****	**>150**	0.00	**0.55*****	**>150**	0.00	**0.55*****	**>150**	0.00

Note. Frequentist statistics: ***, p < .001; **, p < .01; *, p < .05. P values are one-tailed (testing for a positive association). Significant results are in bold. Bayesian statistics: BFs > 3 are indicated in bold. BF_{+0} indicates the strength of the evidence in favor of a positive relation between home numeracy practices and math skills. BF_{0+} values (in grey columns) indicate the evidence for the null (in favor of the absence of a positive relation between home numeracy practices and math skills).

null hypothesis. Bayesian statistics indicated substantial to strong evidence for a lack of positive association. Therefore, *H4* and *H5* were not supported.

Because the word "one" (i.e., "un") has a particular status in French, the correlations between children's math skills and parental math talk were also controlled for word "one" in exploratory analyses. All the correlations remained non-significant (ps > 0.05, rs < 0.15), except for a positive relation between parental overall number talk (controlled for the use of the word one) and children's transcoding skills ($r = 0.18$, $p < .05$). However, the effect was driven by parental small number talk ($r = 0.19$, $p < .05$) rather than parental large number talk ($r = 0.07$, $p = .47$).

Finally, we followed Eason et al. (2021) and tested in exploratory analyzes whether parental number talk instances might be related to children's numerical skills through their own number talk instances. We observed a positive relation between children and parents' overall number talk ($r = 0.53$, $p < .001$, $BF > 100$) and small number talk ($r = 0.46$, $p < .001$, $BF > 100$). We also observed small positive relations between children overall math talk and their knowledge of the verbal numerical sequence ($r = 0.18$, $p = .04$, $BF = 0.89$) as well as transcoding skills ($r = 0.18$, $p = .04$, $BF = 0.89$). There was also a larger relation between children overall math talk and calculation skills ($r = 0.30$, $p < .001$, $BF = 27.15$). To explore these effects, we ran a formal mediation bias-corrected bootstrap tests with 1000 iterations, using parents' overall number talk as independent variable, children's numerical skill as dependent variable, and children's overall number talk as mediator variable (see Fig. 3). Given the exploratory nature of this analysis and to limit the risk of type 1 error, we only performed this analysis on children's calculation skills because this was the largest effect observed with children's overall math talk. The indirect effect of this mediation analysis was significant, suggesting that children's number talk mediated the relations between parental number talk and children's mathematical skills (indirect effect, estimate = 0.09, $Z = 3.68$, $p < .001$). Note that the direct effect in this mediation (i.e., the relation between parental overall number talk and children's skills controlling for children overall number talk) was significantly negative (direct effect, estimate = 0.03, $Z = -2.94$, $p < .01$). This might indicate a suppression effect, i.e., an effect that arises when an indirect effect has an opposite sign to the total effect (and therefore the absence of the suppressor may reveal a small or insignificant total effect) (MacKinnon et al., 2000). Here parental overall number talk (*X*) is positively related to children overall number talk (*M, A path*), and children overall number talk is positively related to their calculation skills (*Y, B path*). However, parental overall number talk (*X*) has a direct negative effect on children math skills, holding constant children's number talk (*C′ path*) while indirect effect of parental number talk through children's overall number talk (*AB*) shows a positive effect on children's math skills.

4. Discussion

Here we aimed to identify the specific relations between math skills of 5-year-olds and different aspects of their HNE, while (1) considering different ways to measure this HNE (using a questionnaire and direct measures of number talk) and (2) distinguishing confirmatory from exploratory findings by pre-registering our hypotheses and analytic strategy. We made six pre-registered hypotheses. Below we discuss each of these hypotheses and whether they are supported by our data.

4.1. Informal numeracy activities (as measured by the questionnaire) should be specifically related to non-symbolic skills (H1)

Contrary to our first hypothesis (*H1*), but in line with several studies (e.g., Ciping et al., 2015; De Keyser et al., 2020; Girard et al., 2021; Huntsinger et al., 2016; LeFevre et al., 2010), we did not observe any relation between informal numeracy practices and children's non-symbolic skills. This is inconsistent with an influential model of the HNE assuming a link between non-symbolic skills and informal numeracy activities (Skwarchuk et al., 2014). On the one hand, our results may suggest that this relation may not be as strong as previously thought and may have been inflated by analytic flexibility in previous studies. This is consistent with a growing number of studies showing that non-symbolic numerical skills are more difficult to enhance in interventions than previously thought (Bugden et al., 2021; Szkudlarek et al., 2021). On the other hand, it is also possible that the relation exists but is difficult to measure using a questionnaire. Indeed, by definition, informal math activities are activities that parents engage in at home without any specific didactic goal in mind (e.g., playing a board game). Such activities may thus represent an aspect of math transmission that parents are not fully aware of. It may be quite difficult for them to accurately report the frequency of these activities in a questionnaire. It is also possible that the extent to which parents may actually expose children to actual mathematical contents through these informal activities vary greatly among families. For instance, in Cheung and McBride-Chang's (2015) intervention study, parents were asked to play with their children. However, children's math skills improved after parents have been trained to make the game beneficial to their children's math learning (i.e., the effect was driven by an increase in math intentionality from parents). Finally, it is also possible that formal content may be implemented by some families during these informal activities, such that formal and informal home numeracy activities may overlapping (Hornburg et al., 2021).

4.2. Formal numeracy activities should be related to symbolic skills (H2) and that relation should be stronger for advanced HNE than basic HNE (H3)

In line with our second hypothesis (*H2*), we observed that the frequency of formal home numeracy activities was related to children's symbolic skills, but also that this relation was dependent upon the complexity of the activity (*H3*). That is, the frequency of advanced formal home numeracy activities (i.e., activities that are typically considered above the average level of kindergartners in French schools) was related to knowledge of the verbal numerical sequence, calculation and transcoding skills. Distinguishing formal home activities as a function of their complexity was proposed by Skwarchuk et al. (2014) and is broadly consistent with the idea that beneficial activities should be in the so-called "zone of proximal development" (Vygotsky & Cole, 1978), which refers to the gap between skills that children already master and immediate skills that they do not yet know but could be mastered with appropriate guidance.

Despite the prevalence of this concept in the developmental literature, relatively few studies have distinguished between basic and advanced formal math activities, as suggested by Skwarchuk et al.

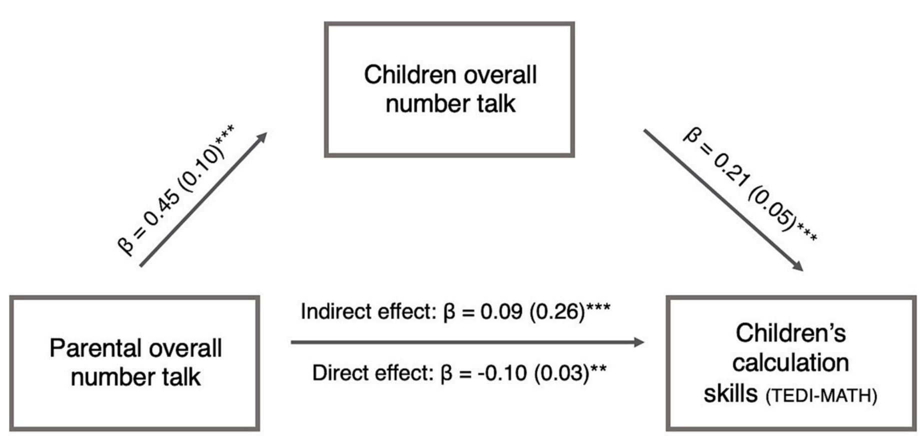

Fig. 3. Exploratory mediation model of the effect of parental overall number talk on children's calculation skills, through children's overall number talk.

(2014). Yet, studies that did uniformly demonstrate the relevance of this distinction. Not only have studies showed a consistent positive relation between children's math skills and the frequency of advanced (but not basic) formal numeracy activities (del Río et al., 2017; Skwarchuk, 2009; Skwarchuk et al., 2014; Susperreguy, Douglas, et al., 2020; Thompson et al., 2017; Zippert & Ramani, 2016), they have also shown a lack of positive relation between the frequency of basic numeracy practices and children's math skills (Skwarchuk et al., 2014; Zippert & Ramani, 2016, 2016) (Skwarchuk, 2009). Therefore, consistent with Elliott and Bachman (2018), our results suggest that it is important to take into consideration the complexity of numeracy activities (with respect to children's age or school curriculum) when investigating the HNE.

It is also interesting to note that the relation between the frequency of advanced formal numeracy practices and math skills was the largest with transcoding and calculation skills. These two skills are foundational for elementary math education and are at the core of the advanced formal activities listed in the questionnaire (e.g., "written numbers up to 20" or "memorizing results of simple addition problems", see also Fig. 2). The relation between home numeracy practices and these skills has also been observed in previous studies in children of the same age (transcoding skills: Bernabini et al., 2020; Soto-Calvo et al., 2020; calculation skills: Huang et al., 2017; Mutaf-Yıldız, Sasanguie, De Smedt, Reynvoet, 2018a; Vasilyeva et al., 2018).

4.3. Parental number talk should be positively related to children's math skills (H4), and this relation should be stronger for number talk involving counting and labeling large sets of present objects than other types of number talk (H5)

Overall, the average amount of parental number talk measured during the free play session was consistent with previous studies using similar laboratory situation (for 10-minute-free play, M = 33.13 (19.31), DePascale et al., 2021; M = 24.93 (29.55), Mutaf-Yıldız, Sasanguie, De Smedt, Reynvoet, 2018b). Interestingly, our measures of parental number talk were not related to the frequency of activities as measured in the questionnaire. This finding, which is consistent with previous studies (Mutaf-Yıldız, Sasanguie, De Smedt, Reynvoet, 2018b; Thippana et al., 2020), suggests that both methods might capture different aspects of the home numeracy environment. However, inconsistent with several previous studies (Elliott et al., 2017; Levine et al., 2010; Ramani et al., 2015), we did not find any predicted relation between parental number talk and children's math skills (*H4* and *H5*). Instead, we largely found evidence in favor of a lack of relation, the only exception being a small exploratory relation between children's transcoding skill and parental number talk when that talk was controlled for the use of the number "one". However, that effect was driven by small number talk, which is at odds with the claim that the relation should be greater for large number talk with 5-year-olds (Elliott et al., 2017).

It is interesting to consider that the categories that we used for describing parental math language (i.e., small versus large numbers) might also be conceived as basic versus advanced, much in the same way as we categorized activities. Our results may thus not only appear to conflict with previous studies on parental math talk (Dearing et al., 2022; Eason et al., 2022) but also with our own results on the frequency of formal math activities at home. Nevertheless, our results are not necessarily unique in failing to show a relation with children of the same age (DePascale et al., 2021; Mutaf-Yıldız, Sasanguie, De Smedt, Reynvoet, 2018b; Silver et al., 2021; Thippana et al., 2020; Zippert et al., 2020). We can see two potential explanations for these null results. First, much like the relation between non-symbolic skills and informal practices, it is possible that the relation between parental number talk and children's math skills in previous studies might have been inflated by analytic flexibility, given the large number of ways to analyze aspects of parental number talk and the absence of pre-registration. This is consistent with the small effect size for the relation between math talk and children's math skills (compared to the effect size observed for questionnaire measures, $r = 0.03$ vs 0.20) which was reported in a recent meta-analysis and was explained by the large differences in the measures used across studies (Daucourt et al., 2021). Second, it is also possible that the relation might not have been adequately captured by our free play situation in the lab, which may be non-ecological. This is notably suggested by Thippana et al. (2020), who found that number talk measured at home was not correlated with number talk measured in the laboratory (and only the former was related to children's math skills). There might be a number of different reasons for that. For example, families may be exposed to play materials that they are not familiar with or parents may show a desirability bias given that they know they are being observed.

Interestingly, exploratory analyses suggest that the free play session may nonetheless capture some genuine measure of number talk between parents and children. Indeed, we found that (1) parental number talk was positively related to children's number talk, (2) children's number talk was positively related to some aspects of their math skills (calculation skills), and (3) children's number talk mediated the relation between parental number talk and children's math skills. In other words, parental number talk was related to children's math skills through children's number talk. This suggests that children's number talk during that free play session might reflect a more valid measure of their typical verbal interactions with their parent, perhaps because they are less sensitive than adults to the evaluative dimension of the free play situation in the laboratory and therefore present a reduced desirability bias (Scott, 2008). As suggested by Eason et al. (2021), it may also be that the reciprocity of the interactions between parents and children is more relevant to children's math skills than the description of parental talk itself. This idea is also broadly in line with previous results on the importance of conversational turns for children language development, above and beyond the contribution of the total amount of verbal adult input (Romeo et al., 2018).

4.4. The relations between the HNE and children's math skills should hold even when controlling for parental income and education (SES), children's IQ, parental math skills, and subjective estimates of children's skills (H6)

The relation between measures of the HNE and measures of children's math skills is often interpreted as reflecting an effect of home numeracy practices on children's abilities. However, it is important to acknowledge that measures of the HNE may be confounded with a number of factors. For example, it is well documented that the math achievement may depend upon family SES (Denton & West, 2002). The relation between the HNE and children's skills may also be reversed, such that parents may react to children with high cognitive abilities or children who are perceived as skilled (rather than the other way around) (Hunt, 1961; Zippert & Ramani, 2016). It is also possible that the relation between the HNE and children's math skills may be influenced by parental math skills, either because of genetic heritability (Hart et al., 2016; van Bergen et al., 2016) or because they may influence the quality of HNE (Dearing et al., 2012). Finally, early numeracy skills may be influenced by the HNE as well as by intrinsic cognitive abilities (Bernabini et al., 2020; Kleemans et al., 2016). Therefore, we tested whether the relations between the HNE and children's math skills remained after controlling for parental income and education levels, children's IQ, parental math skills, and subjective estimates of children's skills (*H6*). As predicted, this was largely the case. It may be worth noting that parental skills showed a significant positive relation with their children's math skills (especially for arithmetic skills, $r = 0.29$, $p < .001$). However, when parental skills were entered as covariate, they no longer significantly explained the variance in children's scores, while child-specific variables (e.g., IQ) or family numeracy activities (i.e., advanced and formal numeracy practices) did. In addition, parental scores were not related to any math practices (all $rs < 0.10$, all $ps > 0.27$). Therefore, our results may support the hypothesis of realistic environmental effects

(Hart et al., 2016, 2021).

4.5. Limitations

To our knowledge, our study is the first pre-registered study on the relation between the HNE and math skills in children. However, this work has some methodological limitations. First, the dataset was correlational in nature, such that the directions of the relations are unknown. For example, the activities that parents reported doing at home may be in response to a perceived interest or ability in their children rather than the other way around. To control for this effect, we measured the parental perception of their child's math skills and controlled for this variable in our analyses. Nonetheless, the design of the present study does not allow us to draw any strong directional inferences about the observed associations. Longitudinal and interventional studies are needed to gain a better understanding of the direction of the relations observed.

A second limitation concerns the power of our study to detect the effects we planned to measure. Although our sample size was a priori calculated based on a meta-analysis (Dunst et al., 2017), a more recent meta-analysis now indicates a power of 74 % (Daucourt et al., 2021). Although this power level remains adequate (Bacchetti, 2010; Lakens, 2022), future studies with even larger sample sizes are needed to replicate our conclusions. A third limitation is that home numeracy was assessed from one parent only, i.e., the parent who came to the lab for their child's testing. Most parents were mothers and only 14 % of fathers were included in the sample. To obtain a more complete picture of the HNE, future studies would need to focus on assessing the entire parental dyad. Finally, because we assessed the HNE through a questionnaire and observation in the lab, it is possible that parents might have behaved in a manner that would be viewed favorably by experimenters (i.e., a social-desirability bias). This bias is difficult to minimize in the lab, but studies might consider measuring number talk without the presence of an experimenter at home, for example using small discrete recording devices (Susperreguy & Davis-Kean, 2016) or using video call technology (Thippana et al., 2020).

5. Conclusions

Over the past decades, a growing number of studies have found relations between the home numeracy environment and math skills in young children. However, studies are not always consistent and there is substantial variability in measures and analytic choices (Daucourt et al., 2021). Our pre-registered study confirms that the frequency of advanced formal numeracy activities (measured using a questionnaire) relates to symbolic numerical skills (transcoding and calculation) in 5-year-olds. However, we did not observe the anticipated relation between informal math activities and non-symbolic skills. We also failed to find relations between parental number talk (measured from a free play session) and children's math skills. Together, our findings call for the use of more comprehensive measures the HNE and math skills in young children, but also for the systematic use of pre-registration to parse out exploratory findings from confirmatory findings.

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Declaration of competing interest

None.

Data availability

The questionnaires and data that support the findings of the experiment are available via the OSF at https://osf.io/7j9t2/.

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