The Performance of Young Deaf Children in Spatial and Temporal Number Tasks

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Deaf children tend to fall behind in mathematics at school. This problem may be a direct result of particular experiences in the classroom; for example, deaf children may find it hard to follow teachers' presentations of basic, but nevertheless quite abstract, mathematical ideas. Another possibility is that the problem starts before school: They may either be worse than hearing children at early, nonlinguistic number representations, they may be behind in learning the culturally transmitted number string, or both. This may result in deaf children failing to develop informal problem-solving strategies, which prepare most children for the more formal learning of number and arithmetic that they will have to do at school. We compared 3- and 4-year-old deaf and hearing children's ability to remember and to reproduce the number of items in a set of objects. In one condition, we presented all the items together in a spatial array; in another, we presented them one at a time in a temporal sequence. Deaf children performed as well as the hearing children in the temporal tasks, but outperformed their hearing counterparts in the spatial task. These results suggest that preschool deaf children's number representation is at least as advanced as that of hearing children, and that they are actually better than hearing children at representing the number of objects in spatial arrays. We conclude that deaf children's difficulties with mathematical learning are not a consequence of a delay in number representation. We also conclude that deaf children should benefit from mathematical instruction that emphasizes spatial representation.

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Introduction

There is a great deal of evidence that children begin to grasp mathematical concepts long before they go to school. For example, preschool children can discriminate different sets of objects on the basis of their number and can reproduce a set of objects with the same number as the one that they have just been shown (Mix, Huttenlocher, & Levine, 2002; Saxe, Guberman, & Gearhart, 1987). It is also clear that the understanding of number that children acquire through informal learning before they go to school plays an essential role in their learning about mathematics when they begin to receive formal instruction about mathematics at school (Mix et al., 2002; Nunes and Bryant, 1996).

However, very little indeed is known about preschool mathematical understanding in deaf children. There is evidence about deaf children's progress in mathematics at school, and most of this suggests that mathematics does not come easily to the deaf schoolchild. This raises questions about the preschool period. Can the origins of deaf children's mathematical difficulties be traced to the preschool period? Is their grasp of number already less advanced than that of hearing children even before they go to school? There are no empirical answers to these basic questions.

The evidence about lower levels of mathematical success in deaf pupils in comparison with hearing pupils comes from studies across different countries, age levels, and cohorts. For example, in a mathematics

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attainment test, Wollman (1965) tested approximately one third of the pupils from 13 schools for the deaf in the United Kingdom and a comparison group of 162 pupils in secondary schools. The deaf pupils had an average score that was 1 standard deviation below the hearing pupils' average. Hine (1970) examined the performance in mathematics of deaf pupils aged 7 to 16 years and found a significant delay in the deaf pupils' mathematics age: The 10-year-olds had an arithmetic age of 8 years, and the 15-year-olds had an arithmetic age of 10 years.

Some time later, Wood, Wood, Kingsmill, French, and Howarth (1984) found a delay of about 3.5 years in the mathematical competence of deaf school-leavers who were 16 to 17 years of age. More recently, Nunes and Moreno (1998) reported that deaf pupils in England in the age range 8 to 12 years had a mean standardized score in mathematics achievement that was more than 2 standard deviations below the mean. Similar discouraging results have been observed in Sweden by Heiling (1995) and in Norway by Frostad (1996).

The recent norming of the Stanford Achievement Test (9th edition) for deaf and hard-of-hearing students carried out in the United States (Traxler, 2000) confirms this lag again. To avoid giving students assessments that were too difficult and thus would prove frustrating, the ninth edition of the Stanford Achievement Test was not administered at the grade-appropriate level to all the participants; students were given assessments that were judged appropriate on the basis of an initial screening. Well over half of the students aged 9 years or older and as many as 90% of the 15-year-olds were given tests that were appropriate for hearing pupils at grades lower than their own. This by itself suggests an educational delay. The two mathematics tests administered, Problem Solving and Procedures, showed results that were similar in one way: The growth curves for the deaf and hard-of-hearing students were much flatter than those for hearing students. In Problem Solving, the national median for 11-year-olds was equivalent to the performance of hearing children in their third year of school (aged about 8 years) and reached the equivalent of Grade 5 by the time the students were 16 to 18 years old. In Procedures, the national mean for 11-year-olds was between Grades 3 and 4 and almost reached the equivalent of Grade 6 by the time the children were 17 and 18 years old. These levels are considered below basic. Students in the 80th percentile were at the same below-basic level in Procedures by age 14 years, but were at the next level, basic, in Problem Solving at this age.

Finally, studies that focus on specific concepts, carried out in the United States, have documented significant delays in deaf students' mathematical conceptual development in comparison with hearing students. Austin (1975) found a delay in measurement and number concepts. Titus (1995) observed a delay in the development of fraction concepts, and Kelly, Lang, Mousley, and Davis (2003) reported a similar delay in college students' ability to solve arithmetic compare problems. These studies illustrate the generality as well as the seriousness of deaf schoolchildren's mathematical difficulties because they show deaf children at a disadvantage in a wide variety of mathematical tasks, but they do not pinpoint the reason for these difficulties.

A good way to start the search for the causes of deaf children's mathematical problems is to establish when deaf children first begin to fall behind. If the time in their lives when deaf children begin to do worse than hearing children at mathematics is known, we would be in a far better position to understand what causes these difficulties. Broadly speaking, there are two possible periods when this disadvantage might appear. The first is the preschool period, a time when children's mathematical learning is entirely informal. The second possibility is that deaf children's specific difficulties in mathematics only begin in school when they need to learn and use culturally transmitted numerical representations, such as a counting string and written numbers.

The case for the first possibility, that differences between deaf and hearing children have their origin in the preschool period, is quite plausible. There is no doubt that much informal mathematical learning takes place outside school (Nunes, Schliemann, & Carraher, 1993) and before children go to school (Bryant, 1994). There is growing consensus among researchers (see Ginsburg, Klein, & Starkey, 1998) that this informal knowledge is grounded in children's problem-solving experiences with concrete objects (Hughes, 1981, 1986; Langer, 1986). It is currently hypothesized that ‘‘the basic components of informal mathematical knowledge are universal’’ and ‘‘that children’s developing informal knowledge of mathematics is a necessary foundation for formal mathematical knowledge’’ (Ginsburg et al., 1998, p. 413).

It might be expected that deaf children are disadvantaged if these informal experiences involve spoken language, but some informal mathematical experiences may be entirely nonverbal. Infants and toddlers, who have not yet learned to count, can accurately recognize arrays of one to three objects (Starkey & Cooper, 1995). This range expands during the preschool years to four or five objects when children are aged 4 and 5 years (Gelman & Gallistel, 1978; Starkey & Cooper, 1995).

Later, this informal knowledge becomes progressively more coordinated with culturally transmitted knowledge when children learn number words and start using them to indicate set sizes (Saxe et al., 1987). Through a combination of children’s logic and the appropriate use of number words, children develop informal addition and subtraction strategies in their first 2 years of school (Carpenter & Moser, 1982; Groen & Resnick, 1977), which support their school learning of number and arithmetic operations.

If deaf children were found to lag behind hearing children in the development of the informal addition and subtraction strategies, this could be because they have difficulty with the early nonlinguistic representations of number, with their knowledge of counting, or with both.

There is some evidence that deaf children are behind in their knowledge of counting. Nunes and Moreno (1998) studied the counting skills of 82 deaf children in the age range 8 to 11 years who were being educated orally or in British Sign Language in eight schools in London. They found that the majority of the deaf children in their second and third years in primary school were still not able to count to 60. This compares poorly to hearing children’s knowledge of the counting string: The majority can count to 60 by the end of their first year in school. Secada (1984) and Leybaert and Van Cutsem (2002) studied deaf and hearing children’s counting in the United States and Belgium. The deaf children in their studies were all educated in sign. The participants in Secada’s study were in primary school, and those in Leybaert and van Cutsem’s study were in kindergarten or in their first 2 years at school. Both studies showed that the deaf children were significantly worse than hearing children in knowledge of the counting string. Whether this delay in learning to count is a result of lack of experience or a result of the serial recall nature of the task (serial recall tasks that place heavy demands on memory are more difficult for deaf than for hearing children; see Marschark, 1993), the implication is that deaf children should be at risk for a delay in developing informal addition and subtraction strategies in preschool and the early years in school.

These are interesting results, but they do not indicate whether preschool deaf children’s nonlinguistic representation of number is in any way inferior to that of hearing children. Research with younger children using tasks that assess their early representations of number and that do not involve counting is required to clarify the status of their early ability to represent number.

Number representation tasks used with preschoolers can rely on either spatial or temporal presentation of the numerical information. Although much research on children’s early numerical representation used only spatial displays (e.g., Starkey & Cooper, 1995), because it was assumed that these early representations are visually encoded (Butterworth, 1999), other researchers have also analyzed how young children deal with temporal numerical information. The importance of considering both spatial and temporal numerical information to understand children’s number knowledge was already recognized by Piaget in his conservation studies. Some of Piaget’s (1952) conservation tasks involved showing children spatial displays in which the items in two arrays were initially in visual correspondence, and then this correspondence was disrupted. Other tasks involved temporal correspondence. In the latter, marbles were placed in temporal correspondence into containers of different diameters, with different levels reached by the marbles in the two containers.

Many of the experiences and routines that characterize preschool mathematical learning, such as counting and sharing, are sequential. For instance, sharing is the first systematic experience that most children have with one-to-one correspondence (Frydman & Bryant, 1988). Children usually share in a sequential—one for you, one for me—manner (Desforges & Desforges, 1980; Frydman & Bryant, 1988; Squire & Bryant, 2002). So, when testing deaf children's early numerical representations, it is important to analyze their abilities under both spatial and temporal testing conditions.

It is quite possible that deaf children perform significantly better on spatial than on temporal number tasks. There is evidence that, in other spheres of behavior, deaf children deal more effectively with information when it is presented spatially than when it comes in temporal sequences. Hermelin and O'Connor (Hermelin & O'Connor, 1975; O'Connor & Hermelin, 1972, 1973) identified qualitative differences in the coding strategies of deaf and hearing children in short-term memory tasks; they showed that deaf children prefer to encode information spatially, whereas hearing children prefer to encode it temporally.

Todman and Seedhouse (1994) extended this finding when they reported that deaf children actually did better than hearing children in spatial memory tasks, although their scores were worse than those of hearing children in temporal, serial memory tasks (i.e., tasks in which recall had to reproduce the order of presentation).

If preschool deaf children were found to be as good as hearing children at representing number in spatial tasks but worse than hearing children at representing number in temporal tasks, this difference would have consequences for the development of their mathematical knowledge. Deaf children might be slow to understand the mathematical significance of sharing, for example, because of its sequential nature. It is thus important to find out about young deaf children's ability to represent numerical information presented to them spatially and temporally.

Finally, it is not possible to discard the hypothesis that deaf children's mathematical problems only start after they go to school. It is possible that teachers concentrate too greatly on helping deaf children understand the verbal aspects of word problems, for example, and spend too little time on encouraging them to learn problem-solving strategies, as Kelly, Lang, and Pagliaro (2003) have claimed. We should certainly take quite seriously any explanation that is couched in terms of the children's opportunities to benefit from formal teaching because there is some evidence that, in general, deaf students' progress in mathematics is heavily influenced by the quality of mathematical teaching that they receive (Allen, 1990; Nunes, 2004; Nunes & Moreno, 1997, 2002; Pagliaro, 1998).

There are pressing educational and theoretical reasons why we need to know which of these perfectly plausible origins of the deaf children's mathematical disadvantage is the right one, or whether they are all tenable. Yet, the relevant research is so far missing.

The aim of our study was to begin to provide an answer to this question by investigating young deaf children's ability to represent number. We focused on early number representation because this is the basis of their subsequent learning of arithmetic (Gelman & Gallistel, 1978; Nunes & Bryant, 1996). Children cannot learn to carry out addition, subtraction, multiplication, or division unless they can distinguish and represent numbers.

The study had two primary aims. The first was to determine how well preschool deaf children remember and reproduce number. This information should tell whether, when deaf children first go to school, they are likely to be at a disadvantage with this ability, which is fundamental to the understanding of arithmetic. The second aim was to find out whether any such difficulty is affected by the form of presentation of the numerical information; to this end, we compared spatial with temporal, sequential presentations of the sets of objects for which the children had to remember the number. We expected that any difficulties on the part of the deaf children would be seen in the sequential tasks only.

In addition, we decided to compare the children's performance in two different contexts as a check that any pattern results that we found were not specific to one context only. The comparison was between a context in which the items were set out by a filmed puppet (the films were presented on a laptop computer) and another more abstract context in which the objects simply appeared impersonally on the computer screen. The inclusion of the more abstract mode of presentation made it possible for us to demonstrate that the children were not just imitating another person's actions when reproducing numbers in our tasks because no imitation was possible with the abstract form of presentation. The use of spatial displays also ruled out the possibility that correct reproductions were simply the result of imitation because, in the spatial condition, the actions on the film were precisely the same across the different numbers.

Method

Participants

Twenty children aged between 31 and 54 months (2.5 to 4.5 years, $\bar{x} = 39.75$ months) took part in the study. Of the children, 10 were deaf ($\bar{x} = 40.2$ months, *SD* 6.73 months), and 10 were hearing children ($\bar{x} = 39.3$ months, *SD* 5.14 months). Four of the deaf children were girls, and 6 were boys. There were also 4 girls and 6 boys in the hearing group. In the deaf group, 9 of the children were profoundly deaf, and 1 was moderately deaf. Eight of the profoundly deaf children had cochlear implants.

At least twice a week, the deaf children attended a specialist nursery school, which combined both teaching and therapeutic intervention. The announced aim of this nursery was "to develop attention and listening skills and to encourage the child to maximize auditory potential, through use of residual hearing or following a cochlear implant." Thus, the school concentrated on spoken language, and the nursery also offered advice and support to parents on how to develop communication through spoken language. On the remaining days of the week, most of the deaf children attended local mainstream nurseries. The hearing children attended a local nursery five times a week.

Apart from this explicit attempt to encourage spoken language in the specialist nursery school for deaf children, the two nursery schools in this study followed a very similar educational approach. Both nursery schools encouraged play activities, and the teachers in both schools regarded informal experience as the most fruitful source of learning for children of nursery school age. The teachers in the two schools considered young children's early experiences with number and number words as an important precursor to their mathematical understanding, but these nursery schools did not give any direct and explicit formal instruction about number or any other aspect of mathematics.

Design

To design a task that required informal mathematical knowledge and was suited for both deaf and hearing children in the age range 3 to 4 years, we used a paradigm initially developed by Piaget (1952) and employed more systematically by Saxe et al. (1987). In this task, children are shown a set of objects that is then removed. The children then have to construct a set identical to the one they have just seen. This task requires representation of number. Because the set is no longer perceptually present, the children need to represent its number in some way to reproduce it later.

In this study, each child was given 24 trials of a "bricks-copying task" in one session. In each of the trials, the children were shown a small number of bricks (2, 3, or 4) on a laptop computer screen. The colors of the bricks varied from set to set, but within a set, the bricks were all the same color, so they were all red bricks, all green bricks, or the like. The number and color of the bricks varied independently, so that, for example, in one trial a child would see a set of two red bricks and in a later trial a set of two yellow bricks. Thus, the children could copy the set that they had seen on the basis of the number of bricks in the set, of the color of the bricks in each set, or of both.

As soon as the presentation of the set had finished and the laptop screen was clear, the children were asked to reproduce the set that they had just seen, using the bricks available to them, and to place them in a box on the table in front of them. To do this, the child was provided with 16 colored bricks 4 cm × 4 cm × 2 cm, with 4 bricks of each of four colors (red, yellow, blue, and green), and with an empty box (20 cm × 17.5 cm × 7.5 cm).

The presentation of the sets of items varied in two ways:

Conditions. There were two different conditions, spatial and temporal. In the spatial condition, all the items in the set shown to the child were presented together in one horizontally arranged spatial display on the laptop screen, and then all disappeared together. In the temporal condition, we presented each item on its own in a sequence: Each item appeared on the screen and disappeared before the next item was presented. These two conditions were given in separate blocks of 12 trials, with an interval between them. One block of 12 trials was devoted to each condition. We gave half the children in each group the spatial block first and the temporal block second. The other half of the children received the blocks in the opposite order.

Presentation Modes. There were also two different presentation modes, and six trials in each block were devoted to each of these two forms of presentation. (1) In the puppet-plus-bricks presentation mode, we showed each child a film on the laptop computer of a puppet which first displayed some bricks in her hands and then placed them in a box: this was the same box as was used by the children themselves. (The puppet in these films was actually a person dressed as a puppet.) In this presentation mode, the puppet did exactly what the children were asked to do, and thus the children were in effect asked to copy the puppet. In the six spatial puppets-plus-bricks trials, the puppet showed all the bricks simultaneously in her open hands and then put them all in the box at the same time. In the six temporal puppets-plus-bricks trials, she presented the bricks successively, displaying each brick in her open hands first and then placing each one in the box. (2) In the bricks-only presentation mode, pictures of bricks simply appeared (in an animated PowerPoint presentation) on the laptop screen and then disappeared. In the six spatial bricks-only trials, the pictures of bricks all appeared in a horizontal line and then disappeared together. In the six temporal bricks-only trials, each pictured brick appeared and then disappeared before the next brick was presented.

We did not counterbalance the order of the presentation modes. In each block of trials, we always began with the six puppet-plus-bricks trials and then continued with the six bricks-only trials. We kept this order constant because we were concerned that the children might be put off if a block of trials began with the more abstract, and therefore possibly more difficult, bricks-only presentations.

There were two, three, or four items presented in each trial, and in every set of 6 trials, each of these numbers was presented twice. We varied the color of the items from trial to trial. Each mode of presentation contained 6 trials. The sequence of numbers across trials in each set of trials was randomized for each child. However, the color change occurred only every 3 trials (across the whole condition block). Thus, an example of a 12-trial block would be 2 red, 4 red, 3 red, 3 blue, 2 blue, 4 blue (puppet-plus-bricks presentation); 3 yellow, 2 yellow, 4 yellow, 4 green, 2 green, 3 green (bricks-only presentation).

There was no possibility in either condition that the children were simply reproducing the correct number on the basis of cues about spatial position. In the temporal condition, the children saw each item in the same position; thus, there were no spatial cues. In the spatial condition, the positions on the screen in the bricks-only task bore no relation to the spatial layout of the box in which the children had to place the bricks. Thus, in both conditions, correct reproduction of number had to be based on number itself and not lower-level cues like position.

Procedure

Each child was seen individually. Two experimenters attended each session. One of them gave the children the necessary instructions; the other filmed the session. One of the experimenters explained to the children that they should try to copy what they saw on the screen by placing the equivalent set of bricks in the box. The experimenter repeated these instructions before each mode of presentation within both blocks (i.e., every six trials).

The instructions were given in very short and simple phrases (e.g., "copy puppet" or "look and copy") with appropriate manual gestures to allow uniform understanding by both hearing and deaf groups.

The children were given positive feedback after each trial, no matter what their response, to encourage them, but not to bias their own understanding of the task. There was no restriction on the length of time that the children were given to respond.

Throughout the procedure, the children were videotaped so that their responses could be coded at a later date. We recorded (1) the number of bricks placed in the box in each trial, (2) the color of the bricks placed in the box in each trial, and (3) the length of time in each trial between the beginning of the presentation and the child placing the last brick in the box. We also recorded the number of times that we observed each child counting. However, because there were many instances when we were not sure whether the children had counted, we do not report the results of this measure.

Table 1 Mean number of accurate number representations by the deaf and hearing children

	Spatial-first order group		Temporal-first order group	
Group	Spatial condition	Temporal condition	Spatial condition	Temporal condition
Hearing ($N = 20$)				
Mean	7.20	7.20	6.20	2.00
SD	4.55	4.15	2.59	2.12
Deaf ($N = 10$)				
Mean	8.80	7.60	10.80	3.00
SD	2.28	2.07	1.09	1.01

Note. Maximum correct score is 12.

Results

Accurate Representation of Number

Our first concern was with the number of trials in which the children in the two groups correctly created a set of the same number as the one that they had just been shown.

Preliminary analyses established that neither the number of items in the set nor the presentation mode (puppet versus bricks only) had any significant effect on the correct representation of number. Therefore, we carried out a three-way analysis of variance of correct number representation. The independent variables were groups (deaf and hearing children), order (spatial condition first, temporal condition first), condition (spatial and temporal), with repeated measures on the last variable. This analysis established that condition had a significant effect on levels of accuracy, $F(1, 16) = 59.67$, $p < .001$: The spatial condition was significantly easier than the temporal condition. The other two main terms (groups and order) were not significant.

The analysis also produced a significant Groups × Condition interaction, $F(1, 16) = 7.89$, $p < .025$. The mean scores in Table 1 suggest that the best explanation for this interaction is that there was a difference between the two groups in the spatial, but not in the temporal, condition. The table shows that the deaf children did better than the hearing children in the spatial condition. The two groups produced similar scores in the temporal condition. Post hoc Tukey's HSD (honestly significant difference) tests confirmed a significant difference between the two groups in the spatial condition ($p < .05$), but no significant difference in the temporal condition.

Although the main term of order was not significant, there was a highly significant Order × Condition interaction, $F(1, 16) = 39.95$, $p < .001$. This was because there was a difference between the two order groups in the temporal condition (Tukey's HSD, $p < .01$), but not in the spatial condition. Table 1 shows that the scores in the more difficult temporal condition were much lower for the children who were given this condition first than for the children who were given it as the second condition after having been through the spatial condition. In contrast, the scores in the easier spatial condition were not very different for these two groups.

Time Taken to Respond

We also wanted to see whether differences in the accuracy of the two groups might be reflected in the speed with which they responded. Preliminary analyses showed no significant effects of order, so we carried out a three-way analysis of variance of response times. The independent variables were groups, condition, and presentation mode, with repeated measures on the last two variables. This showed that the children took longer to complete their response in the temporal than in the spatial trials [$F(1, 18) = 8.57$, $p < .01$], and that they were also slower in the puppet-plus-bricks than in the bricks-only presentation, $F(1, 18) = 6.95$, $p < .05$). Group membership had no effect in this analysis as a main term or in any interaction. Thus, the differences that we found between the two groups in the pattern of their accuracy in the two conditions were not in any

Table 2 Mean response times (in seconds) in the deaf and hearing children

Group	Spatial: Puppet + bricks	Spatial: Bricks only	Temporal: Puppet + bricks	Temporal: Bricks only
Hearing ($N = 10$)				
Mean	13.21	11.29	26.96	17.77
SD	5.67	5.49	17.07	12.51
Deaf ($N = 10$)				
Mean	13.33	7.75	19.94	16.88
SD	4.62	2.24	6.48	5.60

Table 3 Mean number of trials in which the deaf and hearing children used the right color bricks

Group	Spatial: Puppet + bricks	Spatial: Bricks only	Temporal: Puppet + bricks	Temporal: Bricks only
Hearing ($N = 10$)				
Mean	2.600	2.600	3.100	1.500
SD	2.547	2.319	2.331	2.014
Deaf ($N = 10$)				
Mean	4.600	3.200	2.800	2.400
SD	1.838	1.932	2.616	2.271

Note. Maximum correct score 6.

way a function of the time that they took to solve these problems.

Table 2 shows the mean response times (in seconds) in the spatial and temporal conditions. The table shows that the deaf children were slightly faster than the hearing children in both conditions, but that this difference was always small. It is unlikely, therefore, that differences in speed could be used as an explanation for the different pattern of number of correct responses in the two conditions.

Table 2 also shows that both groups took considerably longer to complete the set in the temporal than in the spatial condition. This was undoubtedly because in the temporal condition the children in both groups tended to pick up one item at a time and put it in the box before picking up the next item. This procedure generally took longer than the procedure more commonly adopted in the spatial trials, which was to assemble all the items first and then put them in the box together. From this table, it can also be seen that responses took longer for the puppet-plus-bricks mode of presentation than for the bricks-only presentation.

Reproduction of Color

The sets varied not only in number, but also in color, and our instructions were neutral as far as these two dimensions were concerned. We only asked the children to copy the set that they had just seen, and we did not specify either number or color when we made this request. On the whole, the children were less likely to copy the color of the bricks correctly (e.g., to produce a set of blue bricks after seeing a set of blue bricks) than the number of the bricks in the set (see Table 3).

We did a three-way analysis of variance of the number of times that the children produced a set of bricks of the same color as the set just seen. The independent variables were groups (deaf and hearing children), condition (spatial and temporal), and presentation mode (puppet plus bricks and bricks only), with repeated measures on the last two variables. Condition had a significant effect on correct color reproduction, $F(1, 18) = 4.636$, $p < .05$: The scores were higher in the spatial condition than in the temporal condition. This difference echoes the conditions difference in the analysis of correct number reproduction. The deaf and the hearing children remembered both the number and the color of the bricks better in the spatial than in the temporal condition.

Presentation mode was also significant in this analysis, $F(1, 18) = 7.882$, $p < .025$. The children reproduced the correct color less often when the puppet made the presentation than when the bricks appeared on their own. This is the only difference in the study that was attributable to the mode of presentation, and we do not have a ready explanation for it.

This analysis of correct color reproduction produced no significant differences between the two groups, either as a main term or in any interaction (Table 3). Thus, although deaf children remembered the number of items in spatially presented sets better than the hearing children did, they were no better or worse than the hearing children in terms of memory for the color of the objects in these sets.

Summary of Results

The deaf children reproduced the number of items correctly significantly more often than the hearing children in the spatial condition.

There was no significant difference in the accuracy of the two groups with number in the temporal condition.

The children who were given the more difficult temporal condition first fared worse in reproducing number in that condition than those who were given the temporal condition after having already been through the easier spatial condition.

There was no evidence of any difference between the deaf and hearing children in the speed of their reactions.

There were no differences between the two groups in their success in reproducing the correct color of the spatially and temporally presented sets.

Discussion

Our aim was to fill a serious gap in our knowledge about the intellectual development of deaf children. It was clear that the grasp of number that children acquire before they go to school lays the basis for much of their understanding of the mathematical instruction that they receive when they do go to school. Preschoolers' knowledge of number includes nonlinguistic number representation and the use of counting. We thought it was important to know whether deaf children are behind in either or in both of these types of number representation. Yet, we could find no research to clarify this issue. This gap in research raised a pressing question whether the mathematical difficulties of deaf schoolchildren can be traced to a difficulty with number representation in the preschool period.

In our attempt to find a first answer to this question, we studied the ability of preschool deaf children to discriminate and represent numbers using set sizes that they should be able to represent even if they did not know how to count. We asked deaf and hearing children to reproduce a set of objects that they had just been shown, and we looked at their ability to copy the number and the color (a nonnumerical dimension) of the objects that they had just seen.

The study produced a clear answer to our original question. The deaf preschool children in the study were at no disadvantage in representing and discriminating number. Even in temporal tasks, in which deaf children tend to be at a disadvantage, the children in the deaf group were able to represent the numbers of the different sets as well as the hearing children. In the spatial tasks, the deaf children were actually at an advantage. The advantage that the deaf children had in the spatial task was specific to number. They used the right colors in assembling sets in the spatial condition as well as, but no better than, the hearing children. They only excelled in reproducing the right number in the spatial condition.

These results led us to two tentative conclusions. The first is that, in their early years, deaf children do not have any particular problem with representing number. This is an important conclusion because it suggests that the mathematical difficulties that older deaf children encounter at school are not caused by beginning school with inadequate number representation. On the contrary, our results suggest that these difficulties are because deaf children either have fewer opportunities to learn or are less able than other children to learn the culturally transmitted aspects of mathematical knowledge. Previous research (Leybaert & Van Custem, 2002) showed that deaf children in kindergarten know fewer counting words and hypothesized that this may be a consequence of teaching them in smaller groups, thus providing fewer opportunities to learn larger numbers. This should be the subject of further research.

We need to sound two notes of caution about this first conclusion. One is that our results come from 10 deaf children only, all of whom were being given oral education. We cannot be sure that deaf children who are being educated in a signing environment will also react in the same way. Another study is needed to test the generalizability of our results. However, the fact that these orally educated deaf children showed a specific superiority in reproducing number in the spatial condition does suggest that these results will generalize to a signing population. Previous research has shown that deaf people who sign have an advantage in some spatial tasks when compared to those who do not sign and to hearing people (see Emmorey, 1998, for a review). However, it remains possible that deaf children who are not educated orally might have a disadvantage on the temporal version of this task (see Marschark, 1993, for a review).

The next caveat is that our number representation task is not a comprehensive test of preschool mathematical understanding. Number representation is certainly a central mathematical achievement in the preschool period (Bryant, 1994; Mix et al., 2002). However, we also need to investigate other aspects of the understanding of number, such as the understanding of the logical basis of number comparisons and of ordinal number, before we can be sure that preschool deaf children have no particular difficulties with numbers. In this sense, our study of preschool children's mathematical cognition is a first, but nonetheless an encouraging, step.

Our second conclusion is an exciting one. The discovery that young deaf children are particularly good at representing numbers when sets are presented as spatial arrays leads to an interesting educational implication. Deaf children may learn about mathematics more quickly and effectively if the teacher's presentations take a spatial rather than a temporal form. One possible example is instruction about one-to-one correspondence and one-to-many correspondence, which are concepts of great importance in children's mathematical development (Nunes & Bryant, 1996). Teachers can demonstrate the numerical correspondence of two sets either by sharing (one for A, one for B, one for A, one for B, etc. so that for every item that A receives, B will also receive one) or by using spatial displays in which two sets of items are lined up in parallel like two ranks of soldiers. Deaf children should benefit a great deal more from spatial than from temporal presentations.

Many other mathematical concepts, such as addition, multiplication, proportions, and fractions, can be represented either in spatial displays or as temporal sequences. Nunes and Bryant (1991), for example, compared temporal and spatial methods in a study of ways of teaching hearing children about additive reasoning. In this study, the spatial methods were more effective, and we can now suggest that they should be even more successful with young deaf children. At the moment, this idea is, of course, an educational hypothesis. Nunes and Moreno (see Nunes, in press; Nunes & Moreno, 2002) have made a first attempt to test this idea. They created visual–spatial representations for a variety of mathematical concepts, creating a comprehensive program that was used by teachers of the deaf with their pupils. The project children made significantly more progress from pre- to posttest on a standardized mathematics assessment than a comparison group. However, it would be desirable to carry out more rigorous tests of this hypothesis by working with specific concepts one at a time.

We also want to note that the sequential array was no more difficult for the deaf than for the hearing children. This may be because the number of items was small enough that they were able to encode a representation for each one in they time they had to observe the display. Marschark (1993) has shown that visual and verbal codes appear to be as effective for deaf individuals when the tasks involve visual presentations of three to five stimuli. Another possible reason is that the task we used is effectively like a free recall task rather than a serial recall, and deaf individuals show weaker performance in sequential tasks when the recall condition is serial, but not when it is free recall (Todman & Seedhouse, 1994).

Of course, the two conclusions that we have made are tentative. Our study was only about number reproduction, and although this is an important part of children's preschool achievements, there are other aspects of mathematics that need to be studied as well before the possibility of particular mathematical difficulties in the preschool deaf population can be ruled out.

We also need to confirm our own more specific claim that deaf children encode and remember number as well as, and sometimes better than, hearing children in the preschool period. There are other ways of investigating number judgments than the task that we used; interestingly, some of these deal with the possible effects of spatial cues on children's judgments about number. Piaget (1952) and many other investigators since (Bryant, 1994; Mix et al., 2002; Tan & Bryant, 2000) have established beyond any possible doubt that preschool children and even children in the first 2 or 3 years at school are often misled by irrelevant spatial cues when they have to compare the number of items in two sets. At the ages of 4, 5, and 6 years, most children routinely judge the longer of two rows of objects as the more numerous one, even when this row actually has fewer items in it than the other row does. Further research on deaf preschoolers, their use of logic and counting, and the development of their informal problem-solving strategies is also needed.

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