This study examines basic number processing (subitizing, automaticity, and magnitude representation) as the possible underpinning of mathematical difficulties often evidenced in deaf adults. Hearing and deaf participants completed tasks to assess the automaticity with which magnitude information was activated and retrieved from long-term memory (using a Stroop-like paradigm to assess congruity effects), the representational format of magnitude information (by analysis of distance and Spatial Numerical Association of Response Codes effects), and the ability to rapidly enumerate small sets (subitizing). Both groups showed distance effects taken to indicate the use of a visual–spatial analog number line representing approximate quantity. Furthermore, both groups showed similar patterns of performance on the subitizing tasks and showed similar amounts of interference in an analysis of congruity effects. This is taken as evidence against the notion that idiosyncratic differences in basic number processing account for mathematical difficulties experienced by deaf individuals.

Deaf children and adults often lag behind their hearing counterparts on assessments of mathematical performance (Allen, 1986; Lang, 2003; Traxler, 2000). This lag is seen to emerge as early as 8 years of age in terms of performance on the (U.S.) national norming of the Stanford Achievement Test, ninth edition (SAT9, Traxler, 2000). From 8 years onward the lag remains relatively constant at “below basic” levels of performance and deaf students’ scores also appear to asymptote at about 13 or 14 years. A range of factors have been suggested to explain this academic lag including access to equal educational opportunities, motivation, teaching and learning styles, language, and the effectiveness of classroom communication (Marschark, Lang, & Albertini, 2002; Swanwick, Oddy, & Roper, 2005), although fewer studies have considered the underlying differences in cognitive processing that may account for the differences in mathematical skill development between deaf and hearing individuals. Many of the studies examining mathematical skills in deaf populations have only considered mathematical achievement as part of broader studies of general educational performance where often the main focus is literacy (Swanwick et al., 2005). Clearly, language skills are important for allowing access to mathematical information, and studies from both deaf and hearing populations typically show a strong relation between language and mathematical skills. However, few studies provide specific information on the numerical underpinnings of mathematical difficulties and how differences between deaf and hearing individuals in experience and information processing may influence even the most basic of numerical skills. Understanding the potential barriers to mathematical achievement for both deaf and hearing individuals is becoming particularly important as society becomes more scientifically and technologically advanced.

Researchers argue that although deaf individuals may process information differently from hearing individuals, they are not deficient in processing information...
In some aspects of cognitive processing, deaf individuals (particularly deaf signers) show distinct advantages, for example, in speed of shifting visual attention and visual scanning (Rettenbach, Diller, & Sireteanu, 1999), in peripheral detection of motion (Bavelier et al., 2000; Corina, Kritchevsky, & Bellugi, 1992; Neville & Lawson, 1987; Proksch & Bavelier, 2002; Swisher, 1993), and in the generation and manipulation of mental images (Chamberlain & Mayberry, 1994; Emmorey & Kosslyn, 1996; Emmorey, Kosslyn, & Bellugi, 1993; Talbot & Haude, 1993).

Beyond differences in visuo-spatial skills, studies of long-term or semantic memory have revealed several important differences in the way that deaf individuals organize and utilize information. Studies using word association tasks, for example, have revealed that deaf individuals tend to have weaker associations between concepts, asymmetrical category-exemplar relations, smaller set sizes, and much more variable associative structures relative to hearing peers (Marschark, Convertino, McEvoy, & Masteller, 2004; McEvoy, Marschark, & Nelson, 1999). Deaf adults and children also have been shown to tend toward item-specific processing, focusing on individual item information rather than relations among items (Marschark, De Beni, Polazzo, & Cornoldi, 1993; Ottem, 1980; Richardson, McLeod-Gallinger, McKenn, & Long, 1999; see Marschark, 2003, for a review).

Although the extent to which such differences might affect the acquisition of mathematical skills by deaf students is yet to be determined, the understanding of mutual relations between quantities is a key aspect of basic number processing. It is argued that the ability to judge the relative value of numerical symbols plays an important role in numerous aspects of number processing, including rapid and accurate calculation, comparison of magnitude, and estimation of numerosity (Dehaene, 1992; Delazer & Butterworth, 1997; Fischer, 2003; Gelman & Gallistel, 1978; Girelli, Lucangeli, & Butterworth, 2000; Griffin, Case, & Capodilupo, 1995; Nunes & Bryant, 1996), and that with increasing exposure to numbers in school these key aspects of basic numerical processing become automatic (Berch, Foley, Hill, & Ryan, 1999; Girelli et al., 2000; Rubinsten, Henik, Berger, & Shahr-Shalev, 2002).

Dehaene’s (1992) “triple-code theory” assumes that when Arabic or verbal numerals are identified, this information is automatically translated into an analog magnitude representation that conveys semantic information such as magnitude (relative amount) and contributes to mathematical performance. It has been argued that an impaired nonverbal representation of approximate magnitude may constrain typical development of exact number abilities across time (Ansari & Karmiloff-Smith, 2002). A less clear and/or less accurate representation or a tendency to process information on an item-specific rather than relational basis may result in more difficulty establishing these efficient links between Arabic numerals and their associated semantic information or weaker links due to more variability between the boundaries of different magnitudes along the mental number line (deaf individuals, Bull, Marschark, & Blatto-Vallee, 2005; developmental dyscalculia, Rubinsten & Henik, 2005). Consistent with this suggestion, Epstein, Hillegeist, and Grafman (1994) and Gregory (1998) have argued that differences between deaf and hearing individuals in early incidental exposure to numerical ideas and later mathematical instruction might result in a difference or lag in both number processing and calculation between deaf and hearing individuals.

There are various methods by which one can examine how magnitude information is represented and how automatically it can be retrieved. One commonly used method in studies with hearing participants is the use of the Stroop paradigm (see MacLeod, 1991, for a review), which assesses interference from an irrelevant aspect of the stimulus. Participants are presented with two-dimensional stimuli (e.g., a color word typed in a particular ink color) and are asked to focus on one dimension (ink color) and ignore the other dimension (the color word). Many participants cannot ignore the irrelevant dimension that interferes with their processing of the relevant dimension. This is considered an indication for the automatic nature of the irrelevant dimension and as a failure of selective attention. An example of a numerical Stroop-like task requires participants to indicate which number is physically larger when presented with stimuli that are congruent (physical size and magnitude match, e.g., 1 3), incongruent (1 3), or neutral (3 3). Results show that incongruent
(yet task irrelevant) numerical magnitude interferes with physical size judgments, resulting in a congruity effect, that is, slowing of response times on incongruent compared to neutral trials, and/or faster response times of congruent compared to neutral trials (size congruity effects; e.g., Girelli et al., 2000; Rubinsten & Henik, 2005; Rubinsten et al., 2002).

This Stroop-like paradigm also allows an examination of other aspects of number representation. Numerous studies report that magnitude information is represented conceptually in the form of a visual number line, with small magnitudes associated with the left side of space and large magnitudes with the right side of space, that is, there is an association between numerical and spatial codes. This has been referred to as the Spatial Numerical Association of Response Codes (SNARC) effect (Dehaene, Bossini, & Giraux, 1993). SNARC tasks typically ask participants to make a judgment, unrelated to magnitude, about a presented number (e.g., parity or physical size). Patterns of response times show that participants are faster to make responses to lower magnitude numbers with the left hand and higher magnitude numbers with the right hand. This has been taken as an indication that magnitude information is being activated and influences nonmagnitude judgments, even when this is irrelevant to the task. So, the SNARC effect tells us not only about the spatial format in which numerical information is represented but also about the automaticity with which it is activated. In the context of the Stroop-like task described above, we would predict that where participants are required to press a key to indicate the physically larger number, they will respond faster when the spatial positioning of the key press is congruent with number line position (e.g., 1 3, respond left hand) than when it is incongruent with number line position (3 1, respond right hand).

Additional evidence for this form of magnitude representation comes from studies of distance effects in the comparison of numbers (e.g., Dehaene & Akhavein, 1995; Dehaene & Changeux, 1993; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Dehaene Dupoux, & Mehler, 1990; Duncan & McFarland, 1980; Moyer & Landauer, 1967; Tzelgov, Meyer, & Henik, 1992). Where numbers are in close proximity on the mental number line (e.g., 4 and 5) the time to decide which is the larger number will be greater relative to numbers that are more distant on the number line (e.g., 1 and 5). To examine this effect, the current study includes number pairs for comparison that differ in magnitude between 1 and 4. Again, note that magnitude distance is irrelevant to the task of making a physical size judgment about the presented numbers.

The current study aimed to examine the strength and nature of numerical magnitude representation in deaf adults. If deaf adults have less automatic activation of numerical information, we would predict that in a Stroop-like paradigm where participants are asked to make physical size judgments, incongruent magnitude information from the presented numbers would not be so automatically activated and so should result in less slowing compared to conditions where physical and magnitude information are congruent. Furthermore, if deaf adults process numerical information on an item-specific basis, then again, we might anticipate a less marked SNARC effect, as the relations to other magnitudes will be processed more slowly (i.e., less automatically) or to a lesser extent.

The automaticity of number recognition also was explored via subitizing tasks. Subitizing refers to the rapid enumeration of small sets, thought to be limited to four items (Mandler & Shebo, 1982; Peterson & Simon, 2000; Trick & Pylyshyn, 1993). Koontz and Berch (1996) found that hearing children with arithmetic learning disabilities have difficulty subitizing, instead using time-consuming counting strategies for set sizes as small as three items. In the present study, number patterns to be identified were presented either centrally, in random or canonical (dice-like) patterns, or in “skewed” presentations that would be expected to require two visual fixations. Given the demonstrated superiority of deaf adults in both the speed of shifting visual attention (Rettenbach et al., 1999) and the sensitivity of their peripheral vision (Corina et al., 1992), it is possible that deaf individuals have some cognitive advantage in subitizing tasks requiring multiple fixations or where the items are presented in the periphery of the display.

For all tasks with the exception of subitizing, we used two forms of stimuli, Arabic numerals and handshapes (as would be used to indicate numerals in American Sign Language [ASL]). The ASL numerals
were included to allow for a direct comparison between performance on Arabic numeral versus ASL numeral tasks. Furthermore, because ASL numerals should be processed relatively automatically by deaf individuals, performance with the ASL numerals for deaf individuals might equate to performance with Arabic numerals for hearing individuals (i.e., the preferred format/mode for which each hearing status group would be most adept at processing numerical information).

Information from this range of tasks assessing quantity recognition, magnitude representation, and magnitude retrieval will provide a solid starting point for identifying whether these basic numerical skills account for the development of mathematical difficulties in deaf individuals or, equally importantly, can be eliminated as contributory factors to mathematical difficulties.

Methods

Participants

Twenty deaf college students (11 males) and 20 hearing college students (12 males), ranging in age from 18 to 27 years, participated in the experiment as paid volunteers. All were enrolled as undergraduates at the Rochester Institute of Technology (RIT) and were recruited via posters and contacts with student groups. Deaf students’ hearing thresholds ranged from 77 to 120 dB in the better ear, with a mean of 89 dB. All the deaf students used sign language, sometimes accompanied by speech, as the primary means of communication. Institutional records showed that the age of hearing loss onset ranged from birth to 3 years.

Although demographic and academic data were not available for the hearing students and there were some missing data for deaf students due to incomplete institutional records, deaf students’ scores on the American College Test (ACT) entrance examinations (n = 15) indicated them to have an average mathematics subtest score of 15.66 (SD = 2.4) of 36 possible. This mean corresponds to approximately the 22nd percentile relative to national norms for all students taking the test. The mean compares with an average mathematics subtest score of 17.7 (SD = 4.3; approximately 40th percentile) for the 838 deaf RIT students enrolled during the academic year for whom ACT scores were available. At face value, these scores are consistent with those of deaf students on the SAT9 (given in grades 1 through 12) in suggesting that deaf students, on average, lag behind hearing peers in math skills (Traxler, 2000). Hearing participants had no formal knowledge of ASL, although they would have been exposed to signing via occasionally being in classes with deaf students and interpreters.

Procedure

Subitizing task. Stimuli for the subitizing tasks ranged in number from 1 through 6, presented in three formats with 36 trials of each type (six trials with each quantity). Stimuli were presented in three separate blocks as a random arrangement in the center of the display, skewed dot arrangements (with two dot subgroups), or a canonical arrangement as they would appear on a dice. Blocks were randomly ordered, each with a preceding block of three practice trials. The dots in both random and skewed arrangements measured 12 mm each. Skewed dot subgroups were separated by 4–6 cm. Dice stimuli measured 4 cm on a side with 7-mm dots.

Test trials. The experiment generator package E-Prime was used for this and all other tasks described here. Prior to each trial, a fixation point in the center of the screen appeared for 500 ms. A stimulus then appeared for 50 ms, followed by a checkerboard mask (7-mm black and white squares) that remained in view until a response was made by pressing one of six numbered keys (‘‘Z’’ = 1, ‘‘X’’ = 2, ‘‘C’’ = 3, ‘‘B’’ = 4, ‘‘N’’ = 5, ‘‘M’’ = 6) to indicate how many items were presented. Participants kept their fingers resting on the keys between trials. Responses were followed by feedback, which remained on the screen for 500 ms, and then the next trial began automatically. Procedures for all participants were identical, with the exception that interactions involving hearing students were conducted in spoken language, whereas those with deaf students involved sign language or simultaneous (signed and spoken) communication, according to student preference.
Stroop SNARC task (herein referred to as the SNOOP task). For the SNOOP task, stimuli were presented in four blocks. Prior to each block there were three practice trials. The stimuli in one block (64 trials) consisted of two numerals that varied in physical size (24 or 56 point Times Roman font) and magnitude (1–6). The stimuli in a parallel block (72 trials) consisted of two numerals, indicated by fingers on a hand in ASL number configuration, varying in physical (4.5 or 9.5 cm) and magnitude (1–5) size. The ASL 6-hand was not used, as it consists of (the middle) three fingers, and thus would yield different responses from deaf and hearing participants. In terms of the magnitude size, the numerals differed by distance (1, 2, 3, and 4). Examples of the ASL stimuli can be seen in Figure 1.

In one subtask (four blocks) the participants were instructed to make a judgment about the physical size of the numerals by pressing a key indicating which of the two was physically larger. If the physically larger number was on the left-hand side of the computer screen, participants were asked to press the “Z” key (marked with a “L”). In a second subtask (four blocks), the design and materials were identical to those just described, except that participants responded with the side corresponding to the larger magnitude number rather than the physically larger stimuli.

There were four different stimulus conditions in each block of the experiment, presented in random order. In the first condition the two numerals were presented in SNARC congruent position and incongruent size (e.g., 1 3), in the second in SNARC congruent position and congruent size (e.g., 1 3), in the third in SNARC incongruent position and congruent size (e.g., 3 1), and finally in the SNARC incongruent position and incongruent size (e.g., 3 1). In each block, stimuli were constructed so as to yield 16 pairs at each magnitude difference 1, 2, 3, and 4, with four pairs in each of the conditions described above.

Test trials. After prompting the participant to “get ready,” a fixation point was presented prior to presentation of each stimulus. Stimuli were centered on a white computer screen. Each new stimulus appeared
automatically following feedback to the previous trial. The computer package recorded response times to the nearest millisecond for each individual trial. The order in which each participant completed each block of the experiment randomized across the four tasks described here.

Results

Subitizing Task

Because this task involved only very brief presentations (50 ms), the main differences expected are in accuracy; accuracy for stimuli within the subitizing range should be higher than those outside the subitizing range. One deaf participant performed very poorly on this task, yet his performance on other tasks ruled out any difficulty in simple set size enumeration. Therefore, his data were removed from the subitizing analysis. Accuracy across the different set sizes was averaged to give mean accuracy for the subitizing range (1–4) and mean accuracy for the counting range (5–6).

A 3 (format) × 2 (hearing status) × 2 (number range) analysis of variance (ANOVA) revealed a significant main effect of presentation format, $F(2, 74) = 20.31, p < .001, \eta^2 = .35$; number range, $F(1, 37) = 40.08, p < .001, \eta^2 = .52$; and a significant interaction between presentation format and number range, $F(2, 74) = 26.27, p < .001, \eta^2 = .42$. There was no main effect of hearing status $F(1, 37) = 1.14, p = .29$, and none of the remaining two- or three-way interactions were significant. Observation of the mean proportion of correct responses shown in Figure 2 reveals that for both deaf and hearing adults, performance on the dice patterns was very high across the subitizing and counting range. Performance on the dots and skewed dots formats showed that although accuracy was, as expected, high in the subitizing range, performance outside the subitizing range deteriorated to around 77% and 65% accuracy in the dot and skew dot presentation formats, respectively. Performance patterns of both the deaf and hearing groups were very similar.

SNOOP Task

Distance effects. Analysis compared the time and accuracy with which participants made both physical and magnitude decisions when the numbers presented varied by a distance of 1, 2, 3, or 4. A 4 (distance) × 2 (judgment; physical vs. magnitude) × 2 (hearing status) mixed-design ANOVA of response times to digits, with repeated measures on the first two factors revealed a significant main effect of judgment type, $F(1, 38) = 143.27, p < .001, \eta^2 = .79$; distance, $F(3, 114) = 15.47, p < .001, \eta^2 = .29$; and a significant interaction between judgment and distance, $F(3, 114) = 10.85, p < .001, \eta^2 = .22$. No other main effects or interactions were found to be significant. Figure 3 shows that for both deaf and hearing participants, response time decreased with increasing distance when magnitude decisions are required. However, no such effect is found when participants were asked to make physical size judgments. Overall, response times to make physical judgments were significantly faster than to make magnitude judgments.
An identical analysis was performed on the ASL numeral data. This revealed significant main effects of distance, $F(3, 114) = 36.43, p < .001, \eta^2 = .49$, and judgment type, $F(1, 38) = 192.92, p < .001, \eta^2 = .84$, along with significant interactions between distance and judgment, $F(3, 114) = 34.76, p < .001, \eta^2 = .48$, and between distance and hearing status, $F(3, 114) = 3.28, p < .05, \eta^2 = .08$. No other main effects or interactions were significant. Again, physical size judgments were made significantly faster than magnitude judgments. Response time did not change with increasing distance for physical size judgments but decreased with increasing distance for magnitude judgments, with the exception of distance of 4. Overall, this distance effect was slightly more pronounced for hearing than for deaf participants.

Similar analyses were conducted for the accuracy data. It should be noted that overall accuracy was very high, so ceiling effects may affect these analyses. For the digit task, main effects of judgment, $F(1, 38) = 39.16, p < .001, \eta^2 = .51$; distance, $F(3, 114) = 4.39, p < .01, \eta^2 = .10$; and hearing status, $F(1, 38) = 4.52, p < .05, \eta^2 = .11$ were found, along with two-way interactions between judgment and distance, $F(3, 114) = 9.29, p < .001, \eta^2 = .20$, and judgment and hearing status, $F(1, 38) = 9.91, p < .01, \eta^2 = .21$. Accuracy to physical judgments was higher and consistent across all distances. Overall, hearing participants were significantly more accurate, and accuracy increased with increasing distance. For the deaf participants, accuracy was significantly lower for distance of 1 (magnitude decisions), whereas the accuracy of the hearing
participants showed a gradual improvement with increasing distance.

Similar results were found for the ASL numerals, with main effects of judgment, $F(1, 38) = 6.21, p < .05$, $\eta^2 = .14$; distance, $F(3, 114) = 8.90, p < .001$, $\eta^2 = .19$; and an interaction between judgment and distance, $F(3, 114) = 2.95, p < .05$, $\eta^2 = .07$. Performance on the physical size judgment task was consistently high across all distances. For both deaf and hearing participants, accuracy on the magnitude decision task was poorer at a distance of 1 but differed little on distances 2 through 4.

Size congruity effects. Response times for all size congruent and size incongruent stimuli were collapsed across distance and position congruency to determine a mean response time for congruent and incongruent stimuli. This was calculated for both hand and digit stimuli on the response times for both magnitude and physical size judgments. Congruity effects were also calculated by finding the difference in response times between size congruent and incongruent stimuli. A 2 (congruity) × 2 (hearing status) mixed-design ANOVA was conducted to determine the presence of congruity effects. For digit stimuli, congruity effects were present for both physical size judgments, $F(1, 38) = 10.22, p < .01$, $\eta^2 = .21$, and magnitude judgments, $F(1, 38) = 58.07, p < .001$, $\eta^2 = .60$. In both cases, response times to congruent stimuli were faster than those to incongruent stimuli. There was no main effect of hearing status and no significant interaction. Analysis of the size of the congruity effect by judgment type (physical size vs. magnitude) revealed a significant main effect of judgment type, $F(1, 38) = 30.54, p < .001$, $\eta^2 = .45$. The congruity effect was greater when participants were required to make magnitude compared to physical size decisions (see Figure 4). Identical analyses were performed on the ASL numerals but revealed no significant congruity or hearing status effects and no interactions for either physical size or magnitude judgments.

SNARC congruity effects. The time taken to respond to the numbers 1 through 6 with both the right and left hand was calculated, and the difference (right − left hand) response time was calculated. This was done separately for Arabic and ASL numeral tasks and for magnitude and physical size judgments. The nature of the SNARC effect was captured by regression analyses (Lorch & Meyers, 1990, method 3; for a detailed discussion, see Fias, Brysbaert, Geypens, & d’Ydewalle, 1996). A regression equation was computed for each participant, with number magnitude as the predictor variable and response time difference as the criterion variable. The standardized beta weight for each participant was recorded. Finally, one-sample $t$ tests were conducted to determine whether the regression weights for each hearing status group differed significantly from zero. Figure 5 shows variable SNARC effects, dependent on the stimulus type and, in the case of magnitude decisions, the presence of congruent or incongruent size information. The clearest evidence of SNARC effects was found for magnitude judgments where physical size was congruent with magnitude. Here, both deaf and hearing participants show a pattern of results conducive with typical SNARC effects, although this effect was reversed when physical size was incongruent with magnitude. For the ASL numerals, only deaf participants showed evidence of SNARC effects for the size congruent stimuli, with again both groups showing reversed effects for the incongruent stimuli. Regression lines tended to be fairly flat for physical size judgments of both digits and handshapes. Despite some of the patterns of results indicating SNARC effects, one-sample $t$ tests comparing the average standardized beta weight for each group under each of the conditions revealed that none of the beta weights were significantly different
from 0 (see Table 1). The number of participants displaying the expected negative slope is also reported in Table 1. This shows that for many of the stimulus formats, approximately 50% of participants showed the expected negative slope. The only slight difference between deaf and hearing participants was for ASL numerals (congruent magnitude and physical size), where 14 deaf participants (compared to 10 hearing participants)
showed a negative slope indicating SNARC effects. However, chi-square analysis showed that this was not a significant effect, $\chi^2(1, N = 40) = 1.67, p = .197$.

**Discussion**

The central aim of this study was to begin to examine the possible cognitive underpinnings of the frequently observed lag in arithmetical and mathematical skills in deaf individuals. The focus here was on basic aspects of number processing: fast and accurate enumeration of small set sizes, automaticity of activation of semantically related numerical information (magnitude), and the nature of the visual–spatial representation of number.

Because deaf individuals show enhanced abilities in some aspects of visual and spatial processing, it was anticipated that deaf participants would perform particularly well on the subitizing task, particularly in conditions where stimuli were not presented in well-known canonical patterns and where the subitizing process may require rapid refocus of attention to a second group of dots. In fact, the patterns of results were very similar for both deaf and hearing participants in the tasks employed here. If participants are able to rapidly enumerate small set sizes (i.e., subitize), then we would expect overall accuracy to be higher for set sizes within the subitizable range. For all presentation formats, accuracy was very high in this range (85–97%). Accuracy remained high for larger item sets in the dice presentation format, presumably because all participants were able to use knowledge of dice patterns to accurately estimate the number presented. For the dot and skew dot formats, both hearing status groups showed a significant drop in performance (to approximately 70% accuracy). Deaf participants did not show the anticipated advantage on the skew dot format but did show completely typical subitizing effects, with performance not significantly different from the hearing group. Therefore, basic differences in subitizing skills do not contribute to the mathematical difficulties of deaf individuals.

Analysis of distance effects revealed that both groups only showed distance effects when asked to make magnitude judgments, not physical size judgment. As distance between the numbers increased, participants were faster to state which number was the larger in magnitude. Accuracy was significantly lower when the numerals presented only differed by a distance of one, but overall accuracy levels were very high. Previous studies have also found distance effects when participants are asked to make judgments of the numbers unrelated to magnitude (e.g., Dehaene & Akhavein, 1995), although recent developmental studies (e.g., Rubinsten et al., 2002) did only show a numerical distance effect when magnitude judgments were being made. The current findings extended the effect typically found with Arabic numerals, finding the same distance effect with the ASL numerals for both deaf and hearing adults. It was anticipated that an interaction might be present if the retrieval of magnitude information from ASL numerals was more automatic for deaf participants, although the interaction of distance

<table>
<thead>
<tr>
<th>Stimulus and judgment type</th>
<th>Deaf Mean $\beta$</th>
<th>Deaf $t$</th>
<th>Deaf $p$</th>
<th>Hearing Mean $\beta$</th>
<th>Hearing $t$</th>
<th>Hearing $p$</th>
<th>N with $-ve$ slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digits physical</td>
<td>$-0.05$</td>
<td>$-0.50$</td>
<td>$.62$</td>
<td>$11$</td>
<td>$-0.04$</td>
<td>$-0.37$</td>
<td>$.71$</td>
</tr>
<tr>
<td>Digits magnitude (size congruent)</td>
<td>$-0.12$</td>
<td>$-1.11$</td>
<td>$.23$</td>
<td>$12$</td>
<td>$-0.07$</td>
<td>$-0.72$</td>
<td>$.48$</td>
</tr>
<tr>
<td>Digits magnitude (size incongruent)</td>
<td>$0.00$</td>
<td>$-0.03$</td>
<td>$.97$</td>
<td>$9$</td>
<td>$0.13$</td>
<td>$0.87$</td>
<td>$.40$</td>
</tr>
<tr>
<td>Handshape physical</td>
<td>$0.06$</td>
<td>$0.61$</td>
<td>$.55$</td>
<td>$8$</td>
<td>$-0.10$</td>
<td>$-1.10$</td>
<td>$.29$</td>
</tr>
<tr>
<td>Handshape magnitude (size congruent)</td>
<td>$-0.18$</td>
<td>$-1.44$</td>
<td>$.19$</td>
<td>$14$</td>
<td>$0.06$</td>
<td>$0.47$</td>
<td>$.64$</td>
</tr>
<tr>
<td>Handshape magnitude (size incongruent)</td>
<td>$0.17$</td>
<td>$1.19$</td>
<td>$.25$</td>
<td>$7$</td>
<td>$0.10$</td>
<td>$0.885$</td>
<td>$.39$</td>
</tr>
</tbody>
</table>
by hearing status indicated that the distance effect was slightly more pronounced for hearing adults. The ASL numerals 1–5 do represent the actual number of items shown in the set and as such may automatically activate information about magnitude for hearing as well as deaf individuals.

Analysis of the SNARC effect produced mixed results. Where participants were asked to make magnitude decisions of numbers that were also size congruent, both deaf and hearing participants showed the expected negative slopes indicating faster responses to low numbers with the left hand and high numbers with the right hand. This effect was also found for magnitude decisions of congruent ASL numerals for the deaf individuals, suggesting that, just like digits, ASL number signs are directly mapped onto an underlying visual–spatial representation of magnitude. However, note that although graphical illustration shows these effects, none of the average regression weightings were found to be significantly different from 0. No SNARC effects were apparent when participants made physical size judgments, and reversed (although nonsignificant) SNARC effects were found when participants made magnitude decisions of numbers that were size incongruent. The lack of significant SNARC effects was surprising as the effect has been found in a variety of task contexts, although a number of recent studies have indicated that the presence of SNARC and congruity effects may be dependent on the salience of the relevant dimensions (Pansky & Algom, 2002) and that the SNARC effect may be absent despite other evidence of analog magnitude representation such as distance effects (Ito & Hatta, 2004). One explanation for the lack of SNARC effects in the current study could be the complexity of the stimuli used; in most studies only one stimulus is presented at a time (as in parity judgment tasks), or two stimuli are presented that only differ along one dimension, for example, physical size (3 3) or magnitude (3 4), with participants asked to indicate the larger physical number or the larger magnitude number in each task, respectively. In the current study, the stimuli always varied along two dimensions, both physical size and magnitude. Unfortunately, no conditions were included with only one stimulus dimension manipulated, but this would be the obvious follow-up condition to examine for basic SNARC effects. Furthermore, because of the inclusion of ASL numerals, the range of numbers presented was more restricted than usual, only ranging in size from 1 to 6. In previous studies we have elicited evidence of clear SNARC effects in both deaf and hearing adults when participants are asked to make a simple magnitude judgment (Bull et al., 2005), so for the time being at least, we conclude that there are no obvious differences between deaf and hearing participants in the visual–spatial representational format of magnitude information. Additional support for this finding should be sought through the use of alternative methods for examining magnitude estimation using stimuli other than Arabic symbols, for example, displays differing in dot numerosity or number words.

The final analysis of the SNOOP task examined the size congruity effect, the predicted faster judgments when physical size and magnitude are congruent. Both groups showed size congruity effects for Arabic numerals only, not ASL numerals. Furthermore, the size congruity effect was much more pronounced for magnitude than physical size decisions. This indicates that incongruent physical size information interferes with magnitude judgments more so than incongruent magnitude information interferes with physical size judgments. This would seem to suggest that perceptual characteristics of Arabic numerals are processed rapidly, and subsequently this information interferes with magnitude judgments.

A number of previous studies have found that, overall, deaf individuals tend to be slower to process information compared to hearing individuals (Bull et al., 2005, Epstein et al., 1994). In contrast, none of the current findings indicated a significant difference in response times between deaf and hearing participants. This might be accounted for by seemingly trivial changes in the presentation format of the task. In our own previous work examining basic number skills in deaf adults, the information necessary for task completion was presented in a sequential format. For example, participants would be instructed that they should compare each presented number with a target number in order to make their magnitude decision. This requires holding the initial target number in memory, and then continually referring back to this
target number when each new stimulus is presented. There is considerable evidence to suggest that where information is presented in this sequential format, or where target information is to be held in memory, deaf students have problems linking all the information together (e.g., Marschark, 1993, 2003; Todman & Seedhouse, 1994).

In the current study, all information necessary for the physical or magnitude size judgment was presented simultaneously. For example, both numbers appeared on the screen at the same time meaning that there was no requirement to hold a representation in mind and refer back to a previously presented target number. Indeed, results from a follow-up study examining symbolic comparison (not Arabic numerals) with simultaneous presentation of the stimuli to be compared have revealed similar findings. Deaf adults were not significantly slower than hearing participants when making the comparison judgments, in this case, judgment of size of objects. This might have implications for how future studies should present task information to deaf participants. Where presentation formats play to the information processing limitations of deaf individuals, we may be inappropriately inferring difficulties in basic number processing when in fact, tested under a different presentation format, deaf individuals show completely typical findings in terms of number representation and automaticity of retrieval.

Overall, data from all the tasks indicate that the format of numerical representation and the level of automatic activation of magnitude information are not idiosyncratically different in deaf individuals and do not represent the basis of later developing difficulties with arithmetic and mathematics. This is in line with recent findings from Iversen, Nuerk, and Willmes (2004), who reported typical SNARC effects for deaf adult signers. Because sign language is a visually spatially organized language, it may lend itself particularly well to the establishment of connections between Arabic numerals and spatial representations of magnitude. Results from an intervention study by Nunes and Moreno (2002) highlight the benefits of visually presenting mathematical concepts to deaf children, which potentially plays to their preferred (and more experienced) mode of information processing. Therefore, more serious difficulties in mathematical understanding may arise when the presentation format of the mathematical skills being taught does not play to these relative strengths in visual and spatial information processing.

These data cannot rule out the possibility that deaf children may show delays in basic aspects of numerical processing early in development. However, Zarfaty, Nunes, and Bryant (2004) found no difficulties in representing and discriminating number in deaf preschool children, with deaf children showing a distinct advantage when the tasks were spatial rather than temporal in nature. Furthermore, despite deaf children showing age-related lags in their knowledge of the number sequence, their performance in object counting and cardinality task is similar to that of hearing children (Leybaert & Van Custem, 2002). In progressing with research to examine the underlying cognitive underpinnings of mathematical difficulties of deaf individuals, it is clear that the focus should turn to more complex aspects of mathematical cognition and the interplay between spatial and linguistic forms of numerical knowledge, bearing in mind the general cognitive strengths, limitations, and differences in information processing and knowledge organization of deaf individuals that may influence performance.

References


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