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Early numerical cognition in deaf and hearing children: Closer than expected?

Cognición numérica temprana en niños sordos y oyentes: ¿Más cercana de lo esperado?

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Resumen

La cognición de los sordos ha sido objeto de numerosos estudios que buscan comprender cómo los niños y adultos sordos procesan la información. Dichos estudios han demostrado que las personas sordas muestran diferencias en las habilidades numéricas y la función ejecutiva (FE), lo que podría ser la base de las diferencias conocidas en la forma en que las personas sordas aprenden y desarrollan sus habilidades cognitivas. Se han encontrado diferencias entre estudiantes sordos y oyentes en varias áreas de razonamiento numérico, en matemática y en la eficiencia en el procesamiento de representaciones numéricas como la comparación de magnitud. En las tareas de comparación de magnitud, los resultados dependían de si se estaban haciendo comparaciones simbólicas (números arábigos) o no simbólicas (puntos). En un estudio, los niños sordos fueron más lentos que sus compañeros oyentes en las tareas de comparación de magnitud simbólica, pero no en las tareas no simbólicas. Sin embargo, en un estudio más reciente, también se encontraron diferencias en las tareas no simbólicas.

Se considera que la capacidad para comparar y discriminar grandes numerosidades depende del sistema numérico aproximado (ANS, Approximate Number System), un sistema cognitivo que se cree está gobernado por un circuito neuronal dentro del surco intraparietal. Los investigadores plantean la hipótesis de que el ANS subyace en cierta medida al desarrollo de la aritmética. Hay algunos datos que apoyan esta hipótesis: por ejemplo, las diferencias individuales en la agudeza del ANS se correlacionan positivamente con las habilidades numéricas y los logros futuros en matemática. Por otro lado, se ha encontrado un deterioro en la agudeza del ANS en niños con discapacidades de aprendizaje matemático. En consecuencia, los investigadores han propuesto que el ANS contribuye a la aparición de conceptos numéricos que los niños requieren para la competencia básica en el conteo y las comparaciones de magnitud simbólica. Otros han sugerido que la asociación entre la agudeza en la comparación de magnitud no simbólica y el rendimiento en matemática está moderada por factores de dominio general como las funciones ejecutivas (FE), en particular el control inhibitorio.

En general, no está claro si existen diferencias en la agudeza de comparación de magnitud simbólica y no simbólica en niños sordos más pequeños y en qué medida se relacionan con las FE. El estudio actual examina la agudeza de las representaciones numéricas simbólicas y no simbólicas en niños sordos en edad preescolar e investiga la posible influencia del funcionamiento ejecutivo en estas habilidades matemáticas básicas.

Se recolectaron datos de 21 niños portugueses del área de Lisboa, siete de los cuales eran sordos congénitamente y 14 tenían audición normal; los niños tenían entre 4 y 7 años de edad (M = 69.9 meses, DT = 11.42).

Se seleccionaron tareas para medir lo siguiente: (a) FE, (b) memoria de trabajo, (c) lenguaje y (d) habilidades numéricas tempranas. Se empleó la tarea Shape School Task para evaluar FE. Se administró la versión portuguesa de la tarea de *tapping* de bloques de Corsi para evaluar la amplitud visuoespacial. Se desarrolló una tarea de comparación de puntos para examinar la capacidad de los niños de decidir instantáneamente cuál de las dos matrices de puntos es más grande utilizando el *software* Panamath. Se utilizaron dos tareas para evaluar la capacidad de los niños para producir palabras numéricas en un contexto cardinal y el Numeracy Screener para medir su capacidad para comprender la magnitud numérica simbólica.

Los resultados indicaron que los niños sordos mostraron retrasos en las capacidades de comparación de magnitud simbólica y no simbólica. En las FE solo se encontraron diferencias en una tarea que implicaba una combinación de conmutación e inhibición; por lo demás, su función ejecutiva era comparable a la de los niños no sordos.

Palabras clave: cognición numérica, evaluación neuropsicológica, niños sordos, educación de la primera infancia

Abstract

Deaf students show a significant delay in their understanding of numeracy and measurement concepts as well as verbal problem solving. There is still no consensus about the origin of this delay but several studies have shown that deaf people show differences in basic numerical skills and executive function (EF), which could underlie the differences in the way they learn and develop their cognitive abilities. Children have the innate ability to estimate and compare numerosities without using language or numerical symbols. The ability to discriminate large numerosities depends on the approximate number system (ANS), a cognitive system believed to be governed by a neural circuit within the intraparietal sulcus. Researchers hypothesize that the ANS underlies the development of arithmetic and there is data supporting the contribution of the ANS for math achievements. Little is known about the approximate number system of deaf children at early ages. Deaf and hearing preschool children were compared in terms of specific cognitive functions shown to be important for success in mathematics. Executive functions and symbolic and nonsymbolic magnitude comparison abilities of 7 deaf children and 14 hearing children aged 4–7 years (M = 69.90 months, SD = 11.42), were compared. To do so, neuropsychological assessments for school-aged children were adapted into Portuguese Sign Language. Significant group differences were found in abstract counting as well as in symbolic and nonsymbolic magnitude comparisons. These findings suggest that deaf children are less competent in these early numeracy skills than are their hearing peers.

Keywords: numerical cognition, neuropsychological assessment, deaf children, early age education

Introduction

Deaf cognition has been the subject of numerous studies seeking to understand how deaf children and adults process information (Marschark & Hauser, 2008; Marschark, Morrison, Lukomskic, Borgna, & Convertino, 2013). Such studies have shown that deaf people show differences in numerical skills and executive function (EF), which could underlie known differences in the way deaf people learn and develop their cognitive abilities (Geraci, Gozzi, Papagno, & Cecchetto, 2008; Gilmore et al., 2013; Maller & Braden, 2011). Executive functions (EFs; also called "executive control") refer to the abilities necessary to actively maintain information for the purposes of planning and executing goal-directed behavior (Bull, Espy, Wiebe, Sheffield, & Nelson, 2011; Diamond, 2013). Researchers acknowledge three core EFs: inhibition, information updating, and shifting (Miyake et al., 2000). Inhibition is the ability to override a dominant or prepotent response. Updating involves the constant monitoring of working memory, deleting old/no longer relevant contents and adding new/relevant ones. Shifting is the ability to switch between tasks or mental sets and is assumed as an important aspect of executive control (Miyake et al., 2000; Miyake & Friedman, 2012). Studies of young preschool children, from 2 to 5 years (Espy et al., 2004) and children aged around 7 years (Bull & Scerif, 2001) indicate that inhibition and shifting are predictive of mathematics ability. There is also some indication that EF training has a positive effect on mathematic achievement (Goldin et al. 2014).

Over the past two decades, researchers have consistently observed a gap between deaf and hearing students in several areas of numerical reasoning, mathematics (Ansell & Pagliaro, 2006; Bull, 2008; Nunes & Moreno, 1998; for a review, see Gottardis, Nunes, & Lunt, 2011; Marcelino, Sousa, & Costa, 2019), and efficiency in processing numerical representations (Bull, Marschark, & Blatto-Valle, 2005; Epstein, Hillegeist, & Grafman, 1994). A delay in numerical reasoning has also been observed before school-age in deaf children. For instance, Kritzer (2009) found that more than half of a sample of 28 deaf preschool children scored a year or more behind normative age-equivalent scores of numerical reasoning. Mixed findings have emerged in areas such as counting and magnitude comparison: Leybaert and Van Cutsen (2002) found that deaf children's performance on abstract counting was poorer than was their peers, but they scored equally well in tasks of object counting and creating sets of a given cardinality. Abstract counting (verbal counting forward starting at one) and cardinality competence predict later mathematics achievement (Nguyen et al., 2016). As for the magnitude comparison tasks, the results depended on whether symbolic (Arabic numerals) or nonsymbolic (dots) comparisons were being made. In one study, deaf children were slower than were hearing peers in the symbolic magnitude comparison tasks but not in the nonsymbolic tasks (Rodríguez-Santos, Calleja, Garcia-Orza, Iza, & Damas, 2014). However, in a more recent study, differences were also found in the nonsymbolic tasks (Bull, Marshark, Nordmann, Sapere, & Skene, 2018).

Humans and other animals have the innate ability to estimate and compare numerosities without using language or numerical symbols (Dehaene, 1997). This ability manifests in two different ways of representing numerosity: the first focuses on the recognition of small numerosities (up to four) in an exact way, while the second pertains to larger collections and enables the activation of approximate magnitude representations. This second system is not limited by set size, although the acuity of the representations decreases for larger sets (Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004; Gallistel & Gelman, 1992). The ability to discriminate large numerosities is considered to depend on the approximate number system (ANS), a cognitive system believed to be governed by a neural circuit within the intraparietal sulcus (Feigenson, Dehaene, & Spelke, 2004). The acuity of the ANS, which is measured by the Weber fraction, progressively sharpens and levels off at early adolescence, thereby allowing for increasingly precise magnitude representations (Halberda & Feigenson, 2008; Libertus & Brannon, 2010; Xu, Spelke, & Goddard, 2005).

Researchers hypothesize that the ANS to some extent underlies the development of arithmetic. There is some data supporting this hypothesis: for instance, individual differences in ANS acuity were found to correlate positively with numerical abilities (Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011) and future math achievements (Gilmore, McCarthy, & Spelke, 2010; Starr, Libertus, & Brannon, 2013). Impaired ANS acuity, on other hand, has been found in children with mathematical learning disabilities (Mazzocco, Feigenson, & Halberda, 2011; Piazza et al., 2010).

Functional imaging studies have also shown that the ANS system (which is believed, as noted above, to be located in the intraparietal sulcus) activates for both symbolic and nonsymbolic magnitude comparison operations (Sokolowski, Fias, Bosah Ononye, & Ansari, 2017; Piazza, Pinel, LeBihan, & Dehaene, 2007). These findings suggest that both symbolic and nonsymbolic magnitude processing utilize a general system—that is, the ANS. Accordingly, researchers have proposed that the ANS contributes to the emergence of numerical concepts children require for basic competence in counting and symbolic magnitude comparisons (Sokolowski et al., 2017).

Still, contradictory results have emerged. For example, several studies found that mathematics achievement was associated with symbolic comparison task performance, but not with nonsymbolic comparison (Holloway & Ansari, 2009; Kolkman, Kroesbergen, & Leseman, 2013). Others have suggested that the association between nonsymbolic magnitude comparison acuity and mathematics achievement is moderated by general domain factors such as EF, particular inhibitory control (Gilmore et al., 2013). For instance, Gilmore et al. (2013) reported that performance on a typical nonsymbolic comparison task (*e. g.*, dot comparison task) depends not only on the accuracy of participants' magnitude representations but also on their inhibition skills. In dot comparison tasks, participants are simultaneously shown two dot arrays and asked to select the array with the greater number of dots. Visuoperceptual cues, such as dot size, density, and total area of the stimuli may influence the magnitude perception. To control for the use of such cues, the visual characteristics of the arrays were manipulated in ways that are positively or negatively correlated with the number of dots. Through this method, they generate congruent (*i. e.*, higher magnitude arrays have larger dots and a larger area) and incongruent trials (*i. e.*, higher magnitude arrays have smaller dots and a smaller area); thus, on incongruent trials, participants must inhibit responses based on the visuoperceptual cues in order to make the correct choice. Gilmore et al. (2013) studied how participants' performance on congruent and incongruent dot comparison trials related to their arithmetic performance. They found a relationship between dot comparison scores and arithmetic performance only for incongruent trials. Moreover, when controlling for inhibition scores obtained from the NEPSY-II Inhibition subtest (Korkman, Kirk & Kemp, 2007), their performance on the dot comparison task was no longer a significant predictor of mathematics achievement.

There are comparatively fewer studies on ANS acuity in deaf and hard of hearing children. Furthermore, what findings exist are a mixed bag: for instance, Rodríguez-Santos et al. (2014) examined differences in performance on symbolic and nonsymbolic magnitude comparison tasks between deaf and normal hearing children. They found that deaf children tended to be slower in completing the symbolic task but performed at roughly the same level as the normal hearing group in nonsymbolic comparisons. These results led the authors to propose that deaf children tend to show a delay in accessing symbolic magnitude representations (Rodríguez-Santos et al., 2014). In contrast, another recent study, with a large sample of school-aged children, found significant differences in ANS acuity during nonsymbolic comparisons between deaf and normal hearing children (Bull et al., 2018). They further found that ANS acuity predicted mathematics achievement in deaf children even when controlling for the effect of other factors such as working memory and inhibition (Bull et al., 2018).

Overall, it remains unclear whether differences in symbolic and nonsymbolic magnitude comparison acuity exist in younger deaf children and to what extent they relate to EFs. The current study therefore examines the acuity of symbolic and nonsymbolic numerical representations in deaf preschool children, along with their ability to count and create sets, and investigated the possible influence of executive functioning on these basic mathematic abilities. The main hypothesis of the current study is that deaf preschool children score below their pears in early numerical skills tasks such as magnitude comparison and abstract counting.

Method

Participants

We collected data from 21 Portuguese children from the Lisbon area, seven of whom were congenitally deaf and 14 of whom had normal hearing; they were aged between 4 and 7 years old (M = 69.9 months, SD = 11.42). According to school reports (which contains information on children health status and clinical diagnosis), none of the children had any neurological, psychiatric, or neurodevelopmental disorder. The deaf children had profound hearing loss and wore hearing aids (none of which were implanted), and none had deaf parents (Table 1).

Table 1
Demographic characteristics of the deaf children group (n = 7)

Participant	Age (months)	Gender	Therapeutic follow-up (months)	Communication	Hearing aid device	Hearing loss (dB)
1	64	F	23	Sign language	Right ear	> 80
2	81	M	36	Sign spoken language	Bilateral	> 80
3	65	F	48	Sign language	Bilateral	> 80
4	86	M	60	Sign language	Bilateral	> 80
5	49	M	36	Sign language	Bilateral	> 80
6	78	M	72	Sign language	Bilateral	> 80
7	72	M	60	Sign language	Bilateral	> 80

All deaf children used Portuguese Sign Language as their first language (L1), which they had learned in preschool (starting at 2 years old) and through contact with the Deaf community. The family of the deaf children could communicate with them in sign language, which they had learned from deafness associations; this information was obtained by directly asking family members. Hearing children used Portuguese as their L1 and none of them knew Portuguese Sign Language. The groups were regarded as socially and culturally equivalent as the children all attended the same type of school (public) in the same area of Lisbon. This is a convenience sample. All the deaf students and half of the normal hearing students attended the same school. The other seven normal hearing students were selected based on their age, from a nearby similar school. Parents of all participants provided written informed consent for their child to take part on the study.

Tasks

Tasks were selected to measure the following: (a) EFs, (b) working memory, (c) language, and (d) early numerical skills. The instruments selected to evaluate these cognitive domains were selected based on the feasibility of adapting their verbal instructions into sign language. Because all these instruments had standardized test instructions, we had to select tasks that required minimal verbal instruction and relied on non-verbal responses (*i. e.*, pointing), in order to ensure similar assessment conditions for both groups of children. All instruments were administered in the L1 of each group of children: that is, Portuguese (for hearing children) and Portuguese Sign Language (for deaf children). For this reason, all the standardized instructions were translated into Portuguese Sign Language by a native signer.

Executive functions (EF)

The Shape School Task (Espy, 1997) was used to assess EF in preschoolers. This task utilizes a colorful storybook depicting figures of different colors and shapes attending a school. The test has four experimental conditions: A (control), B (inhibit), C (switch), and D (both). In condition A, the baseline naming control, children are asked to name the colors of 15 stimulus figures arranged in three lines of five figures. In condition B, which is used to examine whether the child has the ability to inhibit a response, eight of the stimulus figures have happy faces and seven have sad faces. Children are told that only the happy faces have finished their work and are ready to go out for lunch; subsequently, they are asked to name the color of the happy faced stimuli but not those of the unhappy faces. Condition C tests the ability to switch between two rules (color vs. shape). In this condition, six of the figures wear hats, and children are told that these figures are named for their shapes (rather than their colors), while the figures without hats are still named after their colors. Children are then asked to name each figure accordingly. Finally, in condition D, children must both suppress their responses and switch between rules when making their responses. In this condition, there are nine figures without hats (five have happy faces and four have sad faces) and six with hats (three happy and three sad). Children are asked to name only figures depicting a happy face (Espy, 1997; Espy et al., 2006). Performance efficiency is determined by dividing the number of correct answers by the time taken in each condition (Efficiency = # Correct/Total Time). The Portuguese version of this test (Rato, Ribeiro, & Castro-Caldas, 2018) was used and the instructions translated to Portuguese Sign Language.

Working memory

The Portuguese version of the Corsi Block-Tapping Task was used to evaluate visuospatial span. This task is a part of Coimbra's Neuropsychological Assessment Battery developed by Simões et al. (2017). The classic Corsi board was used; this is a wooden board containing nine blue blocks placed at fixed, pseudorandom locations (Corsi, 1972). Both the forward and backward conditions were used, much like the spatial span subtest of the Wechsler Memory Scale (Wechsler, 1997). After engaging in two practice trials with two blocks, children must repeat successively larger sequences of blocks. At each difficulty level, two different trials of the same number of blocks are presented. The task ends once the child fails to successfully repeat two trials of a given sequence. Participants are given a point for each correct sequence.

Language

The Portuguese Language Assessment Test for Children (TALC - *Teste de Avaliação da Linguagemna Criança*), designed by Sua-Kay and Tavares (2006) for children aged between two and six years old, was administered to both the deaf and normal hearing children. In this study, we only used the naming subtest, which assesses vocabulary. Participants are asked to study a set of pictures depicting either objects or actions, and to name those objects/actions accurately. One point is given for each correct answer, for a maximum total of 30 (12 points for objects and 18 points for actions).

Early numerical skills

Nonsymbolic tasks. We developed a dot comparison task to examine children's ability to instantly decide which of two dot arrays is larger. The task was developed using the Panamath software (www.panamath.org; Halberda & Feigenson, 2008). For this task, children sat in front of a laptop and viewed trials consisting of various arrays of yellow and blue dots, which flashed on the screen for 1000 milliseconds. In each trial, two dot arrays (yellow dots on the left array and blue dots on the right). The entire task comprised 32 trials and the arrays varied from 5–21 dots (the difference ratio ranged from 0.33 to 0.83). The dot size and total area of the array were controlled by the software (Halberda & Feigenson, 2008). Participants' accuracy and reaction time were automatically recorded via the Panamath software, which also estimates the ANS acuity using the Weber fraction. As the accuracy and Weber fraction are strongly correlated ($r = -.954$, $p < .005$), we opted to use only accuracy as a measure of nonsymbolic magnitude comparison ability because several of the children had accuracies near 50%; in those cases, Panamath does not calculate the Weber fraction.

In the abstract counting task, children must count as high as they can. Children were prompted to begin once ("Start with one..."), if necessary. We used only one trial, with participants' score being the last one in a correct sequence.

Two tasks—the "how many?" and "give me" tasks—based on Colomé and Noel's (2012) study were used to assess children's ability to produce number words in a cardinal context. In the "how many?" task, participants were presented with toy cars stopped at a traffic light. The child was asked, "How many cars are waiting in front of the traffic light?" After two practice trials (wherein one and two cars were presented), they were presented with each set of cars twice—once with the traffic light on the left side of a drawn road and once with the traffic light on the right side.

The "give me" task assessed children's ability to create sets of an appropriate number of cars. A small garage was placed in front of the examiner, who asked the children to put *x* cars into the garage (*e. g.*, "Put three [four, six, or seven] cars in my garage"). Participants were initially given a single practice trial: "Put two cars into my garage."

In both tasks, three, four, six, and seven cars were used for the test trials, each presented twice (for a total of eight test trials). One point was awarded to participants for each trial completed.

Symbolic tasks. The Numeracy Screener designed by Nosworthy, Bugden, Archibald, Evans, and Ansari (2013) was used to measure the children's ability to understand numerical magnitude (quantity). In this study, the symbolic part was used for senior kindergarten, which comprises 56 items. Each item comprises two Arabic numerals (ranging from 1 to 9) for comparison; each numeral was counterbalanced in terms of the side it was presented on (*e. g.*, 2/7, 7/2). For each item, children had to decide which number was larger. The total number of correct comparisons performed in two minutes was used in the analysis.

Procedure

We obtained written consent for participation in the study from the parents of all the children. The study was conducted in accordance with the school pedagogical council and has the approval of the Ethics Committee of the Institute of Health Sciences. All testing was conducted individually in a quiet room at the children's school between April and June 2017. Raven's Colored Progressive Matrices (CPM; Raven et al., 2009) was used to assess children's general nonverbal abstract reasoning ability; all the children reached satisfactory performance levels. The testing was carried out by a hearing researcher who was a native user of Portuguese Sign Language and had experience in working with deaf children. All instruments were administered in two sessions within one week of each other. The order of administration was quasi-randomized to avoid order effects; each session took approximately 25 min.

Data Analysis

The data analysis was conducted with SPSS Statistics 24 for Windows (IBM Corp., Armonk, NY). A preliminary analysis was conducted to determine if the data met the assumptions of homogeneity of variance and normality. When those assumptions were met, a *t*-test was used to compare the mean values. When data failed to meet these assumptions, we used the nonparametric Mann–Whitney U-test for the analysis. A chi-square test was employed for comparison of categorical variables. The significance level was set at .05.

Results

Table 2 shows the demographic and general cognitive data of the participants.

Table 2
Demographic and general cognitive data (N = 21)

	Deaf (n = 7) M (SD)	**Control (n = 14) M (SD)**	**Test statistic**		**p**
Age (months)	70.71 (12.54)	69.50 (11.29)	t	-.22	.825
Sex (F/M)	2/5	8/6	χ^2	1.52	.361
Therapeutic follow-up (months)	47.86 (17.20)	Na			
Raven CPM	22.14 (4.26)	20.06 (5.05)	*t*	11.02	.326
Naming - TALC	28.71 (1.25)	29.5 (.94)	*U*	30.5	.098

	Deaf (n = 7) M (SD)	Control (n = 14) M (SD)	Test statistic		p
Corsi forward	5.14 (3.38)	4.57 (1.89)	*t*	-.495	.626
Corsi backward	2.14 (1.67)	2.64 (.92)	*t*	.888	.385

Note: CPM: Colored Progressive Matrices; TALC: Portuguese Language Assessment Test for Children (*Teste de Avaliação da Linguagem na Criança*)

No significant differences were found between the two groups in terms of age, sex distribution, general nonverbal abstract reasoning abilities (*i. e.*, CPM score), or naming competence (TALC). We also observed no significant differences in visuospatial working memory (forward and backward versions of the Corsi Block Tapping task).

Table 3 shows the group means for all the assessment scores. Significant differences were found in abstract counting (U = 28.00, p = .01) and in symbolic (U = 7.00, p = .002) and nonsymbolic magnitude comparison ($t_{(21)}$= 2.63, p = .018). However, we found no differences in the "how many" and "give me" tasks (U = 42.5, p = .306 and U = 42, p = .156, respectively).

Because the differences in the efficiency found for the Shape School Tasks can be attributed to the time taken to provide answers in sign language in the deaf children group, we thought it preferable to compare only the number of correct answers. A significant difference was found in the number of correct answers only in condition D (inhibit and switch; $t_{(21)}$= 3.57, p = .002).

Table 3

Deaf (n = 7) and control (n = 14) participants' performance on assessment protocol

	Deaf (n = 7) M (SD)	Control (n = 14) M (SD)	Test statistic		p
Counting	7.14 (3.93)	9.59 (1.75)	*U*	28.00	.010
"How many?"	4.00 (.00)	3.78 (.57)	*U*	42.5	.306
"Give me"	4.00 (.00)	3.64 (.89)	*U*	42.0	.156
Magnitude comparison					
Nonsymbolic[a]	60.00 (27.52)	82.21 (16.65)	*t*	2.63	.018
Symbolic	13.14 (15.26)	44.00 (15.27)	*U*	7.00	.002
EF – Shape School					
(A) Control					
Number correct	14.57 (1.13)	15 (.00)	*t*	1.453	.163
Time (sec)	49.34 (28.84)	27.65 (9.48)	*t*	-2.60	.018
Efficiency score	.37 (.20)	.61 (.22)	*t*	2.08	.058
(B) Inhibit					
Number correct	13.71 (2.15)	14.50 (.51)	*t*	1.29	.213

	Deaf (n = 7) M (SD)	Control (n = 14) M (SD)	Test statistic		p
Time (sec)	47.31 (15.78)	24.35 (11.76)	*t*	-3.76	.001
Efficiency score	.33 (.16)	.69 (.24)	*t*	3.08	.006
(C) Switch					
Number correct	11.71 (3.59)	11.86 (5.18)	*t*	.065	.949
Time (sec)	49.94 (9.98)	31.58 (14.53)	*t*	-2.98	.008
Efficiency score	.23 (.05)	.40 (.24)	*t*	1.62	.028
(D) Inhibit/Switch					
Number correct	10.71 (3.54)	14.38 (.96)	*t*	3.57	.002
Time (sec)	45.80 (10.51)	30.70 (14.94)	*t*	-2.36	.030
Efficiency score	.23 (.07)	.58 (.94)	*t*	2.85	.001

[a] Percentage correct (Panamath).

Discussion

This study examined the basic numerical abilities of deaf children in a highly homogenous sample of preschool-aged deaf children. All these children were profoundly deaf and used sign language as their preferential way of communication. None had cochlear implants, and they all went to the same school as their hearing peers. The deaf and hearing groups displayed similar general intelligence, naming competence, and working memory.

Deaf children scored poorer than the control group on both the symbolic and nonsymbolic magnitude comparison tasks. The results of these tasks, which depend on the ANS, can be considered particularly important because several studies found that individual differences in ANS acuity are related to numerical abilities (Halberda et al., 2008; Libertus, Feigenson, & Halberda, 2011) and future math achievements (Gilmore, McCarthy, & Spelke, 2010; Starr et al., 2013). The findings for the nonsymbolic comparisons accord with those of a recently published study with a school-aged sample (5–12 years old) using a similar dot comparison task (Bull et al., 2018). Although our task contained fewer trials than did that used by Bull et al. (2018) study, the same pattern of results was observed. Contrary to these findings, Rodríguez-Santos et al. (2014) found differences between deaf and hearing participants only for the symbolic comparison task. This could be due to the stimulus arrangement of the nonsymbolic task used by Rodríguez-Santos et al. or to the older age of their sample. In their dot comparison task, the dot arrays were not controlled in terms of surface area, which could have allowed participants to use a perceptual strategy in comparing the collection. Additionally, the compared stimuli in Rodríguez-Santos et al.'s study were visible until the child made a response, whereas they were presented for a limited duration (1 000 ms) in this study; this could have made the task harder for both groups and particularly for the deaf group.

Differences were also found in the abstract counting task, but not in the set defining tasks (where children had to count toy cars in quantities up to ten). Similar findings were obtained in previous studies, where deaf children provided shorter sequences in abstract counting (Leybaert & Van Cutsem, 2002; Nunes &

Moreno, 1998) but not in creating sets of real objects of a given cardinality (Leybaert & Van Cutsem, 2002).

Past studies have posited that general domain abilities such as working memory and EF have major roles in mathematical development (Bull & Scerif, 2001; Cragg & Gilmore, 2014; Espy et al., 2004; Fias, Menon, & Szucs, 2013; Geary, 2011; Menon, 2016; Passolunghi & Siegel, 2001; Stelzer, Andrés, Introzzi, Canet-Juric, & Urquijo, 2019). However, there were no differences in visuospatial working memory between the deaf and control groups. Furthermore, a case has been made for the need for inhibitory control in nonsymbolic magnitude comparison tasks, particularly for incongruent trials were a smaller area corresponds to a larger collection (of smaller) dots (Gilmore et al., 2013). However, in this study, differences in magnitude comparison tasks in the deaf group cannot be attributed to lower levels of inhibitory control because we observed no significant differences between the groups in an inhibition task (condition B of the Shape School Task). In fact, differences in EF were only present in condition D of the Shape School Task, with the deaf group naming fewer correct stimuli. This condition demands a higher level of control because both switching and inhibition are necessary to complete the same task. However, a larger sample would be necessary to make any conclusions on the possible influence of inhibitory control on magnitude comparison in both groups of participants.

Some limitations should be noted before the conclusions. First, the deaf sample was very small and came from only one school, which raises concerns about the generalizability of these findings. Second, few of the instruments have been formally validated in deaf children of preschool age using sign language.

Based on the early deficits in the acuity of non-symbolic numerical representations with domain-general abilities weaknesses associated (Bull et al., 2018), or on the later difficulties to understand what exactly the mathematical word problem ask for (Grabauskienė & Zabulionytė, 2018), some training proposals are emerging to find ways to promote reading and math skills in children with hearing loss from an early age (Pimperton et al., 2019).

Conclusion

The findings indicate that both deaf and hearing children have a similar ability to count and to create sets, whereas abstract counting and ANS acuity are less developed in deaf children. These findings indicate possible long-term concerns related to math achievement among students with severe hearing loss and can be considered in order to establish future educational programs to develop and improve abstract thinking and abstract counting for deaf children. This study can be useful for deaf preschool education, especially concerning on how greater emphasis should be placed on the development of abstract counting and magnitude comparison. Nevertheless, further studies on how specific and general cognitive domains related to the development of early numerical abilities differ by deaf status are needed, in order to ensure successful schooling that allows for the true inclusion of these children.

References

Ansell, E., & Pagliaro, C. M. (2006). The relative difficulty of signed arithmetic story problems for primary level deaf and hard-of-hearing students. *Journal of Deaf Studies and Deaf Education, 11(2)*, 153–170. https://doi.org/10.1093/deafed/enj030

Bull, R. (2008). Deafness, numerical cognition, and mathematics. In M. Marschark & P. C. Hauser (Eds.), *Deaf Cognition: Foundations and Outcomes* (pp. 170–200). New York: Oxford University Press.

Bull, R., Espy, K. A., Wiebe, S. A., Sheffield, T. D., & Nelson, J. M. (2011). Using confirmatory factor analysis to understand executive control in preschool children: sources of variation in emergent mathematic achievement. *Developmental Science, 14*(4), 679–692. https://doi.org/10.1111/j.1467-7687.2010.01012.x

Bull, R., Marschark, M., & Blatto-Vallee, G. (2005). SNARC hunting: Examining number representation in deaf students. *Learning and Individual Differences, 15(3),* 223–236. https://doi.org/10.1016/j.lindif.2005.01.004

Bull, R., Marshark, M., Nordmann, E., Sapere, P., & Skene, W. A. (2018). The approximate number system and domain-general abilities as predictors of math ability in children with normal hearing and hearing loss. *British Journal of Developmental Psychology,* 36(2), 236–254. https://doi.org/10.1111/bjdp.12204

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: inhibition, switching, and working memory. *Developmental Neuropsychology, 19(3)*, 273–293. https://doi.org/10.1207/S15326942DN1903_3

Colomé, A., & Noël, M. (2012). One first? Acquisition of the cardinal and ordinal uses of numbers in pre-schoolers. *Journal of Experimental Child Psychology*, *113*, 233–247. https://doi.org/10.1016/j.jecp.2012.03.005

Corsi, P. M. (1972). *Human memory and the medial temporal region of the brain* (Unpublished doctoral dissertation). McGill University, Montreal, Canada.

Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in Neuroscience and Education, 3*(2)*,* 63–68. https://doi.org/10.1016/j.tine.2013.12.001

Dehaene, S. (1997). *The Number Sense*. New York: Oxford University Press.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750.

Epstein, K., Hillegeist, E. G., & Grafman, J. (1994). Number processing in deaf college students. *American Annals of the Deaf, 139(3*), 336–347. https://doi.org/10.1353/aad.2012.0321

Espy, K. A. (1997). The Shape School: Assessing executive function in preschool children. *Developmental Neuropsychology, 13*, 495–499. https://doi.org/10.1080/87565649709540690

Espy, K. A., Bull, R., Martin, J., & Stroup, W. (2006). Measuring the development of executive control with the shape school. *Psychological Assessment*, *18(4)*, 373–381. https://doi.org/10.1037/1040-3590.18.4.373

Espy, K. A., McDiarmid, M. M., Cwik, M. F., Stalets, M. M., Hamby, A., & Senn, T. E. (2004). The contribution of executive functions to emergent mathematic skills in preschool children. *Developmental Neuropsychology*, *26(1)*, 465–486. https://doi.org/10.1207/s15326942dn2601_6

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Science, 8(7)*, 307–314. https://doi.org/10.1016/j.tics.2004.05.002

Fias, W., Menon, V., & Szucs, D. (2013). Multiple components of developmental dyscalculia. *Trends in Neuroscience and Education, 2,* 43–47. https://doi.org/10.1016/j.tine.2013.06.006

Gallistel, C. R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition, 44(1-2)*, 43–74. https://doi.org/10.1016/0010-0277(92)90050-R

Geary, D.C. (2011). Cognitive predictors of achievement growth in mathematics: a five-year longitudinal study. *Developmental Psychology, 47*, 1539–1552. https://doi.org/10.1037/a0025510

Geraci, C., Gozzi, M., Papagno, C., & Cecchetto, C. (2008). How grammar can cope with limited short-term memory: Simultaneity and seriality in sign languages. *Cognition, 106,* 780–804. https://doi.org/10.1016/j.cognition.2007.04.014

Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, N. M., Marlow, N., . . . Inglis, M. (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlate with mathematics achievement. *PLoS ONE, 8*(6), e67374. https://doi.org/10.1371/journal.pone.0067374

Gilmore, C. K., McCarthy, S. E., & Spelke, E. S. (2010). Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. *Cognition*, 115, 394–406. https://doi.org/10.1016/j.cognition.2010.02.002

Goldin, A. P., Hermida, M. J., Shalom, D. E., Costa, M. E., Lopez-Rosenfeld, M., Segretin, M. S., Fernández-Slezak, D., Lipina, S. J., & Sigman, M. (2014). Far transfer to language and math of a short software-based gaming intervention. *PNAS Proceedings of the National Academy of Sciences of the United States of America, 111*(17), 6443–6448. https://doi.org/10.1073/pnas.1320217111

Gottardis, L., Nunes, T., & Lunt, I. (2011). A synthesis of research on deaf and hearing children's mathematical achievement. *Deafness and Education International*, *13*, 131–150. https://doi.org/10.1179/1557069X11Y.0000000006Grabauskienė, V., & Zabulionytė, A. (2018). The Employment of Verbal and Visual Information for 3rd Grade Deaf Students in Arithmetic Story Problem Solving. *Pedagogika*, 129(1), 171-186. https://doi.org/10.15823/p.2018.12.

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the Number Sense: The approximate number system in 3-, 4-, 5-, 6-year-olds and adults. *Developmental Psychology, 44*, 1457–1465. https://doi.org/10.1037/a0029472

Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*, *455*, 665–668. https://doi.org/10.1038/nature07246

Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology, 103(1)*, 17–29. https://doi.org/10.1016/j.jecp.2008.04.001.

Kolkman, M. E., Kroesbergen, E. H., & Leseman, P. P. (2013). Early numerical development and the role of non-symbolic and symbolic skills. *Learning and Instruction, 25,* 95–103. https://doi.org/10.1016/j.learninstruc.2012.12.001

Korkman, M., Kirk, U., & Kemp, S. (2007) NEPSY-II: A developmental neuropsychological assessment. San Antonio, TX: The Psychological Corporation.

Kritzer, K. L. (2009). Barely started and already left behind: A descriptive analysis of the mathematics ability demonstrated by young deaf children. *Journal of Deaf Studies and Deaf Education, 14*(4), 409–421. https://doi.org/10.1093/deafed/enp015

Leybaert, J., & Van Cutsem, M. (2002). Counting in sign language. *Journal of Experimental Child Psychology, 81*, 482–501. https://doi.org/10.1006/jecp.2002.2660

Libertus, M. E., & Brannon, E. M. (2010). Stable individual differences in number discrimination in infancy. *Developmental Science*, *13*, 900–906. https://doi.org/10.1111/j.1467-7687.2009.00948.x

Libertus, M. E., Feigenson, L., & Halberda, J. (2011). Preschool acuity of the approximate number system correlates with school math ability. *Developmental Science*, *14*, 1292–1300. https://doi.org/10.1111/j.1467-7687.2011.01080.x

Maller, S. J., & Braden, J. P. (2011). Intellectual assessment of deaf people: A critical review of core concepts and issues. In M. Marschark & P. E. Spencer (Eds.), *The Oxford Handbook of Deaf Studies, Language, and Education* (Vol. 1, 2nd ed., pp. 473–485). New York: Oxford University Press.

Marcelino, L., Sousa, C. & Costa, C. (2019). Cognitive foundations of Mathematics learning in deaf students: a systematic literature review. EDULEARN19 Proceedings. https://doi.org/10.21125/edulearn.2019.1425

Marschark, M., & Hauser, P. C. (Eds.). (2008). *Deaf Cognition: Foundations and Outcomes.* New York: Oxford University Press.

Marschark, M., Morrison, C., Lukomski, J., Borgna, G., & Convertino C. (2013). Are deaf students visual learners? *Learning and Individual Differences*, 25, 156–162. https://doi.org/10.1016/j.lindif.2013.02.006.

Mazzocco, M. M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the approximate number system underlies mathematical learning disability (dyscalculia). *Child Development*, *82*, 1224–1237. https://doi.org/10.1111/j.1467-8624.2011.01608.x.

Menon, V. (2016). Working memory in children's math learning and its disruption in dyscalculia. *Current Opinion in Behavioral Sciences, 10,* 125–132. https://doi.org/10.1016/j.cobeha.2016.05.014

Miyake, A., & Friedman, N. P. (2012). The Nature and Organization of Individual Differences in Executive Functions: Four General Conclusions. *Current Directions in Psychological Science*, *21*(1), 8–14. https://doi.org/10.1177/0963721411429458

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*, 49–100. https://doi.org/10.1006/cogp.1999.0734

Nguyen, T., Watts, T.W., Duncan, G.J., Clements, D.H., Sarama, J.S., Wolfe, C., & Spitler, M.E. (2016). Which preschool mathematics competencies are predictive of fifth grade achievement? *Early Childhood Research Quarterly*, 36, 550-560. https://doi.org/10.1016/j.ecresq.2016.02.003

Nosworthy, N., Bugden, S., Archibald, L., Evans, B., & Ansari, D. (2013). A two-minute paper-and-pencil test of symbolic and nonsymbolic numerical magnitude processing explains variability in primary school children's arithmetic Competence. *PLoS ONE, 8*(7), e67918. https://doi.org/10.1371/journal.pone.0067918

Nunes, T., & Moreno, C. (1998). Is hearing impairment a cause of difficulties in learning mathematics? In C. Donlan (Ed.), *The Development of Mathematical Skills: Studies in Developmental Psychology* (pp. 227–254). Hove, UK: Psychology Press Ltd.

Passolunghi, M. C., & Siegel, L. S. (2001). Short-term memory, working memory, and inhibitory control in children with difficulties in arithmetic problem solving. *Journal of Experimental Child Psychology*, *80(1)*, 44–57. https://doi.org/10.1093/deafed/ens070.

Piazza, M., Pinel, P., Le Bihan, D., & Dehaene, S. (2007). A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron*, *53*, 293–305. https://doi.org/10.1016/j.neuron.2006.11.022

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., Dehaene, S., & Zorzi, M. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition, 116(1)*, 33–41. https://doi.org/10.1016/j.cognition.2010.03.012

Pimperton, H., Kyle, F., Hulme, C., Harris, M., Beedie, I., Ralph-Lewis, A., Worster, E., Rees, R., Donlan, C., & MacSweeney, M. (2019). Computerized Speechreading Training for Deaf Children: A Randomized Controlled Trial. *Journal of Speech, Language, and Hearing Research*, 62, 2882–2894. https://doi.org/10.1044/2019_JSLHR-H-19-0073

Rato, J. R., Ribeiro, F., & Castro-Caldas, A. (2018). Executive functioning of Portuguese preschoolers in the Shape School test: A cross cultural study. *Applied Neuropsychology: Child, 7*(3), 200–207. https://doi.org/10.1080/21622965.2017.1287569.

Raven, J., Raven, J. C., & Court, J. H. (2009). *CPM-P. Coloured Progressive Matrices.* (ParallelForm). Lisbon, Portugal: CEGOC-TEA.

Rodríguez-Santos, J. M., Calleja, M., García-Orza, J., Iza, M., & Damas, J. (2014). Quantity processing in deaf and hard of hearing children: Evidence from symbolic and nonsymbolic comparison tasks. *American Annals of the Deaf, 159*(1), 34–44. https://doi.org/10.1353/aad.2014.0015

Simões, M., Albuquerque, C. P., Pinho, M. S., Vilar, M., Pereira, M., . . . Moura, O. (2017). *Bateria de avaliação neuropsicológica de Coimbra (BANC): Manual Técnico*. Lisboa: Hogrefe.

Sokolowski, H. M., Fias, W., Ononye, C., & Ansari, D. (2017). Are numbers grounded in a general magnitude processing system? A functional neuroimaging meta-analysis. *Neuropsychologia*, *105*, 50–69. https://doi.org/10.1016/j.

neuropsychologia.2017.01.019

Starr, A., Libertus, M. L., & Brannon, E. (2013). Number sense in infancy predicts mathematical abilities in childhood. *PNAS, 110*(45), 18116–18120. https://doi.org/10.1073/pnas.1302751110

Stelzer, F., Andrés, M.L., Introzzi, I., Canet-Juric, L., & Urquijo, S. (2019). El conocimiento de las fracciones. Una revisión de su relación con factores cognitivos. *Interdisciplinaria, 36*(2), 185-201. https://doi.org/10.16888/interd.2019.36.2.12

Sua-Kay, E., & Tavares, M. D. (2006). *TALC – Teste de Avaliação da Linguagem na Criança*. Lisboa: Oficina Didática.

Wechsler, D. (1997). *Wechsler Memory Scale-Third Edition: Manual (WMS-III).* San Antonio, TX: Psychological Corporation.

Xu, F., Spelke, E. S., & Goddard, S. (2005). Number sense in human infants. *Developmental Science, 8,* 88–101. https://doi.org/10.1111/j.1467-7687.2005.00395.x

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