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Motor adaptation in children with myelomeningocele: Comparison to children with ADHD and healthy siblings

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Abstract

Myelomeningocele is a common developmental malformation of the central nervous system that usually results in motor deficits. Previous studies of myelomeningocele have not examined motor adaptation, which involves changes in the control of movements that occur as a result of repeated task exposure but do not depend on conscious recall of the exposure. We studied motor adaptation in 17 children with myelomeningocele and shunted hydrocephalus, 19 children with attention deficit/hyperactivity disorder (ADHD), and 20 healthy siblings. All children were 8 to 15 years of age. They were administered 2 measures of motor adaptation known to be sensitive to subcortical abnormalities in adult neurological disorders. One task assessed the biasing in weight judgments that occurs after exposure to heavy *versus* light weights, and the other assessed the adaptation in reaching movements that occurs when vision is laterally displaced by prisms. Contrary to expectations, the groups did not differ in motor adaptation. Children in all 3 groups displayed significant biasing in their weight judgments and improvement in the accuracy of pointing during prism adaptation trials. Performance on the 2 motor adaptation tasks was not related to age or IQ. Weight biasing was positively related to a measure of response disinhibition. The findings suggest that myelomeningocele does not result in global impairment of motor skills, but instead in a profile of intact and impaired motor functions that potentially may be decomposed in accordance with the neuroscience of motor skills. (*JINS*, 2003, *9*, 642–652.)

Keywords: Myelomeningocele, Attention deficit hyperactivity disorder, Motor adaptation

INTRODUCTION

Spina bifida is one of the most frequent birth defects and represents the most common developmental malformation affecting the central nervous system, with an incidence of from 1 to 5 per 1,000 live births in the United States (Shurtleff & Lemire, 1995). Myelomeningocele is the most severe form of spina bifida, and is usually associated with hydrocephalus and other brain abnormalities, such as agenesis of the corpus callosum, the Arnold-Chiari malformation, and a variety of other subcortical anomalies (Gilbert et al., 1986).

Spina bifida often results in neurobehavioral deficits and associated functional impairments, including poor motor skills (Fletcher et al., 2000; Wills, 1993; Yeates et al., 1998). Both gross and fine motor skills are usually affected (Hetherington & Dennis, 1999). Numerous studies have shown deficits on psychomotor tasks such as finger tapping and pegboards, as well as on other measures of hand function (Grimm, 1976; Prigatano et al., 1983; Shaffer et al., 1986; Zeiner et al., 1985). Children with spina bifida also display deficits on measures of visuomotor coordination, such as drawing and handwriting (Zivani et al., 1990).

Most previous research on the motor skills of children with spina bifida has been descriptive in nature and has relied on either qualitative clinical assessments or standardized test instruments that yield omnibus scores. The research generally has not been based on specific theories of motor function and typically has not attempted to relate motor deficits to the specific brain abnormalities with which spina bifida is often associated. The neuroscience of motor

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skills, however, indicates that motor function can be decomposed into specific components that have distinct neural substrates (Ivry & Corcos, 1993).

One major component of motor function is referred to as motor adaptation. Motor adaptation involves changes in the control of movements that occur as a result of repeated task exposure or practice but do not depend on conscious recall of the previous exposure. Motor adaptation is often regarded as a form of procedural learning, and hence as a form of implicit memory (Saint-Cyr & Taylor, 1992). In contrast to explicit or declarative memory, which involves conscious recollections of past events or experiences, implicit or nondeclarative memory involves the demonstration of learning or facilitation of performance in the absence of conscious recollection. Implicit memory takes several different forms, including priming and procedural learning.

Research with adult neurological populations has shown dissociations between implicit and explicit memory. For instance, adults with amnestic disorders have demonstrated intact procedural learning, despite marked impairment in explicit memory (Benzing & Squire, 1989; Heindel et al., 1991; Paulsen et al., 1993). In contrast, patients with subcortical dementias such as Huntington's disease have demonstrated significant deficits in motor adaptation compared to normal controls and to patients with Alzheimer's disease, despite relatively intact explicit memory (Heindel et al., 1991; Paulsen et al., 1993). These results have suggested that procedural learning, and motor adaptation more specifically, is mediated in part by a cortical–subcortical system involving the premotor cortex and striatum (Saint-Cyr & Taylor, 1992).

Functional neuroimaging has provided additional evidence for the involvement of the striatum in procedural learning (Grafton et al., 1995; Poldrack et al., 1999), although other brain regions also have been implicated (Honda et al., 1998). In particular, the cerebellum also appears to play a role in procedural learning, both cognitive and motoric (Friston et al., 1992; Houk et al., 1996; Pascual-Leone et al., 1993; Thach, 1997, 1998). The cerebellum has been shown to be involved specifically in motor adaptation (Lang & Bastian, 1999; Weiner et al., 1983).

Developmental studies of normal children have also provided evidence for a dissociation between implicit and explicit memory. Implicit and explicit memory develop at different rates during childhood. Implicit memory tends to reach an adult asymptote relatively early and remains stable over time, whereas explicit memory continues to improve with age (DiGiulio et al., 1994; Graf, 1990; Mitchell, 1993; Naito, 1990; Naito & Komatsu, 1993; but also see Drury et al., 2000). The earlier development of implicit memory systems is consistent with evidence that the striatum is among the first telencephalic structures to undergo myelination (Nelson, 1995).

Only a few attempts have been made to investigate the distinction between implicit and explicit memory in children with either neurological or neurodevelopmental disorders. Implicit and explicit memory have been compared in children with mental retardation (Wyatt & Connors, 1998), learning disabilities (Lorsbach & Worman, 1989), autism (Renner et al., 2000), Down and Williams syndromes (Vicari, 2001; Vicari et al., 2001), heavy prenatal alcohol exposure (Mattson & Riley, 1999), brain tumors (Dennis et al., 1998), and traumatic brain injury (Shum et al., 1999; Ward et al., 2002). None of these studies, however, has examined motor adaptation.

One of the few childhood clinical disorders in which motor adaptation has been investigated is attention deficit hyperactivity disorder (ADHD). Several studies examined the performance of children with ADHD on the rotary pursuit task. Leavell et al. (1995, 1999) found that children with ADHD spent less time on target than normal controls on average, but that the two groups demonstrated comparable improvement over time, suggesting equivalent motor adaptation. In contrast, Colvin et al. (1997) found that normal controls demonstrated significant improvement in their time on target, whereas the performance of children with ADHD did not change, suggesting that children with ADHD displayed less motor adaptation. The different findings may reflect procedural differences: Colvin et al. (1997) had children complete a larger number of trials than did Leavell et al. (1995, 1999), and they adjusted the speed of the rotary pursuit task for each child based on performance on practice trials

Research into the neurobiology of ADHD has provided evidence for morphological and metabolic differences in the brain regions responsible for learning and executing motor programs, as well as for procedural learning more generally. Regional cerebral blood flow studies have suggested reduced metabolic activity in the striatum (Lou et al., 1989), and differences in striatal morphology have also been found (Castellanos et al., 1996; Hynd et al., 1993). Structural differences in the cerebellar vermis also have been identified in children with ADHD (Berquin et al., 1998; Castellanos et al., 1996; Mostofsky et al., 1998). The brain differences that characterize children with ADHD may increase the likelihood that they will display deficits in motor adaptation.

Children with myelomeningocele also demonstrate brain abnormalities that may give rise to deficits in motor adaptation. The poor motor skills of children with myelomeningocele are at least partially attributable to cerebellar abnormalities (Dennis et al., 1999). They may also be related to other forms of subcortical dysfunction. Indeed, subcortical structures such as the thalamus and the white matter fibers linking them to the cortex are susceptible to the effects of hydrocephalus, and are often abnormal in children with myelomeningocele (Gilbert et al., 1986). Nonetheless, despite the motor deficits shown by children with myelomeningocele, their motor adaptation has not been examined using experimental tasks like those employed in adult neurological populations. In fact, to the best of our knowledge, no published studies have examined the implicit memory of any sort in children with myelomeningocele.

The primary purpose of the current study was to examine motor adaptation in children with children with myelome-

ningocele, as compared both to children with ADHD and a comparison group of healthy siblings. Children with myelomeningocele were of primary interest because we wanted to determine if their motor deficits encompass specific components of motor function that have been identified in the neuroscience literature. We included children with ADHD in part to extend previous studies of their motor adaptation, but also because the inclusion of a clinical comparison group would enable us to determine if any deficits in motor adaptation shown by children with myelomeningocele are unique or also seen in other clinical conditions. The two clinical disorders also were apt targets for the study of motor adaptation given the brain abnormalities with which they are associated.

The three groups of children completed two measures of motor adaptation, prism adaptation and weight biasing, that have been shown to be sensitive to subcortical dementias in adults (Heindel et al., 1991; Paulsen et al., 1993). Based on previous research in children with ADHD and the brain abnormalities associated with myelomeningocele, the two clinical groups were expected to demonstrate significantly less biasing in weight judgments and significantly less adaptation to distorting prisms than the sibling comparison group.

A secondary goal of the study was to examine motor adaptation in relation to age and IQ. Previous research has suggested that children's implicit memory is largely independent of chronological age and cognitive ability (DiGiulio et al., 1994; Graf, 1990; Mitchell, 1993; Naito, 1990; Naito & Komatsu, 1993), but the relationship of these factors specifically to motor adaptation has not been examined before. Neither age nor IQ was expected to be related to measures of weight biasing and prism adaptation. A final aim of the study was to explore the relationship between response inhibition and motor adaptation. Response inhibition is often thought to depend on brain systems that link the basal ganglia and frontal lobes, and is typically impaired in children with ADHD (Barkley, 1997; Denckla, 1996). Response inhibition and motor adaptation may be correlated to the extent they are mediated by similar brain substrates.

METHODS

Research Participants

Participants included 17 children with myelomeningocele and shunted hydrocephalus, 19 children with ADHD, and a comparison group of 20 siblings recruited from the two clinical groups. All participants were from 8 to 15 years of age. Children were excluded from the study if they had a primary sensory loss or severe spasticity or other motor impairments that would preclude the administration of the experimental tasks. Children also were excluded if their estimated IQ, derived from a short form of the Wechsler Intelligence Scale for Children–Third Edition (WISC–III; Wechsler, 1991), was less than 70.

Children with myelomeningocele were recruited from the roster of a large hospital clinic for children with spina bifida. They were included only if they had a documented history of hydrocephalus that required shunting shortly after birth. Children with myelomeningocele were excluded if they had a history of significant neurological complications aside from hydrocephalus, such as ventriculitis, seizures, or any other brain disease or injury. In the myelomeningocele group, 5 children had lesions in the low thoracic to high lumbar (T12–L2) region and the remaining 12 children had lesions in the low lumbar (L3–L5) region. The number of shunt revisions in the group ranged from zero to 11, with a median of 1. Only 1 child had more than three revisions.

Children in the ADHD group were recruited from the roster of a large hospital clinic for childhood learning and behavior disorders. They were included if clinic medical records indicated they had been diagnosed with the combined subtype of ADHD by clinic medical staff. We restricted recruitment to children diagnosed with the combined subtype of ADHD because of research suggesting that the primarily inattentive subtype may represent a separate and unique disorder rather than simply a subtype of the same attentional disturbance (Cantwell & Baker, 1992; Goodyear & Hynd, 1992).

Diagnoses were made using DSM–IV criteria (American Psychiatric Association, 1994), in accordance with established clinical practice guidelines (American Academy of Pediatrics, 2000; Dulcan & Benson, 1997). Diagnostic procedures included traditional, non-standardized clinical interviews with children and parents and standardized ratings provided by parents and teachers on the Child Behavior Checklist and Teacher Report Form (Achenbach, 1991) and the Conner's Parent and Teacher Rating Scales (Conners, 1990). In addition, at the time of the study, children in the ADHD group were required to meet symptom criteria for ADHD based on parent ratings obtained on the Child Symptom Inventory–Fourth Edition (CSI–4; Gadow & Sprafkin, 1997). On the CSI–4, 3 children met the symptom criteria for the *primarily inattentive* subtype, 5 for the *primarily hyperactive–impulsive* subtype, and 11 for the *combined* subtype.

The comparison group of siblings was recruited from all participating families who had healthy siblings in the desired age range. The sibling nearest in age to each child in the two clinical groups was invited to participate. The group consisted of 12 siblings recruited from the myelomeningocele group and 8 from the ADHD group. A comparison of siblings recruited from the two clinical groups did not reveal any significant differences in age, gender, race, handedness, socioeconomic status, estimated IQ, or the number of inattentive or hyperactive-impulsive symptoms of ADHD endorsed on the CSI–4.

Children were excluded from the ADHD and sibling comparison groups if they had a history of neurological illness or major developmental disability. In addition, children were excluded from the sibling comparison group if they had a history of ADHD by parent report or if they met symptom

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criteria for ADHD based on parent ratings obtained on the CSI–4. Parents rated most siblings ($n = 12$, 60%) as showing no symptoms of ADHD, and none of the siblings was rated as displaying more than 3 out of 9 inattentive symptoms, 4 out of 9 hyperactive–impulsive symptoms, or 6 out of 18 total symptoms. Children were not excluded for any other comorbid conditions. Parent ratings on the CSI–4 indicated that 14 children in the ADHD group met the symptom criteria for a diagnosis of oppositional defiant disorder, but that only 2 children from each of the other groups did. Parents reported that about 50% of the children in the two clinical groups were receiving special education services, as compared to only 1 of the siblings.

In the ADHD group, 17 of 19 children were being treated with psychotropic medication at the time of the study. All but one of those children were receiving stimulant medication; the other child was receiving a tricyclic antidepressant. One of the children in the ADHD group being treated with a stimulant was also receiving clonidine. In the myelomeningocele group, 3 out of 17 children were being treated with psychotropic medication, which in all cases were stimulants. None of the 20 children in the sibling group were being treated with psychotropic medication. Parents were asked to withhold stimulant medication from children for 12 hr prior to their participation in the study. None of the children were receiving longer-acting stimulant medications. We did not feel we could ethically require the two children receiving psychotropic medications other than stimulants to discontinue them.

Table 1 presents demographic information regarding the three groups of participants. The groups did not differ in age, race, or handedness, but did differ in gender, estimated IQ, and socioeconomic status (i.e., Hollingshead Four-Factor Index; Hollingshead, 1975). The ADHD group had a higher proportion of boys than the other two groups, consistent with the demographics of the disorder. The myelomeningocele group had a lower mean IQ than the sibling group, but no other paired comparisons were significant; the same pattern obtained when controlling for socioeconomic status. The socioeconomic status of the ADHD group was lower than that of the other two groups, which did not differ; however, group comparisons on measures of motor adaptation were unaffected when socioeconomic status was included in analyses as a covariate.

As expected, the groups differed significantly on the number of symptoms of ADHD endorsed on the CSI–4. The ADHD group was reported to display more inattentive and hyperactive–impulsive symptoms than the other two groups. The myelomeningocele group was reported to display more inattentive symptoms than the siblings, but did not differ from siblings in the number of hyperactive–impulsive symptoms. The groups also differed on a measure of response inhibition, with the ADHD group displaying more errors of commission than the other two groups on the vigilance task from the Gordon Diagnostic System (GDS; Gordon, McClure, & Aylward, 1996). The groups did not differ significantly in the number of omissions on the GDS.

Measures

Weight biasing task

Materials for the weight-biasing task consisted of 10 containers ranging in weight from 35 g to 485 g in 50-g increments (Heindel et al., 1991). The containers were identical in appearance, and were created by packing white, cylindrical, plastic medicine containers with differing amounts of lead shot and cotton.

All children were tested individually in a quiet, well-lighted room, with the child seated at a table opposite the examiner. The child was instructed as follows:

Table 1. Demographic characteristics of participants

	Group					
Variable	Myelomeningocele $N = 17$		ADHD $N = 19$		Sibling $N = 20$	
Gender (*n*, % male)*	10	59	15	79	8	40
Race (*n*, % white)	16	94	12	63	16	80
Handedness (*n*, % right handed)	14	82	19	100	18	90
Age (*M*, *SD*)	11.94	2.56	10.16	2.14	10.90	2.40
Estimated IQ (*M*, *SD*)*	88.35	11.93	92.63	12.95	102.00	15.55
Hollingshead Four-Factor Index (*M*, *SD*)*	46.65	11.88	26.05	10.71	37.85	15.81
CSI–4 inattentive symptoms (*M*, *SD*)[a]*	3.41	3.37	7.00	1.97	0.60	1.19
CSI–4 hyperactive–impulsive symptoms (*M*, *SD*)[a]*	1.18	2.21	7.32	1.57	0.50	0.83
GDS omissions (*M*, *SD*)	4.75	3.87	7.17	6.53	3.60	3.55
GDS commissions (*M*, *SD*)*	4.56	5.66	43.11	71.36	7.90	10.25

Note. ADHD = Attention deficit hyperactivity disorder. CSI–4 = Child Symptom Inventory–Fourth Edition. GDS = Gordon Diagnostic System.
[a]Number of symptoms endorsed by parent as occurring "often" or "very often." Range 0–9.
*Group difference significant, $p < .05$

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> This is a test of the ability to judge weights. In a minute, I will give you a series of containers to lift. I will give you the containers one at a time. When I give the first one to you, I want you to lift it. I will then take it away. I will then give you another container; and I want you to lift that one. Then I will ask you to tell me whether it is heavier or lighter than the first one. I'll keep giving you containers, and for each one, I want you to tell me whether it is heavier or lighter than the one before it.

The examiner then placed one of the containers on the table in front of the subject and demonstrated the method to be used for lifting the weights. Children were instructed to keep their elbow on the table, grasp the top of the container with the thumb and index finger, lift the container approximately 13 cm off the table, and then set the container back down. The subject was then to report whether that weight felt heavier or lighter than the preceding weight.

The participant was given 40 trials of either the five lightest containers (i.e., the *light bias* condition) or the five heaviest containers (i.e., the *heavy bias* condition). For each condition, the five weights were presented eight times each in a fixed random order, the only constraint being that only one container was visible to the child at any given time.

After a 20- to 25-min delay, a 7-item recall and recognition test was administered to probe the child's memory of the biasing trials. The child was asked a series of questions concerning particular aspects of the bias session (such as which fingers were used to lift the weights). If the child was unable to answer the question in a free recall format, then he or she was asked to choose an answer from four alternatives. The child was provided with the correct answer for any question failed on the recognition test. For scoring purposes, an item was considered correct on the explicit memory test if the child was able to either correctly recall or recognize the answer.

Immediately following the explicit memory test, the subject was given the 10 test trials to assess the level of bias in their weight judgments. Each child lifted the 10 test weights in a fixed random order and then rated the heaviness of each weight on a scale that raged from 1 (*extremely light*) to 9 (*extremely heavy*). The scale, printed on an 21 × 28 cm sheet of paper, was placed on the table in front of the child.

Children were administered the second set of 40 bias trials and 10 test trials approximately 45 min after the first bias condition. The order of conditions was counterbalanced across participants so that half of the children within each group received the heavy bias condition first and the light bias condition second, while the other half received the light bias condition first and the heavy bias condition second. Within each condition, half of the subjects used their preferred hand on the bias trials and the other half used their non-preferred hand. Subjects then used their opposite hand on the second bias condition. For the test trials, subjects always used the hand opposite to the hand used for the bias trials. The order of the test trials was the same for both bias conditions.

Dependent variables derived from the weight biasing task were the average of the heaviness ratings on each set of 10 test trials following the light and heavy weight biasing conditions.

Prism adaptation task

For the prism adaptation task (Paulsen et al., 1993), each child was seated in front of a flat rectangular plywood platform. The platform measured 40 cm × 73 cm, and raised 20.5 cm above a table by two side supports so that the child's arm could pass beneath it. A red vertical line (12.5 cm in length) was placed in the exact center of a 9.5 cm × 73 cm plexiglass strip and served as the child's target. The strip was attached perpendicular to and rising 10 cm above the posterior edge of the wooden platform. A plywood strip was hinged in front of the plexiglass strip, so that the target line was fully visible when the plywood strip was placed in the down position. Vertical lines separated by 1 cm were painted on the back side of the plexiglass strip to measure the accuracy of the child's pointing. The child's head was held stationary by a chin rest, which was centered 37 cm directly in front of the target line.

The distorting lenses consisted of 20 diopter Fresnel base right and base left press-on prisms (3M Health Care) set in laboratory goggles. The goggles were large enough to allow children to wear regular corrective lenses underneath.

The child's preferred hand was placed, palm up, on the near edge of the table, with the index finger pointing up. The child was instructed to touch the target line with the index finger, moving the arm in a continuous ballistic movement under the wooden platform and bringing the index finger up against the back side of the apparatus. On each trial, the examiner recorded the accuracy of the child's target response (i.e., the distance in cm from the target vertical line). The child's hand was moved back to the starting position after each trial.

There were six practice trials, during which each child was asked to point to the target without the prism glasses in place to ensure that participants understood the instructions and to obtain baseline performance. The hinged cover was raised in front of the plexiglass strip so that the children could not see their hands and thereby use visual feedback to determine the accuracy of their pointing. They were provided no verbal feedback concerning the accuracy of their performance.

Goggles were placed on each child by the examiner. Direction of visual distortion was randomized across participants. Within each group, approximately half of the subjects experienced right distortion and the other half, left distortion. While wearing the prisms, each child was given 12 test trials to determine the degree of shift (i.e., distortion) from baseline produced by the prisms (i.e., preadaptation reaching). On each trial, the child attempted to touch the vertical target with the index finger of his or her preferred hand. As with baseline testing, the subjects received no visual feedback regarding the accuracy of their preadaptation performance.

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The next phase assessed prism adaptation. Children again reached under the wooden apparatus to touch the red target line, but in contrast to the preceding conditions, the wooden strip was folded down so that children could see through the plexiglass strip. In this condition, children were allowed to view their index finger through the plexiglass and thereby receive visual feedback as to the accuracy of their responses. Adaptation was assessed by completing 30 trials with this visual feedback.

Following the assessment of adaptation, the plexiglass strip was again covered by the hinged cover, and the child completed 12 test trials to assess post-adaptation performance, or the extent of shift toward the baseline produced by the adaptation experience. As in the baseline and preadaptation conditions, children were unable to view their hands and received no feedback about accuracy.

Finally, the children's goggles were removed and they completed 12 additional test trials to assess the extent of negative aftereffects (i.e., pointing errors in the opposite direction of the distorting prisms). For instance, if the prism distortion was to the right, aftereffects would be demonstrated if the participants placed their finger to the left of the target when the prisms were removed. Again, the participants could not view their hands and received no verbal feedback about the accuracy of their responses.

Dependent variables were the mean absolute distance from the target vertical line for each of the five conditions: *baseline*, *preadaptation*, *adaptation*, *postadaptation*, and *negative aftereffects*.

Additional measures

Children were administered the Vocabulary and Block Design subtests of the WISC–III (Wechsler, 1991) to derive estimated IQ scores. They also were administered the vigilance task from the GDS to assess sustained attention and response inhibition. The GDS is a commercially available continuous performance test. The total number of omission errors on the GDS was considered a measure of sustained attention and the total number of commissions was used as a measure of response inhibition (Gordon et al., 1996).

Procedure

Children completed all testing in a single $1\frac{1}{2}$ to 2 hr testing session. Testing began with the first 40-trial weight biasing condition. The WISC–III Vocabulary subtest and the assessment of explicit memory for the weight-biasing task were then completed. Each participant then completed the first 10-trial assessment of weight biasing. The prism adaptation task was then administered. Each participant then completed the second 40-trial weight-biasing condition, followed by the WISC–III Block Design subtest and the vigilance task of the GDS. Finally, the second 10-trial assessment of weight biasing was administered.

RESULTS

Weight Biasing

All three groups were able to discriminate accurately among different weights during the weight biasing trials, although the siblings were significantly more accurate than the other two groups. Table 2 shows the mean percent correct for judgments of whether the current weight was heavier or lighter than the immediately preceding weight for each group under each condition. A Group × Bias Condition (heavy *vs.* light bias) repeated-measures analysis of covariance (ANCOVA), with age as the covariate, revealed a significant main effect for group [$F(2,52) = 6.93$, $p < .005$]. Age also was positively related to accuracy [$F(1,52) = 5.01$, $p < .05$].

All three groups demonstrated significant biasing in their weight judgments, but did not differ from each other in the amount of biasing. Table 3 shows the mean heaviness ratings for each group during the 10 test trials after each bias condition. Weight biasing is demonstrated if the weights are rated lighter after exposure to heavy weights and heavier after exposure to light weights. A Group × Bias Condition (heavy *vs.* light) repeated-measures analysis of variance (ANOVA), revealed a significant main effect of condition [$F(1,53) = 24.00$, $p < .001$] but neither the group main effect nor Group × Condition interaction was significant.

The groups did not differ in their explicit memory for the biasing trials, as shown in Table 4. An ANCOVA with group as the independent variable and age as the covariate revealed a significant main effect for age [$F(1,52) = 5.85$, $p < .05$], but the group main effect was not significant [$F(2,52) = 0.04$, $p > .10$].

A hierarchical regression analysis was conducted to determine if age, IQ, and response inhibition (i.e., GDS total commissions) would predict the degree of biasing in weight judgments. The dependent variable was a difference score that reflected the degree of biasing, computed by subtracting each child's mean heaviness rating for the light bias condition from the mean heaviness rating for the heavy bias condition. Two dummy variables representing group membership were entered into the regression on the first step, to control for group differences in biasing, and the three continuous predictors were entered simultaneously on the sec-

Table 2. Percent correct weight comparisons by bias condition on weight biasing task

Bias condition	Group					
	Myelomeningocele		ADHD		Sibling	
	M	*SD*	*M*	*SD*	*M*	*SD*
Heavy	0.86	0.07	0.82	0.10	0.91	0.08
Light	0.93	0.06	0.88	0.12	0.95	0.03

Note. ADHD = Attention deficit hyperactivity disorder.

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Table 3. Mean heaviness ratings by bias condition on weight biasing task

Bias condition	Group					
	Myelomeningocele		ADHD		Sibling	
	M	*SD*	*M*	*SD*	*M*	*SD*
Heavy	5.27	0.62	4.97	0.52	5.23	0.60
Light	5.52	0.55	5.53	0.60	5.47	0.56

Note. ADHD = Attention deficit hyperactivity disorder.

ond step. Interaction terms were entered in a third and last step to determine if the relationship between the predictors and weight biasing varied across groups. The interaction terms were constructed by multiplying each dummy variable by the three continuous variables.

After entering the two dummy variables, age, IQ, and response inhibition together explained an additional 14% of the variance in weight biasing [$F(3,48) = 2.93$, $p < .05$]. GDS total commissions accounted for significant unique variance ($t(1,48) = 2.72$, $p < .01$) and was related positively to biasing. Neither age nor IQ accounted for unique variance. The interaction terms did not account for a significant increase in the variance explained, and none of the individual interaction terms was significant.

Prism Adaptation

Mean absolute accuracy scores were computed for each child for the trials constituting each of the five conditions of the prism adaptation task, and are presented in Table 5. Performance across all five conditions was analyzed using a Group × Condition repeated-measures multivariate ANOVA. The analysis revealed a significant main effect of condition [$F(4,50) = 90.56$, $p < .001$], but neither the group main effect nor the Group × Condition interaction was significant. The groups displayed very similar performance across conditions on the prism adaptation task.

The accuracy of pointing during adaptation trials was further examined by dividing the 30 adaptation trials into three blocks of 10 trials each. A Group × Block repeated-measures multivariate ANOVA revealed a significant effect of block [$F(2,52) = 65.96$, $p < .001$], but neither the group main effect nor Group × Block interaction was significant. All three groups showed a significant linear trend reflecting increasingly more accurate pointing across the three blocks, consistent with gradual adaptation to the distorting prisms.

Additional analyses were conducted to correct for baseline performance. Although the groups did not differ in baseline accuracy, individual children did vary substantially. Measures of preadaptation, postadaptation, and negative aftereffects that corrected for baseline accuracy were constructed using the methods described by Paulsen et al. (1993). Corrected scores were computed by taking into account the direction of deviation from the target, with responses to the right of the target generating positive scores and those to the left generating negative scores. Preadaptation distortion was measured by subtracting each child's mean preadaptation score from the mean baseline score; postadaptation was measured by subtracting the mean postadaptation score from the mean baseline score; and negative aftereffects were measured by subtracting the mean aftereffects score from the mean baseline score. Each score was recorded as the absolute difference between the baseline deviation score and the other deviation score. Thus, for corrected preadaptation, larger differences reflected greater distorting effects of the prism; for corrected postadaptation, smaller differences reflected greater adaptation to the prisms; and for corrected aftereffects, larger differences reflected greater aftereffects.

The groups did not differ on any of the corrected scores, as shown in Table 6. A multivariate ANOVA with group as

Table 4. Mean number correct on test of explicit memory for weight biasing task

Bias condition	Group					
	Myelomeningocele		ADHD		Sibling	
	M	*SD*	*M*	*SD*	*M*	*SD*
Light	6.41	0.71	6.32	0.67	6.35	0.59

Note: ADHD = Attention deficit hyperactivity disorder. Range 0–7.

Table 5. Mean absolute accuracy scores by condition on prism adaptation task

Condition	Group					
	Myelomeningocele		ADHD		Sibling	
	M	*SD*	*M*	*SD*	*M*	*SD*
Baseline	0.77	0.72	0.74	0.72	1.04	2.34
Preadaptation	5.57	2.78	6.71	2.22	5.90	4.05
Adaptation	1.41	0.96	1.52	0.86	1.40	0.72
Postadaptation	0.91	0.50	0.90	0.51	0.90	0.95
Negative aftereffects	3.30	1.35	2.76	1.38	2.25	1.47

Note. ADHD = Attention deficit hyperactivity disorder.

Table 6. Mean corrected accuracy scores on prism adaptation task

Condition	Group					
	Myelomeningocele		ADHD		Sibling	
	M	*SD*	*M*	*SD*	*M*	*SD*
Preadaptation	6.03	2.42	6.58	2.18	5.32	2.38
Adaptation	1.07	0.84	0.86	0.72	1.53	2.42
Negative aftereffects	2.84	1.65	2.78	1.56	2.74	2.59

Note. ADHD = Attention deficit hyperactivity disorder.

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the independent variable indicated that the group main effect was not significant [$F(6,104) = 1.15$, $p > .10$]. In addition, none of the follow-up univariate tests was significant.

A hierarchical regression analysis was conducted to determine if age, IQ, and response inhibition (i.e., GDS total commissions) would predict the degree of prism adaptation. The dependent variable was the corrected postadaptation score. As before, two dummy variables representing group membership were entered into the regression on the first step, and the three continuous predictors were entered simultaneously on the second step. Interaction terms were entered in a third and last step. After entering the two dummy variables, age, IQ, and response inhibition together explained only 3% of the variance in prism adaptation [$F(3,48) = 0.53$, $p > .10$]. None of the individual predictors accounted for unique variance. When the interaction terms were added, they also explained only 3% of the variance in prism adaptation [$F(6,42) = 0.22$, $p > .10$]. None of the individual interaction terms was significant.

DISCUSSION

Contrary to expectations, neither children with myelomeningocele and shunted hydrocephalus nor those with ADHD showed less biasing in their weight judgments or less adaptation to distorting prisms than a group of healthy siblings. In other words, they did not display deficits in motor adaptation compared to healthy siblings, despite performing more poorly on other aspects of task performance (e.g., the accuracy of weight judgments). The absence of group differences also was not attributable to a failure of the experimental manipulations. All three groups showed significant biasing in their weight judgments and improvement in the accuracy of pointing during prism adaptation trials.

The absence of deficits in motor adaptation may reflect differences in the nature of the subcortical abnormalities that characterize myelomeningocele and ADHD as compared to those seen in adult neurological disorders known to be associated with deficits in motor adaptation. Adults with Huntington's disease show deficits on weight biasing and prism adaptation tasks (Heindel et al., 1991; Paulsen et al., 1993). Huntington's disease is characterized by substantial degeneration of the striatum, especially the caudate nucleus (Vonsattel et al., 1985). Myelomeningocele is not typically associated with abnormalities in the striatum, and more often is characterized by thalamic abnormalities and reductions in the volume of subcortical white matter (Gilbert et al., 1986). ADHD has been shown to be associated with subtle differences in striatal morphology (Castellanos et al., 1996; Hynd et al., 1993), but not with the pronounced atrophy that accompanies Huntington's disease. Motor adaptation may remain intact in myelomeningocele and ADHD because the brain structures involved in motor adaptation are not consistently abnormal, as is the case in myelomeningocele, or because performance on motor adaptation tasks is not affected by the more subtle striatal abnormalities seen in ADHD.

Another possibility that may account for the lack of group differences is that motor adaptation does not depend on the same brain structures in children as adults. Although neuroimaging studies in normal adults have shown that frontostriatal and cerebellar regions are involved in skill learning, we are not aware of similar studies in healthy children. However, studies of functional brain activity in children in general have revealed greater and more diffuse activity in children than in adults (Casey et al., 2000). The latter finding is consistent with the possibility that motor adaptation may be mediated by more distributed brain structures or systems in children than in adults.

A variant on this possibility is that motor adaptation does not depend on the same brain structures in children with myelomeningocele or ADHD as it does in healthy children. Both disorders occur or become apparent early in life and may be characterized by atypical patterns of brain–behavior relationships. The brain abnormalities that occur in myelomeningocele or ADHD could result in a reorganization of structure–function relationships, such that motor adaptation is not mediated by the same brain systems that are involved in adults. We are not aware of any studies that have examined brain activity during skill learning in children with myelomeningocele or those with ADHD.

Regardless of the reason for the lack of group differences in motor adaptation, the findings are intriguing because they indicate that the motor deficits associated with myelomeningocele and shunted hydrocephalus are not global in nature. Instead, myelomeningocele may result in a profile of intact and impaired motor functions that can be decomposed in accordance with the neuroscience of motor skills. In the study of motor coordination, for instance, two components that have received substantial attention are timing and force control, measures of which have been shown to be largely independent (Ivry & Corcos, 1993). The two components have distinct neural substrates, with motor timing mediated primarily by the cerebellum and force control mediated largely by the basal ganglia. The vast majority of children with myelomeningocele demonstrate cerebellar abnormalities, but most of them do not display abnormalities in the basal ganglia (Gilbert et al., 1986). Thus, they might be expected to display deficits in motor timing but not force control. The current findings are consistent with this notion, because judgments on the weight biasing task depend on whether children adjust the amount of force they exert based on previous exposure (i.e., exerting more force after lifting heavy weights and less force after light weights).

In contrast, children with ADHD have been shown to display subtle abnormalities in the basal ganglia (Castellanos et al., 1996; Hynd et al., 1993), as well as in the cerebellar vermis (Berquin et al., 1998; Castellanos et al., 1996; Mostofsky et al., 1998). Thus they might be expected to show deficits in both force control and motor timing. Inter-

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estingly, the ADHD group displayed significantly more weight biasing than the sibling group, although the overall test of the Group × Condition interaction was not significant. This finding is consistent with the notion that they may have difficulty with the force control component of motor coordination.

A secondary goal of the study was to examine motor adaptation in relation to age, IQ, and response inhibition. As expected, weight biasing and prism adaptation were not related significantly to age or IQ. This finding is consistent with previous research suggesting that implicit memory does not vary substantially by chronological age or developmental level (DiGiulio et al., 1994; Graf, 1990; Mitchell, 1993; Naito, 1990; Naito & Komatsu, 1993). The lack of association between age and motor adaptation stands in contrast to the significant relationship found between age and explicit memory on the weight biasing task, as well as between age and the accuracy of weight judgments on that task. The latter findings suggest that the lack of association between age and motor adaptation is not attributable to a restriction in the age range of the participants.

Response inhibition was related to weight biasing, but not to prism adaptation. The more commissions that occurred on the continuous performance test, the more biasing that was observed in weight judgments. The positive relationship suggests a link between inhibitory control and motor force control, such that deficits in inhibition are associated with more pronounced adjustments in the amount of force exerted. A link between response inhibition and motor adaptation could reflect a shared neuroanatomical basis in the basal ganglia. As already noted, the ADHD group displayed significantly more biasing than the sibling group, consistent with their much higher rates of response disinhibition.

The current study has several shortcomings in terms of sampling and recruitment. One is the relatively small sample size, which limited statistical power. However, the experimental manipulations clearly succeeded in all three groups, and neither of the two patient groups displayed even a trend toward less pronounced weight biasing or prism adaptation. In fact, weight biasing was more pronounced in the ADHD group than in the sibling group. Another shortcoming was the potential ascertainment bias in the two patient groups, both of which were recruited from a clinical setting. Once again, though, this method of recruitment would not tend to bias findings in the direction of no group differences in motor adaptation. Another potential concern about recruitment is that the ADHD group was selected based in part on traditional, nonstandardized clinical interviews, and therefore may be somewhat more heterogenous than samples selected based on more rigorous research criteria. However, clinical diagnoses were made in accordance with established practice guidelines and supplemented by concurrent parent ratings of the behavioral symptoms that define ADHD.

A concern can also be raised about the choice of a sibling control group. Siblings of children with ADHD may be more likely to display some of the phenotypic features of the disorder because of the genetic risk they share with probands. As a result, comparisons between children with ADHD and their siblings could reduce potential differences between groups. However, the control group in this study was made up predominantly of siblings of children with myelomeningocele. Moreover, siblings of children with ADHD did not differ from siblings of children with myelomeningocele on demographic characteristics, IQ, or the number of symptoms of ADHD endorsed by parents. Additionally, most siblings were rated as showing no symptoms of ADHD, and their estimated IQ scores were distributed normally. Hence, we believe that the sibling control group provided a valid basis for comparison.

The study also could be criticized because the weight biasing task relies on an indirect measure of motor adaptation (i.e., weight judgments), as opposed to actual changes in motor activity (cf. Lang & Bastian, 1999). However, the bias that occurs in weight judgments is likely to involve the modification of programmed motor movements. The perception of weight is normally mediated by centrally generated motor commands rather than by peripheral sensory information (Jones, 1986), and sensations of heaviness are influenced by discrepancies between intended, or programmed, force and the actual force needed to lift objects (Brooks, 1986). Thus, the bias in weight judgments that occurs after experience with heavy or light weights is likely to result from an increase or decrease in the amount of force programmed for lifting the weights, and hence would result in an illusory decrease or increase in the perceived heaviness of a standard set of weights. The weight biasing task assesses these illusory changes in perceived heaviness.

The current findings suggest several directions for future research. Implicit memory warrants further study in children with myelomeningocele, using tasks that do not depend on motor skills, such as measures of repetition priming or cognitive skill learning. In addition, studies are needed of motor coordination in myelomeningocele, and particularly of the potential dissociation between motor timing and force control. Future research also should incorporate functional neuroimaging techniques to determine more specifically what brain structures are involved in procedural learning and motor adaptation (e.g., Grafton et al., 1995; Poldrack et al., 1999). Neuroimaging studies are needed both in healthy children and in those with childhood brain disorders such as myelomeningocele and neurodevelopmental disorders such as ADHD.

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