QUANTITY PROCESSING IN DEAF AND HARD OF HEARING CHILDREN: EVIDENCE FROM SYMBOLIC AND NONSYMBOLIC COMPARISON TASKS

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ABSTRACT

Deaf children usually achieve lower scores on numerical tasks than normally hearing peers. Explanations for mathematical disabilities in hearing children are based on quantity representation deficits (Geary, 1994) or on deficits in accessing these representations (Rousselle &Noel, 2008). The present study is aimed to verify, by means of symbolic (Arabic digits) and nonsymbolic (dot constellations and hands) magnitude comparison tasks, whether deaf children show deficits in representations or in accessing numerical representations. The study participants were 10 prelocutive deaf children and 10 normally hearing children. Numerical distance and magnitude were manipulated. Response time (RT) analysis showed similar magnitude and distance effects in both groups on the 3 tasks. However, slower RTs were observed among the deaf participants on the symbolic task alone. These results suggest that although both groups' quantity representations were similar, the deaf group experienced a delay in accessing representations from symbolic codes.

FULL TEXT

Headnote

DEAF CHILDREN usually achieve lower scores on numerical tasks than normally hearing peers. Explanations for mathematical disabilities in hearing children are based on quantity representation deficits (Geary, 1994) or on deficits in accessing these representations (Rousselle &Noël, 2008). The present study aimed to verify, by means of symbolic (Arabic digits) and nonsymbolic (dot constellations and hands) magnitude comparison tasks, whether deaf children show deficits in representations or in accessing numerical representations. The study participants were 10 prelocutive deaf children and 10 normally hearing children. Numerical distance and magnitude were manipulated. Response time (RT) analysis showed similar magnitude and distance effects in both groups on the 3 tasks. However, slower RTs were observed among the deaf participants on the symbolic task alone. These results suggest that although both groups' quantity representations were similar, the deaf group experienced a delay in accessing representations from symbolic codes.
Keywords: deafness, numerical processing, magnitude processing, accessing hypothesis, nonsymbolic task performance

Between 1980 and 2010, several lines of research consistently provided evidence that deaf and hard of hearing children have a delay of 2.0 to 3.5 years compared to hearing children, as shown by mathematics achievement tests (Frosted, 1996; see Nunes, 2004 for a review). In 2000, using the Stanford Achievement Test, Traxler showed that deaf and hard of hearing children obtained worse scores than hearing children. In a study with a group of 10 profoundly deaf students, Zarfaty, Nunes, and Bryant (2004), referencing Traxler, found that the numerical skills growth curves of these children were flatter than those of hearing students. These results suggested that the deaf students had only partially mastered the knowledge and skills needed to do math correctly. Delays in mathematical performance appear and remain relatively constant when findings from standardized achievement tests are applied (Traxler, 2000). Kritzer (2009) reported mathematical difficulties among deaf and hard of hearing children even prior to formal schooling, at ages 4-6 years. Studies addressing spe- cific aspects of mathematical understanding have shown that deaf students experience a delay in acquiring the concepts of measurement and number and the concept of fractions (Titus, 1995). They also present problems in relation to arithmetic comparisons (Kelly, Lang, Mousley, &Davis, 2003) and the arithmetic concepts themselves (Ansell &Pagliaro, 2006). Along these lines, a study by Leybaert and Van Cutsem (2002) showed that deaf and hard of hearing children (ages 3-6 years) presented an agerelated delay of around 2 years in a counting task, whereas they showed age-appropriate skills in a different counting task (finger counting instead of abstract counting).

General explanations for low levels of mathematical achievement among deaf and hard of hearing individuals have focused on the low-level language they often use and their limited access to wide-ranging numerical experience (Bull et al., 2011; Gregory, 1998; Kritzer, 2009; Nunes, 2004). These studies suggest that during the school years, or even prior to formal schooling, deaf and hard of hearing children do not learn the fundamentals subsequently needed to achieve good performance in formal mathematical processing. In line with these explanations, Nunes (2004) suggested that deafness cannot be considered a primary cause of mathematical difficulties, but an accidental condition that simply results in poor performance on mathematical tasks. It is not assumed, therefore, that deaf individuals, as such, should present any specific difficulty in numerical processing; rather, it is assumed that they would present more, or fewer, difficulties due to circumstances secondary to deafness, as pointed out by Bull et al. (2011) and Gregory (1998). Thus, an indirect causal link, but not a direct causal connection, is assumed to exist between deafness and learning difficulties in mathematics (Swanwick, Oddy, &Romper, 2005).

Although these general accounts are plausible and are supported by published studies, more precise explanations could be given in terms of the specific skills gaps presented by normally hearing children who have difficulties with numerical processing. It is possible that problems with mathematics experienced by deaf and hard of hearing children-as a consequence of their low-level language and limited numerical experience-could be restricted to specific areas of mathematics. We would expect more difficulties with symbolic numerical processing (when Arabic numerals or word numerals were being used), as this relies more on linguistic skills, than with nonsymbolic numerical processing (dots, object collections, etc.). The aim of the present study was to investigate this possibility.

One of the most commonly accepted explanations of numerical processing deficits in children with normal hearing is the "defective number module hypothesis" (Butterworth, 1999, 2005b; Butterworth et al., 1999; Landed, Bevan, &Butterworth, 2004). This hypothesis assumes that difficulties in accessing the semantic information of numbers are due to a dysfunction in basic numerical cognition. This assumption is based on the view that humans are born with an innate ability to understand and manipulate quantities. According to Butterworth and colleagues (Butterworth, 1999,2005b; Butterworth et al., 1999; Landed, Bevan, &Butterworth, 2004), numerical processing deficits occur when the basic ability to process the numbers has not developed normally, a circumstance that leads to difficulties in understanding concepts and, consequently, in learning numerical information. This basic skill or "number sense" is represented by the Approximate Number System (ANS), which is universally shared by human beings and emerges without explicit instruction (see Feigenson, Dehaene, &Spelke, 2004, for a review). The ANS is responsible for activating magnitude representations whenever a person thinks about numbers, not only when using them in formal arithmetic operations but also in any daily activity involving magnitudes, such as selecting the queue at the supermarket with fewer individuals and deciding which queue is faster. Therefore, this system would be active not only for symbolic operations but also for nonsymbolic ones (Feigenson et al., 2004; Mazzocco, Feigenson, and Halberda, 2011).

However, Rousselle and Noël (2007, 2008) have modified this account, favoring the "access deficit hypothesis."

According to these authors, deficits in the representation of numerical information in long-term memory are not general, but are linked to the numerical representation codes used for its acquisition (Arabic numerals, number words). Based on this hypothesis, study participants' performance should be assessed by means of tasks with different formats. (It should be noted that previous research has focused on symbolic material.) Poor performance on an Arabic number comparison task, but not on a dot collection comparison task, could be explained by difficulties in accessing the semantic information of numbers by means of symbols. In contrast, if the deficit in numerical processing is general, difficulties with both symbolic and nonsymbolic comparison tasks should be observed, as predicted by the "number sense" thesis.

Few studies have investigated nonsymbolic numerical processing. Research using nonsymbolic tasks includes the work of Bull et al. (2011) and a study by Arfé et al. (2011) done with profoundly deaf preschool children. Bull et al. (2011) used a computerized magnitude estimation task in which the participants were given a number between 1 and 999 and had to estimate the position it occupied on a straight line. Deaf participants in their study obtained lower scores than normally hearing individuals. However, this study had two limitations relevant to our study aims: First, the participants were adults; second, the type of hearing aid used by participants was not reported. The only other information we have on magnitude comparison tasks comes from a previous study by Bull et al. (2010) in which the participants were children. The deaf children in the study showed significantly poorer acuity on the nonsymbolic approximation task compared to hearing children. In contrast, the study by Arfé et al. (2011), which focused on children with a cochlear implant, found that there were significant differences between these children and hearing controls on nonsymbolic tasks (dot collection comparison), whereas the results were similar on symbolic tasks (Arabic digit comparison).

Masataka (2006) conducted a pioneering study with profoundly deaf adults in the area of nonsymbolic tasks. Following arguments advanced by Barth et al. (2006), Masataka found that his study sample was able to perform simple arithmetic subtractions with nonsymbolic materials. He also noted that the scores of these profoundly deaf adults were even higher than those of the normally hearing individuals who formed the control group. However, despite their good performance on nonsymbolic tasks, the deaf adults underperformed relative to the control group on symbolic tasks. These results suggest that the decreased estimation ability of deaf adults only occurs when they have to access the semantic information of numbers using Arabic numerals, that is, through symbols, an outcome that would be consistent with the so-called access deficit hypothesis supported by Rousselle and Noël (2007). It should be noted that the Masataka study used a subtraction task, which involves greater complexity than commonly used tasks, and that the subjects were adults; thus, extrapolating the results to children is difficult.

We attempted to circumvent the limitations of previous studies by investigating whether deaf and hard of hearing children have difficulties with both symbolic and nonsymbolic comparison tasks, as reported by Bull et al. (2010) in their study with deaf children and in line with the findings of Masataka (2006) in his study with profoundly deaf adults. We also investigated the possibility that deaf and hard of hearing children do not show evidence of problems, as indicated by Arfé et al. (2011) in their study, which was also conducted with profoundly deaf children.

Knowledge of numerical magnitude is considered to be the basis of other higher-level processing skills, such as mathematical calculation (Butterworth, 2005b). This suggests a positive relationship between math performance and performance on tasks that involve basic numerical processing. Estimation and comparison of numerical magnitudes are the most commonly used tasks to explore numerical magnitude processing; in the present study, we focused on magnitude comparison tasks.

The representation and processing of numerical quantities by means of nonsymbolic materials has also been suggested as the basis for formal instruction in math skills; this would necessarily be supported by language (Barth et al., 2006). Understanding the role of nonsymbolic number processing is important because it helps to clarify whether the relationship between math skills and basic numerical magnitude processing is due to mere individual differences in the amodal mental representation of generic numerical information, an idea supported by authors such as Walsh (2003) or, on the contrary, whether these differences are due to the ability to access numerical magnitude information using abstract symbols, such as Arabic numerals (Holloway &Ansari, 2009; Rousselle &Noël, 2007).

Support for magnitude comparison tasks is provided by Bugden and Ansari (2011), who found that the mastering of magnitude comparison tasks is a good indicator of the degree of automaticity and predicts future performance on mathematical tasks. Thus, they consider that, unlike other tasks, such as comparing physical congruence, magnitude comparison tasks in which comparisons are made by means of ratios positively correlate with future performance in mathematics, and are better predictors. This is because these kinds of tasks demonstrate the degree of automaticity of numerical processing and show that skill in these tasks is deficient in children who have difficulties with number processing. Therefore, it is assumed that children who show a greater degree of automaticity in processing numerical magnitudes should obtain better results on standardized tests of mathematical performance, since the rapid activation of the semantic reference (numerical magnitude) of Arabic numerals is essential for calculation (Bugden &Ansari, 2011). It is thus assumed that basic numerical skills are prerequisites for future skills (Butterworth, 2005a, 2005b). The distance and size effects that arise in magnitude comparison tasks are considered an important indicator of how individuals internally represent magnitudes (Reynvoet, De Smedt, &Van den Bussche, 2009). The distance effect was originally demonstrated by Moyer and Landauer (1967); it suggests that the greater the difference-i.e., the distance between two numerical magnitudes-the easier the comparison, given that there is less overlap in memory between the compared magnitudes.

In the present study, we attempted to clarify whether the problems with numerical tasks commonly observed in deaf and hard of hearing children can be attributed to a general deficit in numerical processing or a specific deficit that is dependent on the modality of access to the semantic information of numbers stored in memory. More specifically, the study had two aims: first, by means of a low-magnitudes (1-9) comparison task, to verify whether deaf and hard of hearing children show specific difficulties in basic numerical processing; second, to verify whether deaf and hard of hearing children show differences in numerical processing according to the format used (symbolic vs. nonsymbolic), an outcome that would be in line with the explanations given in the field of mathematical processing difficulties in regard to children with normal hearing.

In the experiment we describe below, we evaluated the defective module number hypothesis and the access deficit hypothesis in deaf and hard of hearing children ages 8-9 years. These children and a normally hearing group of children (the control group) performed one symbolic comparison task (comparison of Arabic numerals) and two nonsymbolic comparison tasks (comparisons of dot collections and fingers). The finding of poorer performance by the deaf and hard of hearing children on both types of tasks relative to the control group would suggest a deficit in quantity representations, whereas the finding of differences in the symbolic task alone would indicate a specific problem with access through the symbolic code. Finally, the absence of differences in the distance effect on symbolic and nonsymbolic tasks would suggest that deaf and hard of hearing individuals are able to build internal quantity representations and access them at a level of quality similar to that shown by normally hearing people of a similar age and educational level.

Method

Participants

Experimental Group

The experimental group consisted of 10 Spanish-speaking children who had had hearing loss from birth. Seven were boys; the sample ranged in age from 8 years, 5 months to 9 years, 9 months (M = 8 years, 8 months; SD = 0.53). The children had moderate to severe hearing loss and had been trained in oral language by Cued Speech and the bimodal system in sessions after their normal classes. At the time of testing, they were also attending regular classes in a primary school, receiving inclusive schooling using oral education in the same educational center. All of the children in the experimental group received additional support from a teacher 2-4 hours a week. The background information on the participants' hearing and schooling is presented in Table 1. Subject files showed no other disabilities; none of the parents were deaf or hard of hearing; all of the children were being raised in (Spanish) monolingual families. The parents communicated with their children through oral language with additional support from signs.

Control Group

The control group consisted of 10 hearing, Spanish-speaking children with typical language development, without neurological or developmental difficulties, and without socioemotional behavior problems. These participants were selected from a group of 50 normally hearing children from state schools serving a middle-class population, much as were the deaf and hard of hearing participants. Each hearing participant was matched with a deaf or hard of hearing participant according to age and scores on different cognitive tests. Hence, there were no significant differences between the experimental group and the control group regarding age, nonverbal IQ, visual short-term memory, and language comprehension as assessed with the Spanish-language version of the Test of Nonverbal Intelligence-2 (Brown, Sherbenou, &Johnsen, 1995), the Visual Patterns Test (Della Sala, Gray, Baddeley, &Wilson, 1997), and the sentence comprehension test of the Spanish-language version of the Clinical Evaluation of Language Fundamentals-4 (Semel, Wiig, &Secord, 2006), respectively (see Table 2).

Materials

The Arabic number comparison task used 12 pairs of numbers, varying in two dimensions: number magnitude and distance. Each dimension had two levels: number size (small pairs 1-5, large pairs: 5-9), and the distance between numbers to be compared (1 vs. 3, 4). Twelve pairs were obtained (three pairs for each level: 1-2, 2-3, 3-4, 1-4,1-5, 2-5, 6-7, 7-8, 8-9, 5-8, 5-9,6-9). These pairs were taken from Rousselle and Noël (2007). In the dot comparison task, the same number pairs were used, but Arabic numbers were replaced with dots. Dots were not controlled for surface area (see, e.g., Piazza, Izard, Pinel, LeBihan, &Dehaene, 2004), to allow direct comparison with the finger comparison task. In the finger comparison task, the same stimuli were used, but pictures of hands were employed instead of Arabic numbers. Arabic numbers were presented in 20-point Courier font, and each pair of numbers to be compared were separated by 1 cm. The dots consisted of lxl-cm black squares, which were presented on a 8x8-cm white square; the white squares containing the dots to be compared were separated by 8 cm. Hands showing fingers were presented as line drawings, and numbers higher than 5 were indicated on two hands. Hands were shown on a 2x4-cm white rectangle. The rectangles containing the hands to be compared were separated by 8 cm. Figures 1-3 show examples of the stimuli.

Procedure

The three tasks were performed in a single session with the order of tasks balanced across participants. The Experimental Run Time System (Beringer, 1999) running MS-DOS was used to computer-control presentation of the stimuli and the recording of response times (RTs). The procedure was the same for the Arabic number comparison, dot comparison, and finger comparison tasks. During each trial, a fixation point (+) was presented for 500 ms. Next, the fixation point disappeared, and the two stimuli to be compared appeared simultaneously on the left and right side of the screen until the response was given.

RTs were measured from target onset to the moment the participant responded. In each task, the participants were requested to press the right or left key on the keyboard according to the side of the screen on which the stimulus was larger (Arabic number, dot, or number of fingers). The participants were instructed to make this decision as rapidly and as accurately as possible. In the three tasks, pairs were presented in ascend- ing order (e.g., 1-2) and descending order (e.g., 2-1). Each pair in each order was presented twice across two blocks, for a total of 48 stimuli per participant per task. Each participant received the tasks in different orders. Prior to the 48 experimental trials, the participants underwent a total of 8 practice trials under the same conditions as the experimental trials. The whole session comprising the three experimental tasks lasted approximately 15 minutes.

Results

Analyses of variance (ANOVAs) were conducted on RT and accuracy (proportion of errors), with task (dot, Arabic number, or hand comparison), size (small, large), and distance (close, far) as within-participants factors, and group (deaf and hard of hearing participants, hearing participants) as the between-participants factors. Partial eta-square Crip2) values were computed as a measure of effect size. Post hoc analyses were Bonferroni corrected as required. When the sphericity assumption was not satisfied, we adjusted the F tests using the Greenhouse-Geisser correction.

Response Time Analysis

Only RTs from correct responses were considered. Additionally, times outside the 300-1750 ms range were eliminated from the analysis. (They accounted for less than 3% of the data.) The exploratory analysis of RT by means of the Shapiro-Wilk test and visual inspection of Q-Q plots for each condition in each experimental group indicated that the data followed a normal distribution (allps >.17).

The ANOVA revealed a significant main effect of task, F(2,36) = 70.67, p <.001, Tip2 = .79. Main effects of distance,/^, 18) = 72.04, p <.001, Tip2 = .80, and size, F(l, 18) = 62.03,p <.001, tip2 = .77, were found. These main effects were qualified by firstorder interactions. Task interacted with size, P(2,3 6) = 11.98, p <.001, T)p2= .40, and marginally with distance, F(2, 36) = 3.12, p = .056, tip2 = .15. The analyses of these interactions showed that the size effect was larger in the finger comparison task (218 ms), followed by the Arabic number comparison task (104 ms) and in the collection comparison task (73 ms), all three size effects being statistically significant (allps <.01). In contrast, the distance effect was larger in the collection comparison task (143 ms), followed by the Arabic number comparison task (97 ms) and the finger comparison task (78 ms; all ps <.01).

Regarding the factor group, there were no statistically significant differences between groups, T(l, 18) = 0.9, p = .76, t^2 = .005. Of crucial interest, there was a statistically significant interaction between group and task, F(2, 36) = 3.65, p <.05, t^2 = .17, indicating that the deaf and hard of hearing children were significantly slower (99 ms) on the Arabic number comparison task than the hearing children (p <.05), whereas there were no differences between groups on the collection and finger comparison tasks (p >.22 in both tasks). It should be noted that the factor group did not interact significantly with any other variable (allps >.19; see Figures 4-6).

None of the other first-, second-, or third-order interactions reached statistical significance in the RT analyses (all ps >.2).

Accuracy Analysis

The exploratory analysis of errors by means of the Shapiro-Wilk test and visual inspection of Q-Q plots for each condition in the experimental and control groups indicated slight violations of normality in several conditions. However, the pattern of results of data analysis when the logarithmic transfor- mation was used did not differ from the pattern of results on untransformed data. Therefore, as recommended by Howell (2007), we report the analysis of untransformed data.

A repeated-measures ANOVA using the same factors as in the RT analysis was conducted on accuracy data. Statistically significant effects were found for size, P(l, 18) = 17.1,p <.01, t) 2 = .49, and distance,P(\, 18) = 11.97,p <.01, tip2 = .40. These effects were qualified by a significant interaction between size and distance, with distance effects for large pairs but not for small ones, F(l, 18) = 12.2, p <.01, iflp2 = .40. A marginally significant interaction between task and distance arose, P(2, 36) = 3.25, p = .05, tip2 = .15, with distance effects in collection and Arabic number comparison tasks (p <.01 in both tasks), but not in finger comparison tasks (p >.7).

It should be noted that although the deaf and hard of hearing participants were slightly more inaccurate than the hearing participants, the factor group was not significant, F(1, 18) = 3.1, p = .1, tip2 = -14, and did not interact with any variable (allps >.27).

In summary, analyses of RTs and accuracy showed the distance and magnitude effects usually found in these tasks. Of greater importance, a difference between groups was found in the RT analyses: Deaf and hard of hearing participants did the Arabic number comparison task more slowly than their hearing peers, whereas no differences were found on the nonsymbolic comparison tasks.

Discussion

The present study investigated the nature of (and access to) numerical representations by deaf and hard of hearing children. The participants were presented with two nonsymbolic comparison tasks (finger and dot comparison) and a symbolic comparison task (Arabic number comparison) that required the intentional processing of magnitudes from 1 to 9. The results are very clear: The deaf and hard of hearing experimental group showed size and distance effects similar to those of the hearing control group on the symbolic and nonsymbolic tasks. These results suggest that the deaf and hard of hearing children who took part in the study had no deficits in building abstract numerical representations from dots, fingers, or Arabic numerals. More important, they were significantly slower than the hearing participants at accessing quantity information from symbolic representations. This delay is consistent with the access deficit hypothesis proposed by Rousselle and Noël (2007) in the study of dyscalculia.

It is usual to find that deaf and hard of hearing children show a delay in acquiring mathematical skills (Ansell &Pagliaro, 2006; Kelly et al., 2003; Kritzer, 2009; Titus, 1995; Traxler, 2000). According to the literature, this delay starts early in life. For example, Kritzer (2009) found that preschool deaf and hard of hearing children from various backgrounds showed a delay in acquiring a broad range of mathematical skills, including the performance of tasks that mainly involved the use of symbolic representations (e.g., Arabic number comparisons, word/ story problems, counting by twos and higher multiples, reading and writing of numbers with two or three digits, and addition and subtraction number facts). However, some data seem to contradict these findings. In their study with profoundly deaf children, Zarfaty et al. (2004) found that deaf preschool children (8 of the 10 participants used a cochlear implant) experienced no difficulties in representing and discriminating among numbers. Moreover, in their study with children who had cochlear implants, Arfé et al. (2011) showed that these children performed as well as hearing children on numerical tasks that require symbolic processes (Arabic digit comparison) and on verbal counting; however, the researchers found that the deaf and hard of hearing children outperformed hearing children on numerical tasks that required visuospatial analysis (e.g. analogical comparison). Masataka (2006) found a similar advantage in nonsymbolic tasks among profoundly deaf adults, but whereas they showed a slightly superior performance on the nonsymbolic subtraction task, they had worse performance on the corresponding symbolic task. However, not all studies using symbolic and nonsymbolic stimuli with adult deaf participants have found that they experience such difficulties: Bull, Blatto-Vallee, and Fabich (2006), with a sample of profoundly deaf adults, and Iversen, Nuerk, and Willmes (2004)-but see Bull et al. (2011)-found no differences between deaf participants and hearing controls in subitizing and in number comparison tasks. Our results add to this complex picture, by emphasizing the relevance of paying attention to the symbolic versus nonsymbolic dimension and to the role played by difficulties in accessing number representation from symbolic codes. In this respect, our results are in line with those of Kritzer and Masataka, who also found difficulties in tasks involving the processing of Arabic numbers but not in tasks using nonsymbolic representations.

A key finding of the present study is the existence of similar distance and size effects between both groups for all the tasks. The participants in both groups responded more quickly to small numbers than to large numbers (size effect). Of greater importance to the present study, both groups participants were faster and more accurate at identifying the numerically larger number as the distance between the two numbers increased (the distance effect; see Moyer &Landauer, 1967). The distance effect is an important index of how people internally represent magnitude (for a review, see Cohen Kadosh &Walsh, 2009). In our case, the absence of differences between the two groups in the slopeslope indicating a relationship between distance and RTs-confirms that the deaf and hard of hearing participants' abstract numerical representation was as precise as that of their hearing peers. Following classical models of numerical semantic representation (e.g., Dehaene, 1997; Dehaene &Cohen, 1996), the deaf and hard of hearing participants represented numbers in the same way as the hearing participants, that is, along a horizontal mental number line with small numbers on the left and large numbers on the right of the continuum, irrespective of the code employed in accessing. The distance effect arises because it is more difficult to choose the larger of two numbers when both representations are close together due to the distributional overlap of their representational features.

Consequently, our data do not support the existence in the deaf and hard of hearing group of a deficit in numerical representation, which has been suggested as the explanation for dyscalculia by some authors (Geary, 1994; Walsh, 2003). In contrast, our data support the existence of an access deficit (see Rousselle &Noel, 2007). The deaf and hard of hearing participants showed a delay of about 100 ms in accessing numerical representations from symbols (but not from fingers or dots). Slower responses by these children might be explained by a less proficient coding of Arabic numbers. The deaf and hard of hearing participants would be slower in coding the identity of Arabic numbers, purportedly as a consequence of having less experience with this code. As we pointed out in the introduction to the present article, general explanations for the delay in mathematics shown by deaf and hard of hearing study participants emphasize their low-level language and their limited experience with numbers (Bull et al., 2011; Gregory, 1998; Kritzer, 2009; Nunes, 2004). Our data modify this view in two senses: (a) Given that our deaf and hard of hearing participants showed a good command of oral language, our data empirically support Kritzer (2009), who claimed that good exposure to language does not entail mastery of mathematical skills; exposure to math is needed; (b) as effects were found in the Arabic numeral comparison task alone, it seems that deaf and hard of hearing participants' limited experience impaired access to the numerical representations from symbolic codes, but not from nonsymbolic codes.

Our results may have important implications in relation to predicting the development of deaf and hard of hearing individuals' mathematical skills. Recent research has pointed to the predictive role of number comparison tasks in children's mathematical achievement scores (Budgen &Ansari, 2011; De Smedt, Verschaffel, &Ghesquière, 2009). Furthermore, the adequate use of abstract numerical representation appears to be the basis for high-level mathematical processing (Butterworth, 2005b). The fact that the deaf and hard of hearing participants showed a delay on symbolic comparison tasks appears to indicate an increased risk of difficulties in mathematical tasks that involve the use of Arabic numbers. When individuals are confronted with more complex numerical tasks (e.g., calculation and story problems), difficulties in accessing numerical representations from Arabic integers could have an impact on processing resources, leading to worse performance. Thus, regarding the difficulties described as being experienced by deaf and hard of hearing people when performing more complex tasks (comparison of larger quantities, arithmetic, etc.), our study suggests that their origin might be related to a subtle deficit in accessing otherwise well-preserved numerical representations from Arabic numbers.

The present study offers other aspects of interest. To the best of our knowledge, this is the first study to explore finger comparison in deaf and hard of hearing children. In a numerical Stroop task in which fingers were used as stimuli, Bull et al. (2006) found no differences between deaf and hearing adults; this suggested that direct mapping exists between finger representations and abstract numerical representations in both populations. Similar results were found in our study with children. Distance and size effects were found, whereas group effects and interactions involving this factor were not found. Although the deaf and hard of hearing participants, as occasional users of bimodal systems, could be more experienced with this kind of representation, they and the normally hearing participants were equally fast and accurate when comparing fingers. A possible explanation for the lack of differences could involve the role of fingers in number counting. Studies on the relationship between fingers and numerical representation have suggested that, even in hearing participants with typical development, finger numerical representations play a major role during numerical development. For instance, the specific structure of finger representations-in particular, their sub-base-five structure-seems to influence numerical representations and arithmetic in children (Fayol, Barrouillet, &Marinthe, 1998; Noël, 2005), and even in adults (see Domahs, Moeller, Huber, Willmes, &Nuerk, 2010). Although more studies are needed, our results suggest that deaf and hard of hearing children, much like hearing children, might be taking advantage of the use of fingers to build and access abstract numerical representations.

The extent to which our results can be generalized to deaf and hard of hearing children deserves comment. Our participants-who formed a homogeneous population-attended a regular school that included deaf students and had an academic level similar to that of their hearing peers. They used hearing devices and employed Cued Speech and a bimodal system occasionally in their daily interactions. Using experimental tasks, we found that these deaf and hard of hearing children differed from their hearing peers in their access to numerical representations from symbolic representations (Arabic numbers). The extent to which these results can be extrapolated to other deaf and hard of hearing children is difficult to establish due to the heterogeneity of the deaf and hard of hearing population. However, the finding of a delay even in deaf and hard of hearing children who receive clear support from parents and institutions suggests that educational programs should be designed to overcome the impact of deafness on their experience with (numerical) symbols.

Finally, the limitation of the present study should be kept in mind: We explored dot comparison using pairs of collections not controlled by the surface area occupied by the dots. This could have allowed our participants to use a perceptual strategy to solve the comparison task instead of a purely numerical one (see Mix, Huttenlocher, &Levine, 2002; Rousselle, Palmers, &Noël, 2004). However, participants did not differ on the basis of hearing status in the way they solved the task, as the (similar) pattern shown by both groups suggests. Although future studies should investigate the behavior of deaf and hard of hearing individuals in the comparison of dots controlled by perceptual variables versus noncontrolled ones, recent evidence suggests an advantage of deaf and hard of hearing children over hearing children when stimuli are controlled by perceptual variables (Arfé et al. 2011), thus supporting the hypothesis of normal access to quantity representations in deaf and hard of hearing people.

Conclusion

The aim of the present study was to investigate the nature of and access to numerical representations in children who are deaf or hard of hearing. Our results suggest the conclusion that these children have a deficit in accessing quantity representation from Arabic numbers. When performing nonsymbolic comparison tasks, deaf and hard of hearing participants in our study behaved like their hearing peers. The way in which this deficit affects more complex mathematical tasks remains to be studied.

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