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Early Mathematical Knowledge in Deaf and Hard-of-Hearing Children—Association Between Numerical and Patterning Skills

Viktor Werner * and Barbara Hänel-Faulhaber

Deafness, Language, and Learning (D2L), Faculty of Education, University of Hamburg, 20146 Hamburg, Germany; barbara.haenel-faulhaber@uni-hamburg.de
* Correspondence: viktor.werner@uni-hamburg.de

Abstract

Early patterning skills, particularly those involving linear repeating patterns, are well-established predictors of mathematical development. This relationship has not yet been investigated in visually oriented deaf and hard-of-hearing (DHH) children. It also remains unclear whether a two-dimensional pattern structure contributes to predicting numerical skills in children at the time of school entry. The present study investigates the relationship between repeating patterning skills in two formats (linear and circular) and numerical skills in a total of 38 DHH and typically hearing children. Language competence was additionally assessed in the DHH group to account for its linguistic heterogeneity. In the DHH and hearing groups, repeating patterning skills in each format strongly predicted numerical skills. Among DHH children, prior language experience played a more decisive role in mathematical development. The circular format emerged as a particularly strong predictor for typically hearing children. DHH children, especially those with sign language experience, perform equally well with both formats, and it is argued that this is due to their enhanced visuospatial skills.

Keywords: early mathematics; repeating patterns; numerical skills; deaf and hard-of-hearing children; sign language; visual skills

1. Introduction

From a very early age, children begin to recognize simple shapes and visual patterns. Recognizing regularity and repetition is fundamental to many developmental tasks, including language acquisition. Children detect recurring linguistic patterns and implicitly derive rules from them (Saffran et al., 1996). Pattern recognition also plays a key role in building foundational mathematical knowledge. Through activities with building blocks or manipulatives, for example, children encounter mathematical patterns that explicitly encourage rule generation (Lüken, 2025).

Among hearing children, it is well documented that early patterning skills exert a substantial influence on mathematical development (Junker et al., 2025; Rittle-Johnson et al., 2019; Wijns et al., 2021). The present study explores how repeating patterning skills relate to numerical skills in deaf and hard-of-hearing (DHH) signing children. Prior research has shown that the learning trajectories of DHH children depend on the quality of linguistic input they receive in their early home environment (Lillo-Martin et al., 2025; Morere & Allen, 2024). At the same time, studies indicate that DHH individuals draw on enhanced visual skills to compensate for the absence of hearing (Bavelier et al., 2006). It remains an open question, however, whether these visual skills influence mathematical development

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in DHH children and what role the visual language modality of sign language plays in this process. Accordingly, this study considers both conventional linear repeating pattern sequences and alternative circular repeating pattern sequences (Werner & Hänel-Faulhaber, 2026), comparing them across DHH and typically hearing children.

2. Theoretical Foundations

2.1. Repeating Patterning Skills

Repeating patterns consist of sequences such as ABCABCABC, in which the core unit ABC repeats. Such sequences are traditionally presented in a one-dimensional, linear arrangement. Children encounter this pattern type as early as the preschool years during play and learning activities (Ginsburg et al., 2003; Lüken, 2025). The elements can vary in characteristics such as geometric shapes with different colors (Wijns et al., 2019), sizes (Flynn et al., 2020), orientations (Chen et al., 2026), colored cubes (Lüken & Sauzet, 2021), or visual objects (Larkin et al., 2022).

To assess children's repeating patterning skills, researchers have used a variety of tasks. In the *copy* task (reconstructing a given pattern), *extend* task (continuing an existing pattern), and *repair* task (completing a missing element), children can typically solve the items recursively using simple strategies such as one-to-one correspondence (Collins & Laski, 2015; Junker et al., 2025; Lüken, 2020). By contrast, the *identify the pattern* task (identifying the core unit) and *translate* task (reconstructing the pattern with different shapes and/or colors) require deeper competence, such as relational understanding of the core unit (Lüken & Sauzet, 2021; Rittle-Johnson et al., 2013). This assumption has been debated for the *translate* task, however, because children may also apply a one-to-one strategy in that context (Wijns et al., 2019).

Sarama and Clements (2009) proposed that children follow a learning trajectory in repeating patterning understanding. Naturally, young children first master the simplest sequence, ABABAB, with tasks in the order *repair*, *copy with view* (model pattern visible when responding), and *extend*. As they grow older, they become capable of handling increasingly complex sequences and ultimately grasping the core unit. This learning trajectory has been confirmed in several empirical studies (Junker et al., 2025; Lüken & Sauzet, 2021; Rittle-Johnson et al., 2013). It is reasonable to assume that these studies did not differentiate children according to linguistic or cultural background. A study of four-year-old Australian Indigenous children revealed that their patterning skills do not necessarily follow the commonly assumed trajectory (Warren & Miller, 2010). These children were able to copy AB patterns first, then extend them, and subsequently complete them with a missing element. The authors suggested that the Indigenous children employed a unique copying strategy, synchronously vocalizing the animal elements in the sequence. This example illustrates how strategies may be rooted in the implicit learning processes of a particular (Indigenous) linguistic–cultural group, as in DHH sign language user children, leading to a different developmental pathway than is typically assumed.

2.2. Associations Between Numerical and Repeating Patterning Skills in Typically Hearing Children

Early patterning skills constitute a core component of successful mathematical development (Borriello et al., 2023). This claim is supported by numerous studies examining the relationship between repeating patterning and mathematical skills. Cross-sectional research has revealed strong associations between both constructs in kindergarten-aged children (Bojorque et al., 2021; Wijns et al., 2019). Longitudinal studies have likewise demonstrated the predictive strength of early patterning skills for later mathematical achievement (Lüken, 2012; Rittle-Johnson et al., 2019; Zippert et al., 2020). The study by Wijns et al. (2021), involving 410 children, examined how these associations develop with age. It found a bidirectional relationship between repeating patterning and numerical ability at ages 4–5 when spatial ability was controlled, whereas one year later, only repeating patterning predicted numerical ability.

The association between repeating patterning and numerical skills also appears in populations outside industrialized countries, where differences exist in economic conditions and educational policies. For example, a study of 116 preschoolers and kindergartners in Ecuador found that, despite generally lower overall performance, mathematical ability remained linked to repeating patterning skills (Bojorque et al., 2021). All these studies were conducted with children whose language acquisition is typical.

This naturally prompts the question of how repeating patterning contributes to mathematical reasoning in children whose language development follows a different trajectory. Fyfe et al. (2019) showed that patterning skills are positively associated with calculation performance across children, including those children with developmental language disorder (DLD). However, although children with DLD exhibited comparable patterning skills to typically developing peers, they performed worse on calculation tasks. This indicates that patterning alone does not account for group differences in calculation performance. Instead, these findings suggest that additional factors, particularly language skills, contribute to variation in calculation performance at an individual level, the cited evidence does not support the claim that differences in patterning explain differences in calculation skills between groups.

All the studies described above focused on hearing children who use spoken language. The following section therefore turns to the current state of knowledge regarding mathematical and patterning skills in DHH children. This population holds a unique position: many DHH children are part of a sign language community that constitutes a linguistic and cultural minority, while at the same time a substantial proportion experience limited access to natural language input from birth, which can result in delayed language acquisition.

2.3. Early Mathematics Skills in DHH Children

Past studies have reported that DHH children exhibit lower mathematical skills than their hearing peers (Gottardis et al., 2011). For young DHH children, a study by Kritzer (2009) found that half of the 28 DHH children aged 4 to 6 years scored at or below the average range on a standardized math test. Recent research suggests that the development of mathematical skills in DHH children depends crucially on whether they have access to language (Santos et al., 2023). Such access is absent for the majority, as roughly nine out of 10 DHH children are born to hearing parents who suddenly face the challenge of their child's hearing impairment and cannot readily communicate in a natural language (Mitchell & Karchmer, 2004). Most of these children receive cochlear implants. The device aims to maximize spoken language input for the child. Evidence indicates that bimodal–bilingual upbringing involving both spoken and sign language can lead to effective developmental support (Humphries et al., 2022; Lillo-Martin et al., 2022). Deaf parents hold a distinctive position in sign language promotion because they serve as role models who allow their DHH children to experience unrestricted linguistic input and thereby attain cognitive development appropriate to age (Lu et al., 2016; Terhune-Cotter & Dye, 2025; Wienholz et al., 2026b).

Early language exposure enables children to acquire number concepts appropriate for their age. Walker et al. (2024) examined associations among different representations of the same number, including symbolic Arabic numerals, signed or spoken number words, and nonsymbolic quantities, in 4.5- to 9-year-old children. Their study found that DHH children using American Sign Language performed as well as hearing children using spoken English. The finding points to modality-independent number learning. In contrast, DHH children whose access to either sign or spoken language began later exhibited number understanding below age expectations. Additionally, Quam et al. (2025) reported that children aged 3–7 years who experience early language exposure and have acquired the cardinal principle demonstrate a stronger understanding of small quantities.

Two studies that focused on DHH children raised with spoken language revealed developmental paths for number concepts that resembled those of typically hearing children but occurred noticeably later (Shusterman et al., 2022). These children obtained lower scores on measures of numerical discrimination skills, verbal number knowledge, and conceptual understanding of the word “more”. Performance gradually improved the longer they had access to spoken language through hearing devices (Santos et al., 2023).

The studies were produced by a collaborative team. Nevertheless, they provided the first quantitative evidence from a larger sample that early language access, regardless of modality, is vital for typical mathematical and cognitive advancement. The results supply a plausible explanation for why previous research consistently found that DHH children lacking early language input trailed behind hearing peers and behind DHH children who had sign language from birth across multiple age groups in mathematics performance (Santos & Cordes, 2022).

2.4. Pattern Understanding in DHH Children

To the best of our knowledge, no published research has yet examined whether the well-established relationship between patterning and numerical skills also applies to DHH children. However, two studies conducted in the United States and the Netherlands administered simple repeating pattern tasks to DHH children aged 3 to 5 years. Their results reported lower performance levels among the DHH children relative to hearing age-matched peers (Pagliaro & Kritzer, 2013; Wauters et al., 2024).

A separate sub-study conducted by the authors of the current work examined one-dimensional versus two-dimensional pattern formats while taking account of diverse language backgrounds among DHH participants (Werner & Hänel-Faulhaber, 2026). One-dimensional format (linear pattern) refers to the standard linear sequences employed as stimuli in numerous earlier studies (e.g., Larkin et al., 2022; Rittle-Johnson et al., 2019; Wijns et al., 2019). The two-dimensional format (circular pattern) displays the repeating sequence along the circumference of a circle while maintaining all defining features of the repeating unit. Across *copy from memory* (model pattern no longer visible when responding), *translate*, and *repair* activities, DHH children with early sign language exposure and a control group of hearing children generally achieved higher success rates than DHH children with later sign language exposure. Early signing DHH children and hearing children displayed virtually no differences on the three activities when using the one-dimensional format. With the two-dimensional format, a distinct advantage emerged, particularly on *copy from memory* tasks, with early signing DHH children outperforming hearing children by nearly 20 percentage points. The pattern likely reflects elevated visuospatial attention in early signing DHH children, stemming from auditory deprivation combined with prompt exposure to a visual language. Other studies have shown that visuospatial attention assumes special importance among deaf sign language users, setting unimodal bilingualism apart from bimodal bilingualism (MacSweeney et al., 2008).

3. The Current Study

The existing literature robustly documents an association between mathematical and repeating patterning skills presented in linear format among hearing children. Hearing children with DLD exhibit challenges in numerical skills, as outlined above, highlighting tight links between language and mathematical thinking. By comparison, patterning performance in children with DLD resembles that of children with typical language development. Their patterning skills forecast arithmetic calculation performance but not conceptual understanding (Fyfe et al., 2019).

No investigation has yet explored the association between patterning skills and numerical skills among DHH children. The present research seeks to fill this gap while acknowledging the wide range of language backgrounds represented in the DHH population. It also aims to clarify the degree to which one-dimensional and two-dimensional pattern formats aid in predicting numerical skills among both DHH children and hearing children.

These considerations lead to the following research questions:

(1) What relationship exists between numerical and repeating patterning skills presented in linear formats among DHH children and hearing control children? To what extent does language proficiency among DHH children affect this relationship?

(2) What relationship exists between numerical and repeating patterning skills presented in circular formats among DHH children and hearing control children? To what extent does language proficiency among DHH children affect this relationship?

(3) Which pattern format (linear or circular) more effectively predicts numerical skills in DHH children and hearing control children?

4. Method

4.1. Participants

The study was conducted as part of a broader project examining foundational learning competencies in DHH children. Altogether 46 children between 5 years 6 months and 7 years 9 months took part in it. Participants separated into two language groups consisting of 24 DHH children and 22 hearing control children. The DHH children were enrolled in three schools in Germany that emphasize sign language for DHH students. Hearing control children attended a daycare center characterized by an average social index according to the Hamburg Social Index (Schulte et al., 2023). Parents granted informed consent for their child's involvement, and children received suitable information and agreed to participate.

Four DHH children were excluded because of missing data points or inability to assign them unambiguously to one language subgroup. This left 20 DHH children (M_{age} = 6 years 7 months; 11 assigned female) available for analysis. These 20 children divided further into two subgroups. Ten DHH children (five assigned female) had at least one deaf parent and received sign language input from birth (DHH early signing children, M_{age} = 6 years 3 months). Three of these children acquired a sign language other than German Sign Language as their first language. Ten DHH children (six assigned female) had hearing parents who lacked sign language proficiency and began learning sign language no earlier than the age of three (DHH later signing children, M_{age} = 6 years 10 months). In eight of these 10 cases, the primary home language was not German. For hearing control children, at least one parent spoke German natively in most instances. Two children had parents whose native language was not German. Data collection remained incomplete for two additional children. Consequently, 18 hearing control children (M_{age} = 6 years 4 months; seven assigned female) entered the analyses. Age did not differ significantly between the DHH group and the hearing control group ($t(28.2) = 1.23$, $p = 0.23$, $r = 0.39$). Table 1 provides information on DHH and hearing control children.

Table 1. Demographic background information of DHH children (with separate early and later signing groups) and hearing control children in the study.

	DHH (*n* = 20)	***Early Signing* (*n* = 10)**	***Later Signing* (*n* = 10)**	**Hearing Control (*n* = 18)**
Participant Information				
Age: mean (SD)	6.54 (0.59)	*6.24 (0.50)*	*6.83 (0.53)*	6.36 (0.29)
Gender: n_{female} ($\%_{female}$)	11 (55%)	*5 (50%)*	*6 (60.0%)*	7 (38.9%)
Degree of Hearing Loss				
Mild	0 (0%)	*0 (0%)*	*0 (0%)*	-
Moderate	3 (15%)	*1 (10%)*	*2 (20%)*	-
Severe	3 (15%)	*1 (10%)*	*2 (20%)*	-
Profound	12 (60%)	*8 (80%)*	*4 (40%)*	-
Missing	2 (10%)	*0 (0%)*	*2 (20%)*	-
Assistive Technology				
Cochlear implants (both sides)	6 (30%)	*1 (10%)*	*5 (50%)*	-
Hearing aid (both sides)	9 (45%)	*7 (70%)*	*2 (20%)*	-
None	2 (10%)	*2 (20%)*	*0 (0%)*	-
Missing	3 (15%)	*0 (0%)*	*3 (30%)*	-

4.2. Materials

4.2.1. Repeating Patterning Skills in Linear Format and Circular Format

A 2 × 3 task framework was used to capture the children's repeating patterning performance. Patterns appeared in one of two display formats: (1) one-dimensional (linear) or (2) two-dimensional (circular). Figure 1 depicts both formats with an ABCC example. Structurally, the two formats correspond closely. In the linear format, the basic unit ABCC proceeds from left to right and repeats twice more. In the circular format, the same basic unit ABCC begins at the top of the circle and continues clockwise with B, C, and C, followed by two additional repetitions to close the loop. Unlike the linear version, the circular version forms a self-contained ring without a defined start or finish. A prior study described and validated the utility of both formats (Werner & Hänel-Faulhaber, 2026).

(**a**) (**b**)

Figure 1. Repeating patterns in (**a**) one-dimensional format (linear pattern), and (**b**) two-dimensional format (circular pattern), an example with an ABCC pattern.

Each format included the same three activity types: *copy from memory*, *translate*, and *repair*. *Copy from memory* activities required children to study a pattern sequence displayed on a tablet. A presentation program showed each sequence for 4.5 to 9 s (0.75 s per element) before removing it from view. Children then reconstructed the remembered sequence using matching picture cards on a layout board. *Translate* activities followed a similar procedure except that the model stayed visible on the tablet throughout. Children rebuilt an equivalent structure using picture cards that differed in shape and color. Both activity types, *copy from memory* and *translate*, presented one AB sequence, one ABC sequence, and one ABCC sequence. Video recordings documented the sessions for later scoring. One point was given whenever a child correctly reproduced at least two consecutive units of repeat.

Repair activities utilized a developed tablet-based measure implemented in PsychoPy3 (Peirce et al., 2022). Here, a pattern appeared on screen with one element missing from the second position of the second sequence. Children selected the correct replacement from four options shown below. Analyses incorporated responses to 48 items (2 pattern formats × 3 units [AB, ABC, ABCC] × 8 items per unit) organized into eight blocks with alternating pattern formats, with responses counted as valid only if provided at least 1.4 s after stimulus onset. Each block required at least 75% valid responses for inclusion of the child's data. In each group, the proportion of excluded cases was 2.3% for DHH children and 0.9% for hearing control children.

The percentages of correct scores from *copy from memory*, *translate*, and *repair* were summed separately for each activity, resulting in overall scores for linear and circular patterning skills for each child. The activity types may differ in cognitive demand (e.g., Lüken & Sauzet, 2021; Rittle-Johnson et al., 2013). However, consistent with prior research, the three activities show strong convergence in their observed outcomes (Werner & Hänel-Faulhaber, 2026), suggesting that they tap into the same underlying construct. Accordingly, we aggregate them into a composite using equal weights as a parsimonious approach. Internal consistency reached a strong level in the present sample (α = 0.85).

4.2.2. Numerical Skills

The standardized test of basic mathematical competencies at kindergarten age (MBK 0; Krajewski, 2018), was used to measure numerical skills. The test suits children from 3 years and 6 months through school entry. It assesses progressively more complex subdomains: (1) basic numerical skills (i.e., number word sequence and knowledge of digits), (2) quantity number concept (i.e., quantity concept, quantity seriation, number comparison, and quantity comparison), and (3) number relationships (i.e., arithmetic story problem and differences between numbers) (cf. Krajewski & Schneider, 2009).

Originally developed for spoken German, the test was translated and adapted into German Sign Language with excellent internal consistency (α = 0.89; Werner & Hänel-Faulhaber, 2024). In the present study, video recordings preserved children's responses for subsequent scoring. Correct answers produced a total raw score with a maximum of 54 points.

4.2.3. DGS Competence

The German Sign Language Sentence Repetition Task for Children (DGS-SRT-Kids) was used to evaluate sign language competence in the DHH participants (Wienholz et al., 2026a). Intended for ages 4 to 13, this measure assesses both comprehension and production in signing children. It consists of 19 sentences that vary in morphosyntactic complexity (easy, medium, hard) while controlling sentence length (2 to 4+ signs).

Easy sentences included short declarative forms, lexical modification, and no use of signing space. Medium sentences incorporated complex structures, simple use of signing space, simple classifiers, and non-manual marking. Hard sentences added constructed action and complex use of space. Signed sentences first appeared in a video presentation with a PPT; children then reproduced each sentence as accurately as possible. Their utterances were video recorded and later analyzed. Correctly produced signs were tallied for each child and divided by the maximum possible total of 85 signs. Internal consistency was excellent in the present sample (α = 0.97).

4.3. Procedure

Testing sessions were conducted around the time children were entering school, taking place in quiet, separate rooms within their respective educational institutions. The various tasks were distributed across several days so that no child participated in a session lasting longer than 30 min. The first session administered *copy from memory* and *translate* patterning tasks. A second session presented the tablet-based *repair* task. Numerical skills were assessed during a third session.

This was followed by tests measuring sequential processing and visuospatial working memory. These cognitive control tests are intended to ensure that the DHH and the hearing control groups are similar in relevant baseline characteristics. Thus, the aim is for the target test results to be interpretable. Performance on two cognitive control tasks likewise showed no group differences. The Hand Movement subtest of the KABC-II (Melchers & Melchers, 2015) evaluated sequential short-term memory. Children imitated sequences of hand shapes (fist, palm, or side of hand) ranging from two to seven items. Group comparison showed the following values ($W = 196.5$, $p = 0.66$, $r = 0.07$). Visual-spatial working memory was measured with the Corsi Block task from the PathSpan app (Hume & Hume, 2014). Children reproduced tapped block sequences that increased in length from two to a maximum of eight items. No significant group differences appeared ($W = 232$, $p = 0.13$, $r = 0.25$).

DHH children completed the DGS competence task in an additional session. Each child earned an animal stamp on a collection card after every session to motivate them and to track their progress. To ensure linguistic fairness in the tests, all procedures with DHH children were carried out by a deaf early signer using German Sign Language, while procedures with hearing control children were administered by a hearing examiner in spoken German. Both examiners followed an identical test protocol and practiced the administration of all measures to enhance comparability of test performance across groups. Data gathering occurred amid the COVID-19 pandemic with appropriate protective precautions in place.

4.4. Analyses

The calculated composite scores representing linear and circular patterning skills, together with raw scores for numerical skills and DGS competence, served as the basis for all statistical analyses. Correlation analyses were carried out using the Spearman method. The linear regression model tested the extent to which each patterning format predicted numerical skills, with separate models run for the DHH group and the hearing control group. Differences between groups were evaluated through model comparisons that included interaction. Within the DHH group, a multiple regression analysis additionally incorporated DGS competence as a predictor. A further multiple regression analysis was conducted to determine the relative strength of predictors of numerical skills in each group. Given the small sample sizes, regression models were limited to a maximum of two predictors (Green, 1991). For this reason, an additional paired Wilcoxon test was carried out using the two patterning formats as dependent variables, which shed light on their significance within the overall context.

All statistical computations were performed using R (R Core Team, 2025). The paired Wilcoxon test was calculated using the rstatix package (Kassambara, 2025). Visualizations were generated with the ggstatsplot (Patil, 2026) and ggpubr (Kassambara, 2026) packages.

5. Results

The analyses focused on the associations between repeating patterning skills in each format and numerical skills among the DHH children and the hearing control children.

Table 2 presents descriptive test results for DHH and hearing control children. Given the exploratory nature of the study, the results are first presented separately for each group and then compared across groups.

Table 2. Descriptive statistics of control and test variables in the study.

	DHH (n = 20)	***Early Signing* (*n* = 10)**	***Later Signing* (*n* = 10)**	**Hearing Control (n = 18)**
Control variables [1]				
Sequential processing	9.5 (3.25)	*10.5 (4.5)*	*8 (5.25)*	10 (3.75)
Visual-spatial working memory	4 (3)	*4.5 (2.75)*	*3 (2.75)*	4 (1.75)
Test variables [1]				
Linear patterns	2.70 (0.69)	*2.90 (0.33)*	*2.44 (0.62)*	2.67 (0.83)
Circular patterns	2.44 (0.74)	*2.65 (0.45)*	*2.10 (0.61)*	2.29 (1.09)
Numerical skills	30.2 (27.5)	*47.5 (6.25)*	*19.5 (7.12)*	43.2 (11.1)
DGS-SRT-Kids	24.5 (41.2)	*52 (13.2)*	*9.5 (13.8)*	-

Note. [1] Median and IQR.

5.1. Association Between Linear Format of Repeating Patterning and Numerical Skills

Correlation analyses revealed a significant positive relationship between linear patterning and numerical skills in both groups. The strength of this relationship was $r_s(18) = 0.61$, $p < 0.01$ in the DHH group and $r_s(16) = 0.62$, $p < 0.01$ in the hearing control group. Linear regression was used to determine how well linear patterning skills predicted numerical skills (Table 3). In the DHH group, linear patterning skills emerged as a significant predictor of numerical skills ($\beta = 0.59$, $p < 0.01$). This model explained 35% of the variance in numerical skills. In the hearing control group, linear patterning skills were likewise a significant predictor of numerical skills ($\beta = 0.49$, $p < 0.05$). The model accounted for 24% of the variance in numerical skills. Figure 2 visualizes the scatter plots with the linear regression fits for both groups. Comparison of the models based on the interaction between the two groups indicated no difference in the predictive relationship between linear patterning and numerical skills ($\beta = -0.33$, $p = 0.21$), with an overall model fit of 45%.

A further step within the DHH group examined whether language competence contributed to the prediction of numerical skills. After controlling for linear patterning skills, DGS competence showed a highly significant effect ($\beta = 0.80$, $p < 0.001$). The resulting model explained 85% of the variance in numerical skills. There was no multicollinearity (VIFs < 1.27). In the graphical representation, where nearly all early signing children are positioned above the regression line and nearly all later signing children are positioned below it, the influence of the DHH children's prior language experience on their mathematical skills is further substantiated from the perspective of linear patterning skills.

Table 3. Regression models predicting numerical skills from linear repeating patterning (LP), separated by DHH children (n = 20) and hearing control children (n = 18). Additionally, for DHH children a multiple regression model predicting LP and DGS competence.

	DHH			**Hearing Controls**		
Variable	***B***	***β***	***R*²**	***B***	***β***	***R*²**
Step 1			0.35 **			0.24 *
LP	16.59	0.59 **		8.01	0.49 *	
Step 2			0.85 ***			-
LP	6.30	0.22 *		-	-	
DGS	0.55	0.80 ***		-	-	

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

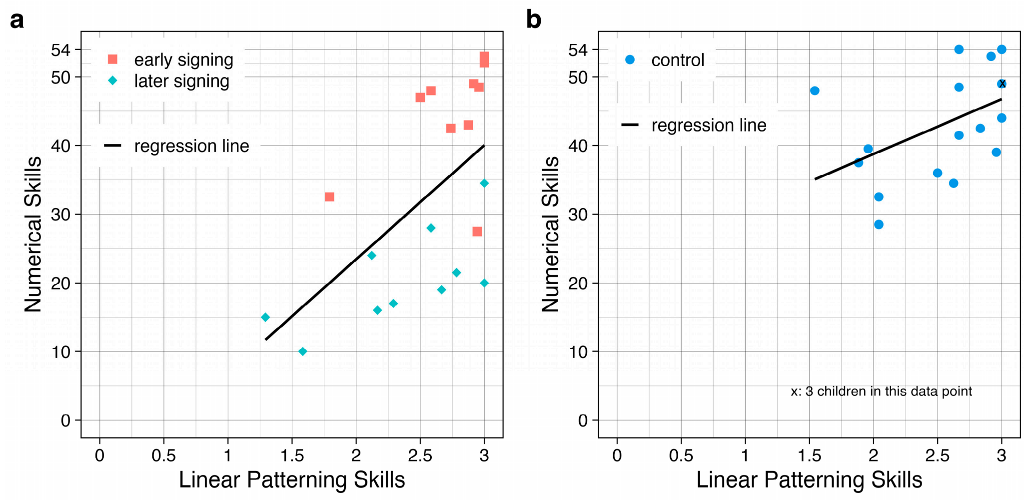

Figure 2. Relationship between linear patterning and numerical skills by (**a**) DHH children (n = 20) and (**b**) hearing control children (n = 18). The squares represent early signing children (n = 10), while the diamonds represent later signing children (n = 10). The regression line indicates the trend between the variables.

5.2. Association Between Circular Format of Repeating Patterning and Numerical Skills

A significant positive relationship was also found between circular patterning and numerical skills in both groups. The strength of this association was $r_s(18) = 0.62$, $p < 0.01$ in the DHH group and $r_s(16) = 0.88$, $p < 0.001$ in the hearing control group. Linear regression was also used to determine how well circular patterning skills predicted numerical skills (Table 4). In the DHH group, circular patterning skills also emerged as a significant predictor of numerical skills ($\beta = 0.61$, $p < 0.01$). The model accounted for 37% of the variance in numerical skills. In the hearing control group, circular patterning skills served as an even stronger predictor of numerical skills ($\beta = 0.83$, $p < 0.001$). The model accounted for 69% of the variance in numerical skills. Figure 3 visualizes the scatter plots with the linear regression fits for both groups. Comparison of the models based on the interaction between the two groups indicated no difference in the predictive relationship between circular patterning and numerical skills ($\beta = -0.15$, $p = 0.54$), with an overall model fit of 54%.

Table 4. Regression models predicting numerical skills from circular repeating patterning (CP), separated by DHH children (n = 20) and hearing control children (n = 18). Additionally, for DHH children a multiple regression model predicting CP and DGS competence.

	DHH			Hearing Controls		
Variable	***B***	***β***	***R*²**	***B***	***β***	***R*²**
Step 1			0.37 **			0.69 ***
CP	12.46	0.61 **		9.69	0.83 ***	
Step 2			0.88 ***			-
CP	5.61	0.27 *		-	-	
DGS	0.54	0.79 ***		-	-	

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Within the DHH group, language competence was tested as an additional predictor in the next step. After controlling for circular patterning skills, DGS competence also exhibited a highly significant effect ($\beta = 0.79$, $p < 0.001$). This model explained 88% of the variance in numerical skills. There was no multicollinearity (VIFs < 1.22). In the graphical representation, where eight out of 10 early signing children are positioned above the regression line and 8 out of 10 later signing children are positioned below it, the influence of the DHH children's prior language experience on their mathematical competence is further substantiated from the perspective of circular patterning skills.

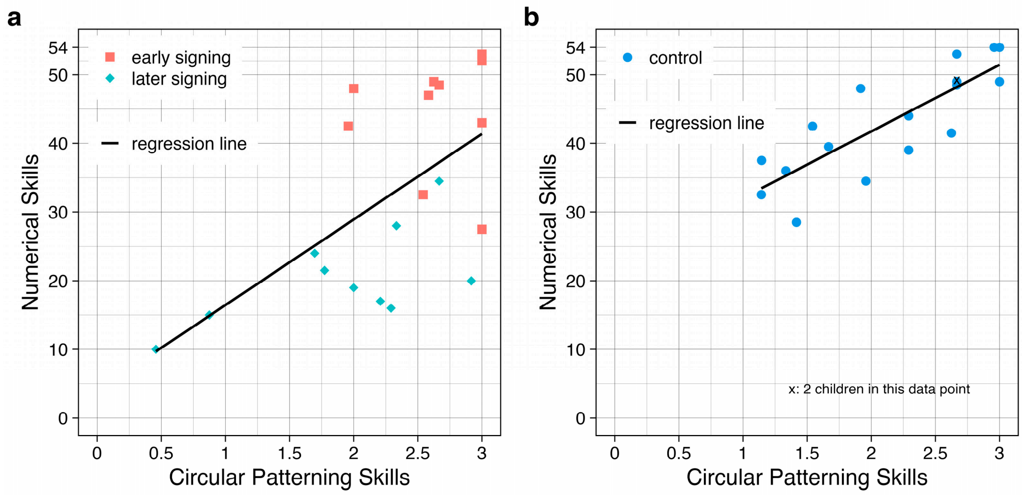

Figure 3. Relationship between circular patterning and numerical skills by (**a**) DHH children (n = 20) and (**b**) hearing control children (n = 18). The squares represent early signing children (n = 10), while the diamonds represent later signing children (n = 10). The regression line indicates the trend between the variables.

5.3. Which Pattern Format Predicts Numerical Skills More Effectively?

When linear and circular patterning skills were entered simultaneously in the model for DHH children, neither format retained a significant predictive effect on numerical skills (see Table 5).

Table 5. Multiple regression models predicting linear repeating patterning (LP) and circular repeating patterning (CP), separated by DHH children (n = 20) and hearing control children (n = 18).

	DHH			Hearing Controls		
Variable	B	β	R^2	B	β	R^2
			0.40 *			0.70 ***
LP	8.57	0.31		−2.85	−0.17	
CP	7.56	0.37		11.12	0.95 ***	

Note. * $p < 0.05$, *** $p < 0.001$.

To explore possible differences between early signing and later signing DHH children, pairwise comparisons of linear versus circular patterning performance were conducted within each subgroup (Figure 4). Early signing children performed equally well on both formats (V = 13, p = 0.53, r = 0.16). Later signing children showed a clear preference for the linear format (V = 3, $p < 0.01$, r = 0.79). These subgroup differences point to substantial heterogeneity in how children process particular pattern formats. Due to the reduced subgroup sizes, a statistical analysis of links to numerical skills was not feasible. In this analysis section, among hearing control children, circular patterning skills emerged as the only significant predictor of numerical skills (β = 0.95, $p < 0.001$) and explained 70% of the variance. A regression diagnostic showed no multicollinearity (VIFs < 1.96). The pairwise comparison on both formats showed a clear preference for the linear format (V = 12.5, $p < 0.01$, r = 0.69).

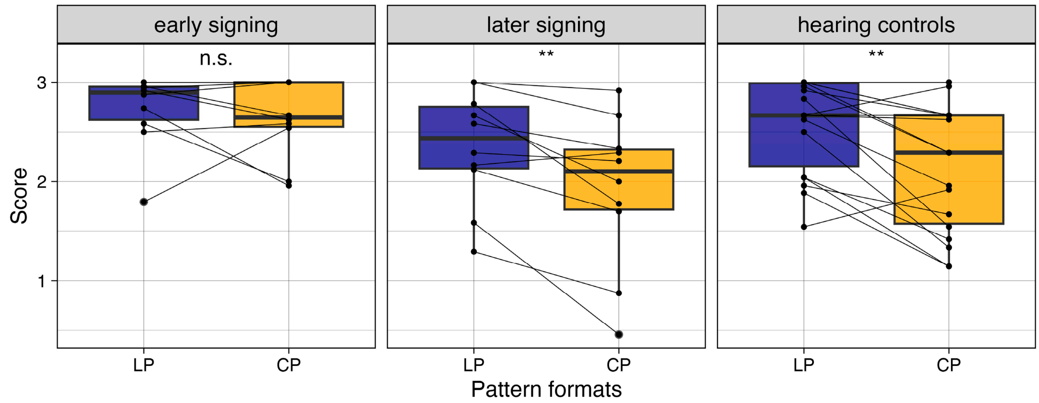

Figure 4. Pairwise comparisons between LP and CP in each group (DHH early signing, DHH later signing, and hearing control children) with Wilcoxon test. ** $p < 0.01$; n.s., not significant.

6. Discussion

Research in mathematics education has consistently shown that early patterning skills predict the later mathematical development. Most of these studies have focused on repeating patterns in young children (Lüken, 2012; Wijns et al., 2021; Zippert et al., 2020). To the best of our knowledge, no published work has examined whether patterning skills are associated with numerical skills in DHH children. Two important aspects must be considered here. First, DHH children often rely on enhanced visual skills, a pattern that is especially pronounced among early signers (Dye & Terhune-Cotter, 2023; Gioiosa Maurno et al., 2024). Second, the language development of these children depends strongly on the presence of sign language in the home environment (Humphries et al., 2022; Lillo-Martin et al., 2025). With these points in mind, the present study used both the traditional one-dimensional linear format and the two-dimensional circular format to assess their predictive value for numerical skills.

6.1. Linear Repeating Patterning Also Predicts Numerical Skills in DHH Children

The first research question asked whether the well-established association between early patterning and numerical skills also holds for DHH children. Materials consisted of the linear pattern format that has been widely used in previous research (Bojorque et al., 2021; Wijns et al., 2019). The results from the hearing control group replicated earlier findings that linear patterning skills predict numerical skills (Lüken, 2012; Wijns et al., 2021; Zippert et al., 2020).

Using the same materials, the present study demonstrated that linear patterning skills likewise predict numerical skills among DHH children. These findings, then, suggest that the fundamental learning relationships are broadly similar in DHH children. At the same time, prior language experience was an important factor: the predictive contribution of DGS is greater than that of linear patterning performance. On average, early signing children scored above the regression line, whereas later signing children tended to score below it. Thus, these findings provide suggestive evidence for an effect of language experience in addition to the association between linear patterning performance and numerical skills in DHH children.

6.2. Circular Repeating Patterning Supports Numerical Skills

The inclusion of circular patterns allowed the examination of whether understanding two-dimensional pattern structures adds to the prediction of numerical skills. Again, language competence showed a greater predictive contribution than that of circular patterning performance in DHH children. As was the case with linear patterns, almost all early signing children fell above the regression line, while almost all later signing children fell below it. A different pattern emerged among hearing control children. Here, the association with circular patterning was noticeably stronger than with linear patterning, and the predictive model explained variance much more effectively.

Multiple regression analyses helped clarify the difference between the hearing control group and the DHH group by evaluating the relative contributions of linear and circular patterning to numerical skills. The analysis that included both predictors from the patterning skills, conducted separately for each group, resulted in the following results: Among the DHH children, neither the one-dimensional nor the two-dimensional repeating pattern tasks retained any substantial influence on their numerical skills. In the hearing control group, on the other hand, circular patterning skills emerged as a highly significant predictor with excellent model fit, whereas linear patterning skills no longer contributed significantly.

The descriptive results suggest potential differences between DHH children and hearing control children. When considered separately, both pattern formats are associated with numerical skills. When entered together, the findings constitute preliminary observations of group-related differences. Bearing in mind the modest sample size in the DHH group, it can be tentatively proposed that visual skills, in line with the *compensation hypothesis* (Dye & Terhune-Cotter, 2023), reduce the importance of format differences in pattern comprehension. DHH children draw on a highly practiced visual perceptual system that is attuned to recognize and interpreting patterns and regularities in the environment.

This tendency is particularly evident among children who have early access to sign language. Pairwise comparisons of success rates on linear and circular tasks revealed opposing patterns in the two DHH subgroups: early signing children performed comparably well on both formats, while later signing children achieved noticeably better results with the linear format. This difference suggests that later signers, who have had less extensive language experience, might have not yet developed the proficient visuospatial skills seen in early signers. Early exposure to sign language fosters visual strategies that allow more effective simultaneous processing of information in peripheral vision (Dye & Terhune-Cotter, 2023). The two-dimensional nature of circular patterns requires scanning movements in both vertical and horizontal directions. This demand aligns closely with the visuospatial strengths that develop through early sign language experience.

Whereas differences in visuospatial skills and sign language quality help explain the results among DHH children, a different perspective accounts for the pattern observed in hearing control children. Hearing children primarily use auditory–verbal language to build mathematical understanding and to develop mathematical language. The resulting mathematical language follows a temporally sequential, one-dimensional code that closely resembles the structure of linear repeating patterns, a format which reflects learning habits shaped by their spoken language modality (Purpura & Reid, 2016; Turan & De Smedt, 2023). Tasks involving two-dimensional pattern arrangements are handled most successfully by children with stronger mathematical skills and provide better prediction of their numerical skills, even when one-dimensional tasks are also considered. This suggests that children with advanced mathematical skills are better equipped to manage unfamiliar and more complex task formats because they possess more developed patterning strategies (Baumanns et al., 2024; Junker et al., 2025).

The present study examined the relationship between two pattern formats and numerical skills in DHH children and a hearing control group. Several limitations should be considered when interpreting the findings. First, the heterogeneous language backgrounds of early and later signing DHH children limited the possibility of direct statistical comparisons between the DHH and hearing groups. Consequently, the relationship between patterning skills and numerical skills had to be described qualitatively. Furthermore, the study was conducted during the COVID-19 pandemic and followed appropriate hygiene measures. Although every effort was made to ensure comparable testing conditions, potential effects of the pandemic cannot be entirely ruled out, but they concern both groups equally. Future research with larger samples is needed to allow for more robust group comparisons. In addition, future studies should more closely examine the role of general cognitive abilities, particularly in relation to two-dimensional pattern formats, to determine whether these abilities contribute to the association between patterning and numerical skills. Finally, longitudinal research is needed to investigate how mathematical competencies develop across the school years in DHH children and how these trajectories relate to early patterning skills.

7. Conclusions

Numerical skills in DHH children can be predicted from their patterning performance with a strength comparable to that seen in hearing children. The strong visual processing abilities of DHH children, especially when combined with typical sign language development, enable them to work effectively with both linear and circular pattern formats. Even DHH children whose language development was delayed demonstrate a basic understanding of patterns; however, they perform less well on tasks that use circular patterns. In contrast, among hearing control children the strength of the association between patterning and numerical skills appears to depend on the pattern format, with circular patterning skills being particularly strongly related to higher levels of mathematical competence.

The findings further suggest that DHH children, particularly early signers, and hearing control children may approach certain mathematical tasks in somewhat different ways. In the present context, DHH children's use of sign language—a visual language closely associated with well-developed visuospatial skills (Dye & Terhune-Cotter, 2023; Gale & Martin, 2024)—may support their understanding of two-dimensional circular repeating patterns. These distinctive visual strengths could be deliberately incorporated into mathematics instruction for DHH children when sign language serves as the primary language of instruction. This leads to the conclusion that educators working with DHH children should have strong sign language skills. With them, they can communicate math in a subject-specific manner with their students (Braidi et al., 2023). At the same time, hearing children may also benefit from such visually oriented approaches within inclusive mathematics education.

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Data Availability Statement: Raw data were generated at University of Hamburg. Derived data supporting the findings of this study are available from the corresponding author on request.

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