Memory Functions in Children With Early Hydrocephalus

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Children with arrested, shunted, and no hydrocephalus were compared on verbal and nonverbal memory tasks assessing multiple components of memory. A gradient of severity was hypothesized, with the shunted hydrocephalus group expected to exhibit the most significant memory impairments and the arrested group expected to perform more poorly than children with no hydrocephalus. Etiologies of prematurity, spina bifida, and aqueductal stenosis were represented by 157 participants. Results supported the hypothesis; the shunted hydrocephalus group performed poorer on all memory measures. Differences for the arrested group were less frequently statistically significant relative to children with no hydrocephalus. Irrespective of etiology, the shunted hydrocephalus group exhibited a pattern of performance suggestive of encoding and retrieval deficits on both verbal and nonverbal tasks, showing a pervasive disturbance of memory processes.

Hydrocephalus represents an increase in cerebral ventricular volume resulting from a disturbance in the balance of cerebral spinal fluid (CSF) production and reabsorption that is caused by a structural anomaly or pathological event. Two of the most frequent prenatal etiologies of hydrocephalus are aqueductal stenosis and spina bifida. Aqueductal stenosis refers to a congenital narrowing of the aqueduct of Sylvius that can result in a blockage of CSF, disturbing its circulatory pattern (Menkes, 1995). Spina bifida is a defect of neural tube closure associated with spinal dysraphisms and the Arnold-Chiari II brain malformation. This malformation consists of neuropathological changes in the hindbrain and cerebellum that create a barrier to CSF outflow from ventricular spaces to subarachnoid spaces (McCullough, 1990). Postnatally, premature infants who suffer intraventricular hemorrhage (IVH) can also develop hydrocephalus because of the resulting blockage of CSF reabsorption (Volpe, 1989).

Severe hydrocephalus poses a significant threat to brain development (Del Bigio, 1993), resulting in stretching and tearing of neural fibers. The corpus callosum can become hypoplastic, and problems with vision can result from damage to the optic tract. Other white matter tracts, particularly in the midbrain, can be affected. The compressive effects of hydrocephalus may damage cortical and subcortical structures associated with memory, attention, and other cognitive functions. In the long term, myelination can be adversely affected, with thinning of posterior brain regions and the cortical mantle. Hence, it is not surprising that early hydrocephalus in children can be associated with poor neurobehavioral outcomes in several domains (Fletcher & Levin, 1988; Wills, 1993). These outcomes reflect direct effects of hydrocephalus and the congenital pathological lesions and associated conditions that lead to hydrocephalus.

Hydrocephalus is most consistently associated with nonverbal cognitive and motor skill deficits that include: (a) fine motor coordination deficits (Thompson et al., 1991), (b) gross motor problems in the lower extremities (Fletcher, Brookshire, Bohan, Brandt, & Davidson, 1995), (c) psychomotor difficulties (Baron & Goldberger, 1993; Thompson et al., 1991), and (d) visuospatial deficits (Donders, Rourke, & Cumady, 1991; Fletcher & Levin, 1988; Wills, 1993).

Studies of psychometric intelligence have consistently demonstrated significantly poorer performance on percep-
tual–performance measures than on verbal measures (Dennis et al., 1981; Fletcher, Francis, et al., 1992). There are identified problems with language at the level of discourse, but form and content tend to be intact (Dennis, Janneck, & Barnes, 1994; Dennis, Hendrick, Hoffman, & Humphreys, 1987). Academic problems involve math computation, written expression, and reading comprehension, whereas decoding skills remain relatively intact (Barnes & Dennis, 1992; Wills, Holmbeck, Dillon, & McLone, 1990).

Two areas of cognitive function infrequently studied in children with hydrocephalus involve attention–executive functions and memory. Fletcher et al. (1996) recently assessed attention and executive functions in children with hydrocephalus, showing that these children perform more poorly than controls on measures of focused attention, selective attention, and problem-solving skills. However, these deficiencies could be explained according to other problems associated with hydrocephalus, such as motor slowing, and were not regarded as true executive function deficits.

Few studies have addressed memory skills in children with hydrocephalus. This area is important because changes in the ventricular system associated with hydrocephalus can lead to compression of temporal lobes, hippocampal structures, and other subcortical structures involved in memory. In a recent review of the literature (Wills, 1993), only six studies involving measures of memory function were reported (Cull & Wyke, 1984; Donders et al., 1991; Fletcher, Francis, et al., 1992; Parsons, 1969; Richardson, 1978; Speigler, 1984). Since Wills (1993), a recent study focusing on verbal learning and memory in children with spina bifida with myelomeningocele was published (Yeates, Enrile, Loss, Blumenstein, & Delis, 1995).

Early studies of memory in participants with hydrocephalus were limited by the lack of theoretically derived memory measures and poorly specified approaches to participant selection (Parsons, 1969; Richardson, 1978). Failure to restrict the study of memory in hydrocephalus to participants who did not meet criteria for a diagnosis of mental retardation has also limited the usefulness of studies completed in the 1980s (Cull & Wyke, 1984; Speigler, 1984). Additionally, in each of the studies cited previously, findings related to hydrocephalus were confounded by etiology, severity, or the presence of other neurological conditions because of failure to carefully define groups and thus control for these other sources of variance. Hydrocephalic participants performed poorly on the memory measures used but were not consistently different from control groups. However, the results were difficult to interpret given the methodological problems present in these four studies.

Donders et al. (1991) attempted to address some of the methodological problems of the previous studies by selecting a specific group of 30 hydrocephalic children who received ventriculoperitoneal shunts before age 12 and excluding participants with other brain lesions. Only participants with Verbal and Performance IQ scores above 70 were included in the study. Spatial Memory, from the Kaufman Assessment Battery (Kaufman & Kaufman, 1983), Verbal Memory II from the McCarthy Scales of Children’s Abilities (McCarthy, 1972), and a selective reminding test (Morgan, 1982) were administered as part of a battery of neuropsychological tests. Comparison groups were not used, and group mean scores were translated into age-adjusted T scores. The results did not reveal that the hydrocephalus participants had impaired memory scores. The study limitations included a relatively small sample size and the lack of a comparison group.

Fletcher, Francis, et al. (1992) included selective reminding memory measures in a broader study of the neuropsychological performance of children with hydrocephalus. This study included shunted children with hydrocephalus due to spina bifida, prematurity–IVH, and aqueductal stenosis, which represent the three most prominent etiologies of early hydrocephalus. Comparison groups included children with unshunted spina bifida and prematurity–no IVH and normal controls with no neurological history. Comparison on a verbal and nonverbal selective reminding test showed that children with shunted hydrocephalus in all three etiologies performed below the comparison groups on both the verbal and nonverbal selective reminding tests. Fletcher, Francis, et al. (1992) obtained these measures when the participants were 6–7 years of age; several children were unable to complete the nonverbal test, and others received extremely low scores. The narrow age range may have influenced the results, and the authors stressed the need to study older children.

Yeates et al. (1995) used the California Verbal Learning Test for Children (CVLT-C; Delis, Kramer, Kaplan, & Ober, 1994) to examine verbal learning and memory in children with spina bifida, children with the most common spinal dysraphism, meningomeningocele, and a normal comparison group matched on age, vocabulary, gender, and socioeconomic status (SES). The myelomeningocele group was also separated into children who received shunts \( n = 33 \) and those who were not shunted \( n = 8 \). Yeates et al. (1995) found the shunted group to perform more poorly than normal controls in their rate of learning and the presence of recency effect. The shunted group performed equally well on measures of recognition, interference, and cued recall but performed significantly poorer on all delayed recall measures relative to the comparison group. The unshunted meningomyelocele group did not differ significantly from the comparison group on any of the memory measures. The other interesting finding was that the shunted myelomeningocele group exhibited higher recognition scores in comparison to their free recall scores than the other two groups. The authors concluded that the impaired performance of the shunted hydrocephalus group was best explained by a retrieval problem, suggesting a relationship between this pattern of deficits and abnormalities of subcortical white matter.

Many of these studies suggest that children and adults with early hydrocephalus are impaired on serial learning tasks and measures associated with the long-term retrieval component of memory (Fletcher, Francis, et al., 1992; Richardson, 1978; Speigler, 1984), but the results have not been consistently replicated (Donders et al., 1991). The study by Fletcher, Francis, et al. (1992) also suggested
impairment on tasks involving learning and memory for nonverbal material. Donders et al. (1991) found no evidence of visual memory impairment, but they used only a recognition memory paradigm. Variations in samples and other methodological differences across the studies may account for the differences in results. To date, studies have failed to systematically investigate the relationship between performance of children with hydrocephalus on memory tests with their performance on other measures of verbal fluency or motor and visuomotor tasks that might explain poor memory performance. At this point, it is not clear whether children with hydrocephalus reliably show memory deficits and, if present, whether these deficiencies are material specific (verbal vs. nonverbal), are related to specific components of memory (e.g., retrieval, Yeates et al., 1995), or are a more pervasive impairment of multiple components of memory.

The present study was designed to evaluate memory for both verbal and nonverbal material using standard serial learning paradigms as well as recognition memory for nonverbal material and measures of prose recall and visuoconstructive memory. Tasks were selected because they measured aspects of memory implicated in previous studies and because the tasks had been previously used in studies of children with brain injury. Verbal serial learning paradigms were used because these methods have been most frequently applied to children with hydrocephalus. They also allow for the measurement of storage and retrieval components of short-term memory (Buschke, 1974). A recent study found the predictive validity of the long-term storage and recall measures to be high for normal participants and a group of patients with a neurological disorder (Beatty et al., 1996). To further evaluate episodic memory, prose recall tasks with immediate and delayed recall components were used. Because children with hydrocephalus have prominent spatial cognition deficits, a variety of nonlanguage memory tests were used, including paradigms based on serial learning of nonverbal memory, recognition memory, and visuoconstructive memory. Previous studies have also failed to evaluate children with hydrocephalus according to etiology and the presence or absence of a shunt. Three etiologies of hydrocephalus were included in the study (aqueductal stenosis, spina bifida, and prematurity—IVH). Children were further divided into subgroups of arrested and shunted hydrocephalus and those participants with no evidence of hydrocephalus.

We hypothesized that comparisons of children with arrested, shunted, and no hydrocephalus would provide evidence for a gradient of severity, so that children with shunted hydrocephalus would exhibit poorer memory performance in comparison to children with arrested and no hydrocephalus. We expected the hypothesized differences to be smaller between the arrested and no-hydrocephalus groups. Based on previous studies, we also hypothesized that children with shunted hydrocephalus would show greater impairment in their recall of nonverbal relative to verbal material across assessment paradigms and that serial learning paradigms would demonstrate more impairment of verbal memory than prose recall paradigms. We addressed previous assertions that impairment on serial recall tasks may represent verbal fluency problems (Baron & Goldberger, 1993) by correlating performance on memory measures with measures of automaticity and verbal fluency. Finally, we hypothesized that performance on memory measures would not be significantly correlated with performance on other verbal or visual tasks.

Method

Participants

The sample for this study included 157 children, representing neurologically normal children (n = 23) and children with spina bifida (n = 57), prematurity (n = 62), and aqueductal stenosis (n = 15). On the basis of medical history and concurrent magnetic resonance imaging (MRI), children in each of the three etiology groups were further subdivided into children with shunted hydrocephalus (N = 69; spina bifida, n = 39; prematurity, n = 16; aqueductal stenosis, n = 14), arrested hydrocephalus (unshunted and nonprogressive; N = 31; spina bifida, n = 7; prematurity, n = 23; aqueductal stenosis, n = 1), and no hydrocephalus (N = 57; spina bifida, n = 11; prematurity, n = 23; normal, n = 23). It is important to recognize that aqueductal stenosis is usually identified because of symptomatic hydrocephalus that requires shunting, so that documented unshunted cases are rare. The groups of children with arrested hydrocephalus were included as a less severe form of hydrocephalus that did not require shunting and presumably is associated with less compression of brain tissue. Children in the no-hydrocephalus groups were combined across etiologies to help control for effects of other CNS lesions, thus helping to isolating the effects of hydrocephalus relative to other medical factors.

Children were included in the study with either Verbal or Performance IQ scores ≥70 on the Wechsler Intelligence Scale for Children—Revised (WISC-R; Wechsler, 1974) so that results would not reflect generalized mental deficiency. Children whose hydrocephalus was secondary to or associated with other neurological problems (e.g., trauma, stroke, tumor) were also excluded from the study. Additionally, children with uncontrolled epilepsy, primary sensory loss (blindness, deafness), severe behavioral disorder (e.g., autism, childhood psychosis), evidence of abuse or neglect, or problems with hand use so severe that the child's ability to manipulate test materials was limited were excluded.

Table 1 provides pertinent MRI and medical history findings by etiology and hydrocephalus groups. All MRI scans were reviewed by a radiologist and pediatric neurologist and were obtained concurrently with the neuropsychological assessment on all but 13 cases. In these latter cases, medical records contained sufficient information to justify classification into the hydrocephalus-type group. Technical problems and parental refusal accounted for the missing MRI scans.

As expected, children in the three hydrocephalus-type groups exhibited a variety of findings on MRI consistent with etiology. A few children with spina bifida in the no-hydrocephalus group had Chiari I (n = 3) or Chiari II (n = 1) malformation. These conditions are frequently found in children with spina bifida and both shunted and arrested hydrocephalus, therefore these participants were not excluded. Children in the shunted hydrocephalus groups exhibited periventricular leukomalacia (n = 17), partial agenesis and hypoplasia of the corpus callosum (n = 60), predominantly Chiari II malformations (n = 59), and predominantly right-sided shunt placements (n = 54). Children in the arrested hydrocephalus groups presented with periventricular leukomalacia (n = 12), hypoplasia and partial agenesis of the corpus callosum (n = 21), and Chiari I and II malformations (n = 6). Problems with ambulatory
status were restricted to children with spina bifida, who were mostly meningomyeloceles. Very few children had a history or current presentation involving a seizure disorder.

Sociodemographic data and WISC-R IQ scores for each of the etiology and hydrocephalus groups are presented in Table 2. The single participant with aqueductal stenosis and arrested hydrocephalus was not included. Comparisons of groups based on type of etiology and hydrocephalus groups are presented in Table 2. The IQ data were consistent with other studies of children with hydrocephalus and were included only for descriptive purposes. The data were not analyzed because the group differences are clear and IQ was not a primary variable for this study.

Procedures

As part of a broad neuropsychological evaluation, each participant was given the WISC-R and five measures of memory function. In addition, measures related to verbal fluency and automaticity (Verbal Fluency and Rapid Naming; Gudles & Crockett, 1975; Denckla & Rudel, 1974), perceptual motor skills (Grooved Pegboard; Beery Test of Visual Motor Integration; Beery, 1982), and a test of fine motor skills (Grooved Pegboard; Knights & Norwood, 1980) were selected from the larger battery. These latter measures are well known and will not be further described. There were instances in which a test was not performed because of fatigue, inability to understand the instructions, or refusal. Sample sizes will therefore vary slightly for each procedure.

Verbal selective reminding test (Buschke, 1974). The verbal selective reminding test has been interpreted as a measure of long-term storage and retrieval for verbal information. Participants are told that they will be read a list of words and that they will be told that they will be read a list of words and that they will be reminded of any words they might forget and then asked to recall as many of the words on the list as they can, in any order. It is also explained that they will be reminded of any words they might forget and then asked to try and recall as many of the words on the list as they can, in any order.

Seizures

None

In past, not under treatment

Under treatment

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Seizures

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In past, not under treatment

Under treatment

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Table 2
Mean and Standard Deviations for Age, Sociodemographic Variables, and IQ Scores

<table>
<thead>
<tr>
<th>Variable</th>
<th>Shunted hydrocephalus</th>
<th>Arrested hydrocephalus</th>
<th>No hydrocephalus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SB (n = 39)</td>
<td>P (n = 16)</td>
<td>AS (n = 14)</td>
</tr>
<tr>
<td>Age (months)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>107.7</td>
<td>91.8</td>
<td>92.3</td>
</tr>
<tr>
<td>SD</td>
<td>30.0</td>
<td>23.4</td>
<td>25.2</td>
</tr>
<tr>
<td>Race (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euro American</td>
<td>72</td>
<td>75</td>
<td>71</td>
</tr>
<tr>
<td>African American</td>
<td>10</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>Latin American</td>
<td>15</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Other</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>% Female</td>
<td>36</td>
<td>44</td>
<td>62</td>
</tr>
<tr>
<td>% Female</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socioeconomic status (%)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Low (IV–V)</td>
<td>55</td>
<td>38</td>
<td>30</td>
</tr>
<tr>
<td>Middle (III)</td>
<td>31</td>
<td>31</td>
<td>14</td>
</tr>
<tr>
<td>High (IV–V)</td>
<td>26</td>
<td>31</td>
<td>57</td>
</tr>
<tr>
<td>WISC—R</td>
<td></td>
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</tr>
<tr>
<td>Verbal IQ</td>
<td>89.1</td>
<td>90.0</td>
<td>104.6</td>
</tr>
<tr>
<td>M</td>
<td>15.7</td>
<td>15.1</td>
<td>17.5</td>
</tr>
<tr>
<td>SD</td>
<td>20.4</td>
<td>14.8</td>
<td>17.3</td>
</tr>
<tr>
<td>Performance IQ</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>M</td>
<td>83.6</td>
<td>73.2</td>
<td>86.5</td>
</tr>
<tr>
<td>SD</td>
<td>15.4</td>
<td>16.5</td>
<td>19.3</td>
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<tr>
<td>Full-Scale IQ</td>
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</tr>
<tr>
<td>M</td>
<td>84.8</td>
<td>80.4</td>
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</tr>
<tr>
<td>SD</td>
<td>14.7</td>
<td>14.9</td>
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</table>

Note. SB = spina bifida; P = prematurity; AS = aqueductal stenosis; N = normal control; WISC—R = Wechsler Intelligence Scale for Children—Revised (Wechsler, 1974).

All participants received an individual trial score and a total age-adjusted score.

Nonverbal selective reminding test (Fletcher, 1985). This test is a visuospatial analogue to the verbal selective reminding test developed to measure serial recall of visuospatial material. Administration and scoring was based on selective reminding methods. The participant is shown a board with eight squares. Each square resembles a domino with five randomly placed dots. The participant is shown a target dot on each square and asked to remember its location. The participant is then asked to point to the target dot in each square. The participant is reminded of any dots recalled incorrectly and is asked to point to the correct dot in each square once again. The participant is given a total of four designs. After each design is shown, the participant is asked to recall the memory (the quadrants designs appeared in), sequential memory (sequence of designs), and visual memory (recalling the numbers or colors used). A scaled score is calculated based on the participant's age-adjusted score.

Design Memory. This test was taken from the Wide Range Assessment of Memory and Learning (WRAML; Sheslow & Adams, 1990). Participants are shown a total of four designs. After the presentation of the design for 10 s, it is removed and the participants are asked to draw it from memory. The design is divided by lines into quadrants, and the sheet the children are given on which to reproduce the design is also divided into quadrants. A practice trial is given so that the children understand that they are to draw the appropriate portion of the design in the corresponding quadrants. The scoring criteria center on the recall of the material, not quality of reproduction, to minimize the penalty for poor visuomotor control. The designs are a combination of simple geometric figures (circles, rectangles, triangles, crosses, etc.) occurring in a specific sequence and orientation. The measure yields a raw score reflecting the participant's spatial memory (the quadrants designs appeared in), sequential memory (order of designs), and visual memory (recalling the shapes used). A scaled score is calculated based on the participant's age-adjusted score.

Continuous Recognition Memory Test (Hamay, Levin, & Grossman, 1979). The Continuous Recognition Memory Test consists of 120 line drawings of familiar plants and animals, including eight pictures that recur on 40 trials. On each trial, the children are asked to respond “old” if the picture has been presented before or “new” if the picture is being shown for the first time. The pictures are presented on index cards, sequentially. The children are given 20 s to respond to each one. This test is a measure of visual recognition memory that has been used extensively in studies of children with brain injury (Fletcher & Levin, 1988). It yields age-adjusted scores for the number of correctly identified old items (hits) and the number of incorrectly identified new items (false alarms).
Results

Before evaluating the main effects of type of hydrocephalus, we performed two analyses to address possible Etiology × Hydrocephalus interactions. This was necessary because the etiology by hydrocephalus cells in the design cannot be filled. For example, children with aqueductal stenosis are almost always shunted for hydrocephalus and only a very few are not. However, testing for main effects without evaluating for Etiology × Hydrocephalus interactions is not justified given the etiology-specific brain anomalies associated with each etiology. The first analysis involved only the spina bifida and premature children, who were represented by each of the three types of hydrocephalus. The aqueductal stenosis children were not included because only 1 did not require a shunt. The second analysis eliminated children with arrested hydrocephalus, comparing children with shunted hydrocephalus (aqueductal stenosis, spina bifida, prematurity) and unshunted hydrocephalus (spina bifida, prematurity, normals) and using the normal group as a comparison to children with aqueductal stenosis. If either of these interactions failed to reach significance (.05/2 = .025), the main effect of hydrocephalus type was interpreted, with post hoc tests comparing the three hydrocephalus type groups conducted at .05/3 = .0167. Main effects of etiology were also evaluated when the interactions were not significant, but these effects were rarely significant and will not be reported. All analyses were coordinated on age-adjusted \( z \) scores when normative data were available. When normative data was not available, age was covaried from the analysis to eliminate this minor source of variability.

Verbal Selective Reminding Test

To assess storage versus retrieval components of short-term memory, we analyzed age-adjusted \( z \) scores for cumulative LTS and CLTR in an Etiology × Hydrocephalus × Score repeated-measures multivariate analysis of variance (MANOVA). In addition, to assess learning curves, we analyzed the LTS and CLTR scores by four blocks of two trials (Trials 1 and 2, 3 and 4, 5 and 6, and 7 and 8). To evaluate the difference in Trial 1 learning, we compared the groups on LTS and CLTR scores for Trial 1.

The MANOVA for the CLTR and LTS measures did not yield significant interactions involving Etiology × Hydrocephalus × Score interactions for the spina bifida–premature or hydrocephalus–no-hydrocephalus comparisons. There was a significant main effect of hydrocephalus type, \( F(4, 302) = 4.55, p < .002 \). Follow-up analyses of variance (ANOVA) were conducted separately for the two memory variables and were significant for CLTR, \( F(2, 154) = 10.24, p < .0001 \), and LTS, \( F(2, 154) = 8.16, p < .0001 \). Post hoc comparisons of the three hydrocephalus groups for both measures showed that children with shunted hydrocephalus performed more poorly than children with arrested or no hydrocephalus, who were not significantly different (see Table 3).

Analysis of Trial × Trial Learning for CLTR and LTS was conducted with age as a covariate because normative data were not available. No etiology effects involving the trials or score factor or significant two-way interactions for either comparison were revealed. There was a significant Hydrocephalus Type × Trials interaction, \( F(6, 298) = 3.55, p < .003 \). We evaluated the interaction by testing for trials effects within each type of hydrocephalus and collapsing across score. The effect of trials was significant for the arrested group, \( F(3, 27) = 6.31, p < .003 \), and no-hydrocephalus group, \( F(3, 33) = 8.77, p < .0001 \). The trials effect did not achieve the critical level of alpha \( (p < .0175) \) for the shunted hydrocephalus group, \( F(3, 65) = 1.18, p < .33 \). However, the shunted hydrocephalus group had a significant Score × Trials interaction, \( F(3, 65) = 4.03, p < .01 \). As Figure 1 shows, learning curves were generally lower in magnitude for children with shunted hydrocephalus for both the LTS and CLTR scores, but the CLTR score was flatter than the LTS score only in the shunted group. This finding implies more problems with retrieval than storage in the

### Table 3

**Mean Scores and Standard Deviations by Group on Memory Tests**

<table>
<thead>
<tr>
<th>Test</th>
<th>Shunted hydrocephalus</th>
<th>Arrested hydrocephalus</th>
<th>No hydrocephalus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N )</td>
<td>( M )</td>
<td>( SD )</td>
</tr>
<tr>
<td>Verbal selective reminding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTS(^*)</td>
<td>69</td>
<td>-1.22</td>
<td>1.80</td>
</tr>
<tr>
<td>CLTR(^*)</td>
<td>69</td>
<td>-1.21</td>
<td>1.19</td>
</tr>
<tr>
<td>Nonverbal selective reminding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTS(^*)</td>
<td>67</td>
<td>-1.90</td>
<td>1.28</td>
</tr>
<tr>
<td>CLTR(^*)</td>
<td>67</td>
<td>-1.52</td>
<td>1.14</td>
</tr>
<tr>
<td>Wide range assessment of memory and learning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design memory(^*)</td>
<td>54</td>
<td>4.24</td>
<td>2.66</td>
</tr>
<tr>
<td>Story memory</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate</td>
<td>58</td>
<td>17.90</td>
<td>9.80</td>
</tr>
<tr>
<td>Delayed</td>
<td>58</td>
<td>13.40</td>
<td>9.38</td>
</tr>
<tr>
<td>Continuous recognition memory</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hits(^*)</td>
<td>68</td>
<td>-1.56</td>
<td>2.04</td>
</tr>
<tr>
<td>FA(^*)</td>
<td>68</td>
<td>-1.75</td>
<td>1.81</td>
</tr>
</tbody>
</table>

*Note.* LTS = long-term storage; CLTR = consistent long-term retrieval; FA = false alarms.

\(^*\)Z scores. \(^*\)Raw scores.
shunted group, although Figure 1 shows that learning curves for both indices are impaired.

We conducted analysis of Trial 1 learning because Yeates et al. (1995) found no differences on Trial 1 learning on the CVLT-C. This analysis of covariance (ANCOVA) with age as a covariate revealed that the hydrocephalus groups remembered few words on the first trial for LTS, $F(2, 154) = 5.52, p < .005$, and CLTR, $F(2, 154) = 7.39, p < .001$. Post hoc comparisons revealed that the shunted hydrocephalus group performed significantly poorer than the no-hydrocephalus group on Trial 1 learning for LTS and performed significantly worse than both the arrested hydrocephalus and no-hydrocephalus groups on the CLTR initial learning trial.

**Nonverbal Selective Reminding Test**

The analysis of the CLTR and LTS scores yielded no significant interactions for Etiology $\times$ Hydrocephalus. There was a significant main effect for hydrocephalus type, $F(4, 298) = 7.98, p < .0001$. Follow-up ANOVAs were significant for CLTR, $F(2, 152) = 15.50, p < .0001$, and LTS, $F(2, 154) = 22.83, p < .0001$. In contrast to the verbal task, the performance of the shunted and arrested groups was significantly poorer ($p < .0167$) than the no-hydrocephalus group for both indices (see Table 3).

The CLTR and LTS scores were analyzed by blocks of trials, with no significant Hydrocephalus $\times$ Etiology interactions. A significant Hydrocephalus Type $\times$ Trials interaction was found, $F(6, 294) = 5.36, p < .0001$. Follow-up tests for trials effects within each type of hydrocephalus revealed a significant effect of trials only for the shunted hydrocephalus group, $F(3, 63) = 3.76, p < .015$. The Score $\times$ Trials interaction was significant within the arrested hydrocephalus group, $F(3, 27) = 5.17, p < .006$, and no-hydrocephalus group, $F(3, 53) = 4.92, p < .005$. As Figure 2 shows, learning curves were flatter for both LTS and CLTR scores in the shunted hydrocephalus group, whereas the other two groups showed more accelerated learning curves for LTS than CLTR scores.

Trial 1 learning revealed a significant effect of hydrocephalus type for LTS, $F(2, 152) = 5.70, p < .005$, and CLTR, $F(2, 152) = 7.73, p < .0006$. For both indices, the shunted hydrocephalus group remembered fewer items than the no-hydrocephalus group, with no differences involving the arrested group.

**Verbal Versus Nonverbal Selective Reminding Tests**

To compare material-specific demands for memory, the age-adjusted $z$ scores for the CLTR index from the verbal and nonverbal selective reminding tests were analyzed for each test. The LTS score yielded an identical pattern of results and will not be reported. Tests involving the Etiology $\times$ Hydrocephalus interaction were not significant for the spina bifida--premature and hydrocephalus--no-hydrocephalus comparisons. There was a significant main effect of hydrocephalus type, $F(4, 298) = 8.14, p < .0001$. The Task $\times$ Hydrocephalus interaction was not significant, $F(2, 149) < 1$, nor was there a main effect of task, $F(1, 149) = 2.36, p < .13$. Hence, these results provide no evidence for material-specific effects on serial learning. Follow-up tests of the hydrocephalus main effect would parallel those previously described for CLTR scores within each test.

**WRAML Design Memory**

For this analysis, only the Design Memory scale score was used in an Etiology $\times$ Hydrocephalus ANOVA. Again, no significant interactions of hydrocephalus and etiology were found. There was a significant main effect for hydrocephalus type, $F(2, 128) = 14.47, p < .0001$. Follow-up
comparisons revealed that the shunted hydrocephalus group had significantly lower scores than did the other two groups ($p < .0167$). The arrested hydrocephalus group did not differ significantly from the no-hydrocephalus group (see Table 4).

**WRAML Story Memory**

The raw scores for the immediate and delayed conditions were used in an Etiology $\times$ Hydrocephalus $\times$ Score multivariate analysis of covariance (MANCOVA), with age as a covariate because age-adjusted scores for the delayed condition were not available. There were no significant interactions, but the main effect for hydrocephalus type was significant, $F(4, 264) = 4.02, p < .004$. For immediate memory, the shunted hydrocephalus group tended to remember less information than the no-hydrocephalus group but did not differ significantly from the arrested or no-hydrocephalus group. However, for delayed memory, the shunted group recalled significantly less material than both the arrested and no-hydrocephalus groups ($p < .0167$), who did not differ significantly (see Table 4).

![Figure 2. Performance across trials on the nonverbal selective reminding test for long-term storage (LTS) and consistent long-term retrieval (CLTR) by type of hydrocephalus (shunted, arrested, and no).](image-url)
Continuous Recognition Memory

Age-adjusted z scores were calculated for hits and false alarms in a Hydrocephalus × Etiology × Score MANOVA. For the two initial comparisons, no significant Etiology × Hydrocephalus interactions were found. There was a significant main effect for hydrocephalus type, $F(4, 300) = 4.00, p < .004$. The follow-up ANOVAs were significant for the number of hits, $F(2, 153) = 4.77, p < .001$, and the number of false alarms, $F(2, 153) = 2.31, p < .011$. On both indices, the shunted hydrocephalus and no-hydrocephalus groups differed significantly from one another ($p < .0167$), but the arrested group did not differ significantly from the other two groups ($p < .0167$; see Table 4).

Correlations With Other Cognitive Skills

There were large mean differences in performance among the groups in this study. Such differences inflate bivariate correlations, so within-group estimates of variability were used. Pooled within-groups correlations were computed between each of the memory test scores and Full-Scale IQ to evaluate effects of IQ on the results. This approach eliminates the contribution of mean differences to the correlations by estimating the correlation separately within each group and then averaging across the groups. Additionally, pooled within-group correlations were conducted between each of the verbal memory measures (Digit Span, Story Memory, and verbal selective reminding), visual memory tests (Design Memory, Continuous Recognition Memory, and nonverbal selective reminding), and measures of fluency and automaticity (Verbal Fluency and Rapid Naming). The memory tasks were also correlated with the Beery Test of Visual Motor Integration and the Grooved Pegboard (both the dominant and nondominant hand) to evaluate relationships with motor skills (see Table 5).

Forty-two correlations were computed. To control for Type I errors, a Bonferroni adjusted level of alpha, $0.05/42 = .001$, was utilized. General intelligence as measured by a Full-Scale IQ score was correlated at significant levels with the number of hits on the Continuous Recognition Memory Test, $r = .35$, backward digit span, $r = .48$, Design Memory, $r = .35$, and Story Memory, $r = .55$, but not with the serial learning measures. Hence, covarying IQ score would have a significant influence on Story Memory but little influence on other measures. There were no significant correlations between measures of fine motor skill coordination or visuomotor integration and the visual memory measures. These correlations were of interest, because strong correlations would indicate that the visual memory measures could be negatively affected by poor fine or visuomotor skills. Significant correlations did exist between some of the visual memory tests and measures of verbal fluency and automaticity, but the magnitude of these correlations was modest ($r = .34-.43$). Altogether, these results do not show strong relationships of memory test performance with other cognitive and motor measures.

Discussion

In this study, children with shunted hydrocephalus displayed a pervasive pattern of memory deficits. Performance on both verbal and nonverbal memory measures differentiated children with shunted, arrested, and no hydrocephalus, but the children with shunted hydrocephalus showed deficiencies on both measures. In addition, children with shunted hydrocephalus performed more poorly on measures involving serial learning, recognition memory, prose recall, and visuconstructive memory.

These serial learning results are consistent with several previous studies (Richardson, 1978; Speigler, 1984; Yeates et al., 1995) and support previous observations that children with early shunted hydrocephalus demonstrate significant impairment on serial learning tasks. However, the pattern of performance was consistent with both encoding and retrieval problems. Because the shunted hydrocephalus participants placed new words into storage more slowly, the number of

<table>
<thead>
<tr>
<th>Test</th>
<th>Word fluency</th>
<th>Rapid naming</th>
<th>VMI</th>
<th>Pegs-D</th>
<th>Pegs-ND</th>
<th>Full-scale IQ</th>
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<td></td>
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<td>.11</td>
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<tr>
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<td>.41*</td>
<td>.34*</td>
<td>.18</td>
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<td>.35*</td>
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<tr>
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<td>.40*</td>
<td>.16</td>
<td>.18</td>
<td>.04</td>
<td>.35*</td>
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</tbody>
</table>

Note. VMI = Berry Test of Visual Motor Integration; Pegs = Grooved Pegboard; D = dominant; ND = nondominant; LTS = long-term storage; CLTR = consistent long-term retrieval; WRAML = Wide Range Assessment of Memory and Learning; CRM = Continuous Recognition Memory Test. *p ≤ .0001.
words available for retrieval remained small. Yeates et al. (1995) also found children with meningoce and shunted hydrocephalus to have significant retrieval problems on the CVLT-C. The administration of the verbal selective reminding test and CVLT-C differ in that words are drawn from three separate categories on the CVLT-C versus one category (animal names) on verbal selective reminding, and children are given only five learning trials on the CVLT-C versus up to eight on verbal selective reminding. The CVLT-C also uses an interference trial that is not included in the administration of verbal selective reminding. Yeates et al. (1995) found that the shunted hydrocephalus group differed from the normal control group in their rate of acquisition but performed well on a recognition measure. They interpreted these findings to mean that although information had entered long-term storage, recall scores were depressed by word retrieval problems. In contrast, this included in the administration of verbal selective reminding.

The CVLT-C versus up to eight on verbal selective reminding. The finding that the severity of hydrocephalus is negatively related to the presence of learning and memory problems is consistent with the hypothesis that compression of the hippocampus and other subcortical structures may occur as a function of the changes in the white matter tract in response to ventricular enlargement and migrational abnormalities. This is consistent with Zola-Morgan and Squire's (1993) suggestion that deficits in declarative memory are primarily related to lesions involving the medial temporal lobe and diencephalon or connections to these areas. Fletcher, Bohan, et al. (1992) also discussed the effect of hydrocephalus on white matter tracts, specifically impairment of projection fibers near the midline connecting the hemispheres to the diencephalon. Likewise, the neuroimaging studies conducted with the hydrocephalus participants included in this study commonly showed compression of the medial temporal lobes and hypothalamus. Thus, the areas implicated in declarative memory deficits are clearly affected by hydrocephalus. This is consistent with the hypothesis that changes in the white matter, particularly midline regions, that can occur in relation to hydrocephalus could account for the memory impairment demonstrated by children with shunted hydrocephalus. The arrested hydrocephalus group generally failed to differ significantly from both the shunted and no-hydrocephalus group but consistently performed as well as the control group. This would support
the hypothesis that the degree of damage to white matter tracts is proportional to the degree of ventricular enlargement. Zola-Morgan and Squire (1993) report that the broader or more severe the lesions to medial temporal and diencephalic structures, the greater the memory impairment.

This study did not attempt to directly measure and compare the hippocampus and other subcortical structures across the three groups. In children with hydrocephalus, midline studies are often so distorted that reliable quantitative measures are difficult to obtain across cases, and many of the relevant structures are displaced or hard to visualize. As technological advances make such measurements increasingly possible, it may become possible to assess this. Such studies would be useful in addressing the assertion that hydrocephalus leads to compression of the hippocampus and other subcortical structures as well as damage to projection fibers that connect the diencephalon with the cerebral hemispheres. Additionally, larger sample sizes would make it possible to obtain the power necessary to test the influence of etiology, which may add valuable information as to what factors may influence learning and memory deficits. Small sample sizes limited our ability to analyze the contribution of various neurological findings such as presence of periventricular leukomalacia, changes in the corpus callosum, the number of shunt revisions, and the presence of Chiari malformations. It would be useful to evaluate whether performance on learning and memory tests differ as a function of any of these secondary neuropsychological factors.

References


