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Motor Contingency Learning and Infants with Spina Bifida

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Abstract

Infants with Spina Bifida (SB) were compared to typically developing infants (TD) using a conjugate reinforcement paradigm at 6 months-of-age ($n = 98$) to evaluate learning, and retention of a sensory-motor contingency. Analyses evaluated infant arm-waving rates at baseline (wrist not tethered to mobile), during acquisition of the sensory-motor contingency (wrist tethered), and immediately after the acquisition phase and then after a delay (wrist not tethered), controlling for arm reaching ability, gestational age, and socioeconomic status. Although both groups responded to the contingency with increased arm-waving from baseline to acquisition, 15% to 29% fewer infants with SB than TD were found to learn the contingency depending on the criterion used to determine contingency learning. In addition, infants with SB who had learned the contingency had more difficulty retaining the contingency over time when sensory feedback was absent. The findings suggest that infants with SB do not learn motor contingencies as easily or at the same rate as TD infants, and are more likely to decrease motor responses when sensory feedback is absent. Results are discussed with reference to research on contingency learning in infants with and without neurodevelopmental disorders, and with reference to motor learning in school-age children with SB. (*JINS*, 2013, *19*, 206–215)

Keywords: Sensory-motor, Neurodevelopment, Disability, Early learning, Memory, Development

INTRODUCTION

Spina bifida (SB) is a neurodevelopmental disorder characterized by incomplete development of the spinal cord and anomalies in brain development particularly involving the midbrain, cerebellum and corpus callosum. Spina bifida meningomylelocele, the most common and severe form of SB, is associated with symptoms that can include flaccid or spastic paralysis, sensory loss below the lesion level of the spinal abnormality, and the Chiari type II malformation (Liptak & Batshaw, 2002), which results in hydrocephalus in most children (Chakraborty, Crimmins, Hayward, & Thompson, 2008; Davis et al., 2005; Del Bigio, 2010; Talamonti, D'Aliberti, & Collice, 2007).

Although most children with SB score within the low average to average range on measures of general intellectual ability, they are at heightened vulnerability for learning disabilities and other cognitive difficulties (Brewer, Fletcher, Hiscock, & Davidson, 2001; Fletcher et al., 2004; Wills, 1993). Considerable research with school age children and adults with SB identifies cognitive and behavioral assets and deficits linked to variability in specific congenital brain dysmorphologies (see Dennis & Barnes, 2010; Dennis, Landry, Barnes, & Fletcher, 2006). We have proposed that the behavioral phenotype of SB is based on a pattern of processing assets and deficits that affects skill development across and within cognitive domains; that these deficits in processing could be discernible very early in development and throughout the life span; and that they could partly account for the pattern of intact and deficient learning that is seen by school-age (Dennis & Barnes, 2010; Dennis et al., 2006).

One way to identify and understand sources of variability in a neurodevelopmental disorder such as SB is to study the early development of the proposed processing assets and deficits among infants. However, little is known about early learning in SB and its relation to the variable outcomes present at school-age and in adulthood. This is an important gap that needs further investigation; an understanding of core deficits discernible very early in development and their relation to later difficulties in learning has implications for early intervention.

In a recent study using infant paradigms to measure attention, we found that difficulties in attention orienting seen

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in older children and adults with SB (Dennis et al., 2005a, 2005b) are also present among 18-month-old infants with SB (Taylor et al., 2010). In a habituation/dishabituation paradigm involving the presentation of a series of faces on a television screen, a blinking light was used to attract the infant's attention on each trial. Infants with SB took significantly longer than typically developing infants to shift or disengage their attention from the salient sensory stimulus, the blinking light, to the face stimulus (Taylor et al., 2010). These parallels between attention shifting in infant habituation paradigms and in covert attention paradigms used with older children indicate continuity in development for attention processes under stimulus control (Colombo, 2001).

The focus of the current study was to assess motor learning in infants with SB. In Taylor et al. (2010) above, we found that although infants with SB had difficulty with shifting attention, they were remarkably similar to typically developing (TD) infants in their ability to learn about face stimuli as shown by their habituation performance. However, motor learning studies of older children with SB show a variable pattern of learning assets and deficits. Error-based motor adaptation and motor learning is generally intact (Colvin, Yeates, Enrile, & Coury, 2003). For example, although children with SB took longer to learn in a mirror drawing task, they learned the task to the same level as their TD peers. Furthermore, their retention after learning did not differ from peers (Edelstein et al., 2004). In contrast, Dennis et al. (2004) found that while children with SB learned to tap along to a rhythm when the rhythmic stimulus was present, they had difficulty continuing to tap that rhythm when the stimulus was withdrawn. The habituation findings for infants and the findings above for school-age children with SB suggest that these individuals have intact stimulus-driven learning and performance, but have more difficulty in learning and retention when performance is not under stimulus control. In other words, children with SB may have more difficulty maintaining a prior response in the absence of sensory feedback.

Motor difficulties impact infants' organization of motor sequences and exploration of the environment, which is essential for development in other cognitive domains (Thelen & Smith, 1995; Thelen & Ulrich, 1991). A key motor milestone is the onset of self-generated locomotion, the timing of which affects the development of perceptual-cognitive skills (Thelen & Smith, 1995; Thelen & Ulrich, 1991). In addition, visually guided reaching and the infant's ability to obtain objects serves to expand his or her experiences in a manner similar to self-generated locomotion. Motor impairment that restricts the infant's ability to explore the environment, thereby restricts sensory experiences with consequences for cognitive development (Thelen & Smith, 1995; Thelen & Ulrich, 1991).

Dennis, Salman, Juranek, and Fletcher (2010) suggest that motor functions requiring predictive signals and precise calibration of the temporal features of movement are impaired among individuals with SB. So, although children with SB learn discrete motor acts, they will have difficulty automatizing them into smooth and predictive motor acts, which provide the foundation for sensory-motor learning needed to promote cognitive development (Dennis et al., 2004). Recent studies on motor development and learning also identify predictive control as integral for contingency learning in infants and view movements in young infants to be organized by the motor and perceptual systems as actions rather than reactions (Thelen, 1994; von Hofsten, 2004; Watanabe & Taga, 2006).

The current study examined learning of a sensory-motor contingency (using a conjugate reinforcement task) that requires the integration of motor and perceptual information (i.e., learning a means/ends relation) and retention of learning when sensory feedback was absent in 6-month-old infants with SB and their TD peers. This task has been used to study learning and memory in infants (Rovee-Collier, 1999) and the dynamics of motor contingency learning in young infants (Thelen, 1994). In Rovee-Collier's mobile conjugate reinforcement paradigm (Haley, Weinberg, & Grunau, 2006; Hartshorn & Rovee-Collier, 2003; Rovee-Collier, 1997; Rovee-Collier, Sullivan, Enright, Lucas, & Fagen, 1980; Rovee & Rovee, 1969), TD infants can associate a motor response with a response-contingent stimulus outcome (i.e., foot kicking that moves a mobile) as early as 2 to 6 months of age. Using this paradigm, other studies have varied how infant contingency learning is measured. For example the acquisition of new movement patterns is similar whether the infant's arm or leg is tethered to the mobile suggesting that infants can learn to move a mobile regardless of the limb that is connected (Timmons, 1994; Wantanabe & Taga, 2009); also see Chen, Fetters, Holt, and Slatzman (2002) and Angulo-Kinsler (1997), for other variations on this task.

Contingency learning has also been studied in at-risk infants using the same paradigm. Gekoski, Fagen, and Pearlman (1984) found that healthy preterm infants needed a second training session before they showed significant increases in responding to the contingency compared to full-term infants (also see Heathcock, Bhat, Lobo, & Galloway, 2004). Other at-risk populations such as infants with Down syndrome have also been assessed using this procedure (Ohr & Fagen, 1991). This is a sensitive paradigm for assessing differences in motor contingency learning between typically developing infants and infants with neurodevelopmental disorders.

We used the conjugate reinforcement paradigm to evaluate learning of a motor contingency. The child learns to associate moving his/her arm with the movement and sounds made by a mobile in the acquisition phase. Learning in this paradigm is typically measured by comparing arm waves at baseline (absence of reinforcement) to responses in a later retention test phase (absence of reinforcement), after an intervening acquisition (reinforcement) phase. In the current study we used this traditional measure of learning, but we also reported infant responding during the acquisition phase. Another difference between this and other studies is that we compared infants in retention phases who did and did not learn the contingency. In most studies, infants who fail to meet the learning criterion are excluded from further study. We compared "learners" and "non-learners," similar to the approach taken in other studies of contingency learning with at-risk infants (e.g., Haley, Grunau, Oberlander, & Weinberg, 2008).

Based on the findings from studies of motor and sensory learning in school-age children with SB as well as our habituation studies of 18-month olds with SB, we hypothesized that: (1) 6-month-old infants with SB would respond similarly to controls (show similar levels of above baseline arm waving) during acquisition reflecting the learning of the motor contingency in the presence of reinforcement; (2) Infants with SB who learned the contingency would show lower retention than TD infants in the absence of reinforcement.

METHOD

Participants

As part of a larger longitudinal study conducted over the course of 3 years, a subsample of 98 infants (37 with SB and 61 neurologically normal, TD infants) participated in this study of motor learning. The infants with SB were referred to the study at birth by treating neurosurgeons and pediatricians in Houston (Memorial Herman Children's Hospital and Texas Children's Hospital) and southern Ontario (Hospital for Sick Children, McMaster Children's Hospital, Thames Valley Children's Centre). The socio-demographics of these two sites are different, which enhances the representativeness of the sample. The Houston site included many economically disadvantaged infants of Hispanic origin, in contrast to the predominantly White and middle socioeconomic status (SES) Ontario population. Both sites recruited equal numbers of children with SB and TD children.

Exclusionary criteria included uncontrollable seizure disorders, other known congenital anomalies, and significant sensory impairments (blindness, deafness). Three infants in this study were reported to have had seizures before recruitment, but no infants had seizure disorders or were being medicated for seizures at the time of the assessment. TD infants were recruited from well baby clinics, advertisements in newspapers, and local pediatricians. Exclusionary criteria for this group included the above as well as no gross sensory or motor abnormalities. Infants were excluded from both SB and control groups if they had experienced other brain insults associated with prematurity (i.e., periventricular leukomalacia; intraventricular hemorrhage). The majority of the infants with SB had myelomeningocele (86%), and three quarters of the sample had hydrocephalus treated with a diversionary shunt. The remaining infants had arrested hydrocephalus and no shunt. The majority of infants with SB had lower spinal lesions (L-1 and below; 94%). Children with upper-level spinal lesion had their lesion at the T12 level ($n = 2$).

Table 1. Descriptive data on age, ethnicity, gender, and socioeconomic status by group

Variable	TD	SB
N	61	37
Age at testing	6.62 (1.08)	6.20 (0.52)
Ethnicity *n* (%)		
Caucasian	42 (69%)	18 (49%)
Hispanic	10 (16%)	10 (27%)
Other	9 (15%)	9 (24%)
Gender		
Female *n*(%)	27 (44%)	16 (43%)
Socioeconomic status	44.5 (14.0)	27.5 (17.1)

Note. Socioeconomic status reports mean (*SD*) based on Hollingshead Scale (1975). Age reports mean (*SD*) in months.
TD = typically developing; SB = spina bifida.

Table 1 shows the distributions of gender, ethnicity, and SES, as assessed with the Hollingshead (1975) 4-factor scale. There were no group differences in ethnicity or gender. For both groups, there were slightly more males than females and the majority of the participants were Caucasian followed by Hispanic, and other ethnicities. The control group had a higher SES than the group with SB, $F(1,94) = 27.55$, $p < .0001$, reflecting the greater number of economically disadvantaged Hispanic children with SB in Texas. Gestational age at birth ranged from 34 to 41 weeks. The groups differed in gestational age (TD $M = 39$ weeks, $SD = 1.25$; SB $M = 38$ weeks, $SD = 1.99$) with 22% of the infants with SB born preterm (< 37 weeks) compared to 2% of typical developing infants. Therefore, gestational age was considered as a covariate along with SES.

Procedures

Assessments involved several standardized tests and other measures (Lomax-Bream, Barnes, Copeland, Taylor, & Landry, 2007; Lomax-Bream, Taylor, et al., 2007). All procedures for consent and data collection were in compliance with the regulations of the institutional review boards. At the 6-month assessment, the entire testing period lasted approximately 2 h. The motor conjugate reinforcement paradigm was the second task in the assessment battery for all infants.

The traditional mobile paradigm was modified for this study. Due to the known lower limb difficulties of infants with SB, a ribbon was secured to the wrist rather than the ankle of all infants. Using accepted positioning procedures, infants were placed supine in a reclined baby bouncer with a secure seat strap that was placed inside an infant crib (e.g., Bhatt, Rovee-Collier, & Weiner, 1994). The crib was lined with a black sheet to minimize distractions. The mobile hung directly above the infant's chest and was composed of toys and bells that hung down from a central disk.

Each infant was exposed to the stationary mobile for 1 min (the baseline phase) when one end of the ribbon was secured to the infant's wrist, while the other end remained free, not attached to the mobile. Therefore, arm waving could not produce mobile movement. The baseline was limited to 1 min to shorten the session in an attempt to decrease fatigue and keep infants engaged in the study, and reduce the duration of the total assessment burden for infants and their families.

Fig. 1. Infant participating in the acquisition phase of the Mobile Contingency Task.

Following the baseline period, the free end of the ribbon was attached to the mobile for 5 min (the acquisition phase). During this phase, any movement of the infant's arm produced a corresponding degree of movement in the mobile and a sound of bells (conjugate reinforcement, acquisition phase) (see Figure 1). Immediately following acquisition was a 2-min immediate retention phase (R1), when the end of the ribbon was detached from the mobile so that the infant's arm waving could not move the mobile (i.e., non-reinforcement). When the 2 min expired, the infant was removed from the crib and, in the same room, was given the remaining assessments that were part of the larger battery. These were administered in the following order: a social competence task in which the examiner interacted with a seated infant with puppets, an exploratory play task with multiple toys presented to a seated infant, and mental and motor assessments conducted on the floor or in a seat depending on the specific task (Bayley, 1993; Chandler, Andrews, & Swanson, 1980). Afterward, the infant was returned to the motor contingency crib for a 2-min delayed retention test (R2) that was procedurally identical to R1. The delay between R1 and R2 was approximately 1 h.

Each phase (baseline, acquisition, R1, R2) was divided into 15-s intervals for coding. The number of times an infant waved his or her arm was recorded by a trained coder from videotape. An arm wave was operationally defined as a movement of the infant's arm that at least partially retracted its arc of excursion in a smooth, continuous motion (Rovee & Rovee, 1969). Four research assistants coded 13% of the tapes for reliability. Interobserver reliability, in terms of a generalizability (intraclass) correlation coefficient (Brennan, 1983; Cronbach, Gleser, Nanda, & Rajaratnam, 1972; Shavelson & Webb, 1991), was estimated to be .94. This value was derived using the VARCOMP procedure in SAS to determine the ratio of the variance components for the individual to the variance components overall.

Because infants with SB have more difficulty with motor functioning than TD infants (Lomax-Bream, Barnes, et al., 2007; Lomax-Bream, Taylor, et al., 2007), we were concerned that motor difficulty might impact trunk control, upper body arm movement, and reaching ability that could affect performance on this task. Therefore, we included the scores of three items from the motor scale of the Bayley Scales of Infant Development – 2nd Edition (Bayley, 1993) that evaluate trunk control (i.e., sits with support; sits with slight support for at least 10 s) and reaching ability at the level of 6 months of age (i.e., reaches unilaterally) as a covariate in the analyses (sitting/reaching score). Overall, 93% of the TD children and 76% of infants with SB were able to perform all three motor items.

RESULTS

Overview of Analysis Approach

To address our hypotheses, we (1) examined whether there were differences at baseline by group, (2) evaluated response to the contingency (acquisition) by comparing infant response across baseline and acquisition phases in the two groups, (3) used two different methods to directly test group differences in learning of the contingency, and (4) evaluated R1 and R2 data based on whether or not infants had learned the contingency and also in reference to group.

The data consisted of frequency counts of arm movements during the coded intervals of observation. Given that each interval was 15 s long, the first phase consisted of four baseline intervals (i.e., four 15-s intervals for a total of 1 min of baseline measurement). The acquisition phase lasted for 20 intervals (or 5 min). Each non-reinforcement retention phase consisted of eight intervals (2 min each) (R1 and R2). To determine if there were differences in responding by group at baseline, over and above the effects potentially caused by (1) deficiencies in sitting and reaching, (2) low SES, or (3) gestational age that may impact arm movements, we included each in our analyses as covariates. Some infants were found to produce no arm-waves during baseline. Therefore, we added .25 to all scores to allow all infants to remain in the ratio analyses. When the outcome variable was a frequency count, we used a nonlinear mixed model with a negative binomial distribution and a log link function. This type of analysis is similar to a generalized estimating equation except that there are random and fixed effects in the model. Due to the potential distribution problems with analyzing ratios, we used a bootstrapping procedure for these models, taking 5000 bootstrap samples (using the actual sample size but sampling with replacement). We then determined confidence intervals for the parameters of interest and obtained effect size estimates. There were no group differences in the frequency of arm waving at baseline even taking into account infants' performance on any of the covariates. To ensure that these findings were not simply due to a strong correlation between any one of the covariates and arm waving, these variables were analyzed separately. Neither group nor any of the covariates were significantly related to the frequency of waves during the baseline phase. In addition, there were no differences between intervals during this phase and no group by interval interactions. In sum, the groups did not differ in their rates of arm waving at baseline.

Hypothesis 1: Groups would not differ responding to the motor contingency over the acquisition phase.

Line graphs revealed considerable variability in responses over time so we averaged the 15-s coded interval data into 1 min average "blocks" to smooth out the expected variation in infant movements over time and to reduce skewness in the data. This produced the following: Baseline (1 block) and Acquisition (5 blocks). The non-linear mixed model analysis revealed a significant block by group interaction, $F(5,470) = 3.85$; $p = .0020$). In follow-up analyses, the only significant difference between group over time was for the baseline *versus* acquisition phases where the TD group was significantly higher (an average of more waves) than the group of infants with SB across all blocks of time except baseline (Figure 2). These findings suggest that both groups responded to the contingency with an increase in arm-waves, however, infants with SB had a lower response to the contingency compared to TD infants.

Hypothesis 2: Groups would differ in their learning of a motor contingency when sensory feedback is absent

Because the amount of arm movement was less frequent for the infants with SB than the TD group, we wanted to determine whether infants with SB had actually learned the contingency. Analyses were conducted at the level of the individual child by considering each child's acquisition or non-reinforcement data in comparison to his or her own baseline data. We used two criteria to evaluate learning, one based on comparing waves during baseline to those during the acquisition phase (Criterion A), and, the other, more traditional method in which waves during baselines are compared to those during retention (Criterion B). First, we looked at the relation of acquisition phase to baseline for each child, Criterion A. We compared the proportion of acquisition waves over the median to the proportion of baseline waves over the median for each child using χ^2 analyses. We used median rather than mean frequency of waves due to the distribution being positively skewed. This method required that the child demonstrate an increase in waves of 25% or more from baseline to acquisition. In this way, an infant was identified as having learned the contingency for Criterion A if the proportion of acquisition waves over the median compared to the proportion of baseline waves over the median was greater than 25%. Fewer infants with SB were found to have learned the criterion compared to TD infants ($\chi^2(1; n = 98) = 8.70$; $p = .0032$).

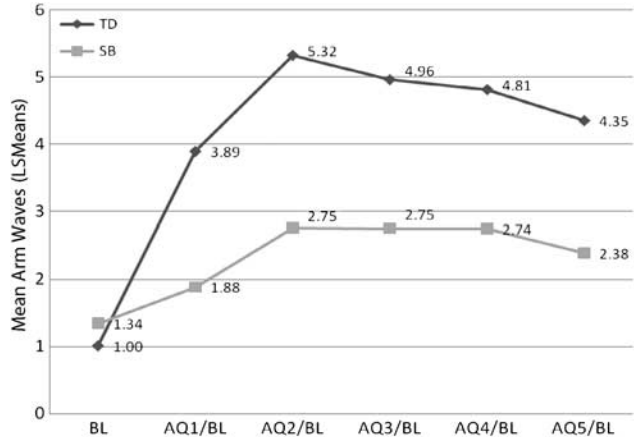

Fig. 2. Mean arm movement over Baseline and Acquisition Phases by group. *Note*: Figure depicts the model least squares means generated during analyses; LSM = least squares means; TD = typical developing; SB = spina bifida; BL = Baseline Phase 1-min block 1; AQ1/BL – AQ5/BL = Acquisition Phase 1-min blocks 1 through 5, each divided by Baseline.

We also used a commonly used learning criterion to distinguish infants who learned and did not learn the contingency task, Criterion B. This was the final level of learning after zero delay measured by an arm-waving rate during the immediate non-reinforcement retention phase that was equal to or greater than 1.5 times the baseline rate (Rovee-Collier et al., 1980). A series of bootstrap procedures were conducted which compared the ratios by group to determine the degree to which infants learned the contingency using this criterion. These compared the mean baseline ratio of each group to 1.5, which would indicate a return to the pretraining operant level. In this way, the results demonstrated if a significant portion of the group had learned the contingency. As part of this bootstrapping analysis, we also evaluated if the learning ratio differed by group (SB and TD). The duration of our baseline phase was equal to 1 min. Therefore, we evaluated baseline in relation to the average of the two retention min together. Effect sizes (ES) were calculated by dividing the mean of the bootstrap samples by the standard deviation of the samples. Both groups demonstrated learning during immediate retention, 95% confidence interval (CI) two-tail (1.82–2.99); ES = 2.92. There was a significant group difference indicating that fewer infants with SB learned the contingency compared to TD infants (SB = 35%; NC = 50%), 95% CI 1-tail (.14-infinity), ES = 1.884; SB mean = 1.72 (2.08), TD mean = 2.74(3.31). The results for Criterion A and B are presented in Table 2. In comparison to Criterion B, a greater number of infants with SB were judged to have learned the contingency using Criterion A. However, both criterion A and B analyses show learning by both groups.

Hypothesis 2: Infants with SB who learned the contingency will show less retention of learning over time than TD infants when sensory feedback is absent.

We then evaluated infant retention. We evaluated the results of the R1 and R2 phases including block, group, and whether

Table 2. Successful contingency learning for Criteria A and B by group

	Learners	
Group	Criterion A	Criterion B
TD	46 (75%)	31 (50%)
SB	17 (46%)	13 (35%)
Total	63 (64%)	43 (44%)

Note: A = Criterion A = 25% increase in waves in acquisition compared to baseline; Criterion B ratio was Retention/Baseline ≥ 1.5.
TD = typically developing; SB = spina bifida.

or not the contingency was learned (contingency). First we used Criterion A as the estimate of learning. The R1 trials did not show a significant contingency by block interaction suggesting no significant difference in performance between infants who learned the contingency *versus* those who did not. However, there was a significant group by block interaction, *F*(1,559) = 6.39; *p* = .01. Examination of the least squares means (Figure 3) indicates that both groups were statistically similar during the first min of retention (block 1), but infants with SB showed a steep decline during the second min of retention (block 2). In contrast, TD infants showed little change across blocks. This suggests that infants with SB had more difficulty retaining the contingency without sensory feedback compared to the TD group.

The analysis for R2 trials showed a significant contingency by block interaction, *F*(1,515) = 9.20; *p* = .00, but this did not vary by group (see parallel performance of groups in Figure 4 for learned contingency *versus* did not learn contingency). Those infants in both groups who learned the contingency had more movement during block 1 (mean = 1.97; *SD* = .28) compared to those infants who did not learn the contingency (mean = .85; *SD* = .35). In block 2, all infants respond similarly regardless of previous contingency learning. Raw ratio means across phases are shown in Table 3.

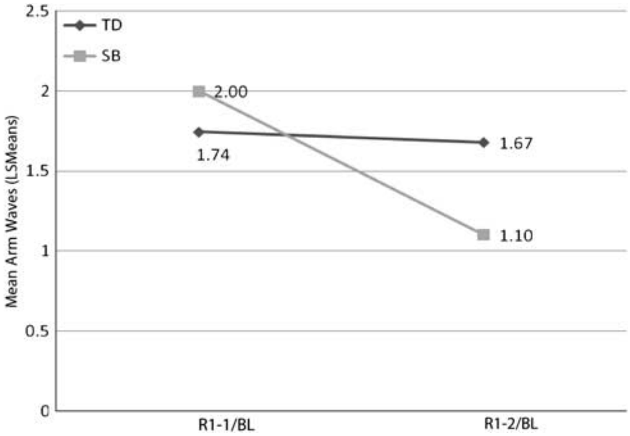

Fig. 3. Mean arm movement over Immediate Retention Phase by group. *Note*: No difference was found between infants who learned the contingency compared to those who did not; therefore, infants were combined by group for comparison in this figure. Figure depicts the model least squares means; LSMeans = least squares means; TD = typical developing; SB = spina bifida; R1-1/BL = First 1-min block of Immediate Retention/Baseline; R1-2/BL = Second 1-min block of Immediate Retention/Baseline.

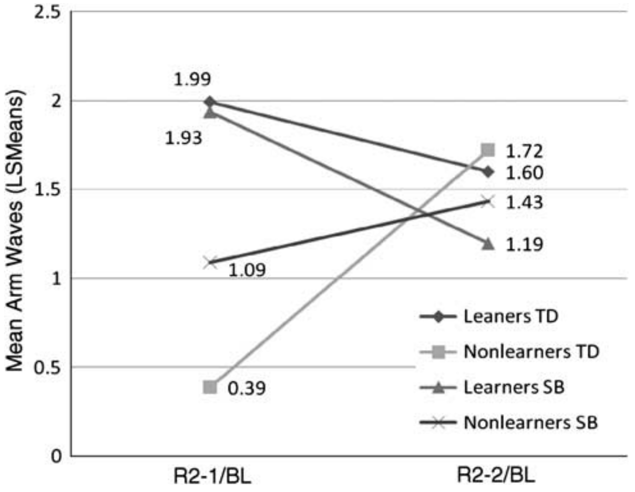

Fig. 4. Mean arm movement over Delayed Retention Phase by group and Contingency Learning Status. *Note*: Figure depicts the model least squares means; LSMeans = least squares means; Learners TD = typical developing infants who learned contingency; Learners SB = infants with spina bifida who learned contingency; Nonlearners TD = typical developing infants who did not learn contingency; Nonlearners SB = infants with spina bifida who did not learn contingency; R2-1/BL = First 1-min block of Delayed Retention/Baseline; R2-2/BL = Second 1-min block of Delayed Retention/Baseline.

Next, we used Criterion B as the estimate of learning to evaluate retention and found similar results. The groups did not differ during the first min of R1 but were significantly different during the last min of R1, 95% CI two-tail (0.236–3.242); ES = 1.98. This suggests that children with SB had more difficulty maintaining what they learned compared to TD children in the absence of feedback. During delayed retention (R2) the ratio for the average of R2 over baseline was not significantly greater than 1.5 (ES = 1.35). However, there was a significant difference between groups, 95% CI one-tail (.01–2.36); ES = 1.486; SB mean = 1.45 (1.46), TD mean = 3.00 (5.50). This suggests that the degree of retention of the contingency with a delay had decreased in both groups below the learning ratio, with fewer infants with SB recalling the contingency after a delay compared to TD children (SB = 29%; TD = 41%).

DISCUSSION

We evaluated the ability of 6-month-old infants with SB and TD infants in learning of a motor contingency requiring the integration of motor and perceptual information when sensory feedback was present, as well as retention of the contingency in the absence of sensory feedback. We hypothesized that infants in both groups would perform similarly in their response to the contingency and learning the

Table 3. Mean ratio of arm waves across Acquisition, Immediate Retention, and Delayed Retention to baseline by group (with standard deviations in parentheses)

	Group	
Minute	SB	TD
Acquisition		
Acquisition/Baseline – 1st min	1.62 (1.75)	3.94 (4.57)
Acquisition/Baseline – 2nd min	2.91 (4.30)	6.52 (12.52)
Acquisition/Baseline – 3rd min	3.51 (6.05)	6.41 (10.90)
Acquisition/Baseline – 4th min	3.44 (5.81)	6.12 (8.42)
Acquisition/Baseline – 5th min	3.20 (5.93)	5.62 (7.93)
Immediate Retention		
Immediate Retention/Baseline – 1st min	2.01 (3.75)	2.48 (2.53)
Immediate Retention/Baseline – 2nd min	1.45 (1.46)	3.00 (5.50)
Delayed Retention		
Delayed Retention/Baseline – 1st min	1.33 (1.13)	2.38 (4.24)
Delayed Retention/Baseline – 2nd min	1.51 (2.18)	2.67 (5.30)

SB = children with spina bifida; TD = typically developing children.

contingency, but that those infants with SB who learned the contingency would have more difficulty than TD infants in retaining that learning in the absence of sensory feedback.

We predicted no differences in acquisition of the contingency between the groups based on the findings of learning in our habituation studies with 18-month-olds (Taylor et al., 2010). To test this hypothesis, we compared the rate of arm waving in the acquisition phase to that at baseline between the two groups. Rates of arm waving did not differ between groups at baseline suggesting that any differences in arm waving between the groups during acquisition would be related to contingency learning. Although both groups increased arm waving from baseline to acquisition, contrary to predictions, the TD infants evidenced a much higher rate of arm waving than infants with SB, suggesting greater response to the contingency. We also measured learning within individuals using two criteria. Criterion A compared infant rate of arm waving during acquisition to that during their own baseline and required an increased arm waving rate of 25% over baseline to qualify as having learned the contingency, and Criterion B was a ratio of Retention/Baseline equal to or greater than 1.5. We found that fewer infants with SB learned the contingency than did their TD peers for both criteria. In sum, the findings from both sets of analyses suggest that infants with SB did not learn the motor contingency as easily or at the same rate as TD infants. It is unknown how many arm waves may have been produced during baseline if the ribbon attached to the infant's wrist was tethered to an empty stand (traditional mobile paradigm) rather than lying loose. It is possible that infants may have produced more waves, which in turn may have caused the ratio for learning to be even lower for infants with SB.

More acquisition sessions are needed for some groups of high-risk infants to learn motor contingencies compared to TD infants. For example, some studies show that infants born preterm require multiple days of training to demonstrate increased responses to contingency compared to one day of training required by full term infants (Gekoski et al., 1984). Similarly, infants classified with failure to thrive syndrome required two to three 10-min sessions to demonstrate significant increases in contingency learning, whereas many TD infants learned the contingency after the first 10-min exposure (Gekoski et al., 1984; Ramey, Heiger, & Klisz, 1972). It is important to note that infants in the current study were given only one 5-min session to learn the contingency. Acquisition sessions typically vary based on the age of the infants being studied, ranging from 15 min for 2- and 3-month-old infants and 6 min for 6-month-old infants (Rovee-Collier, 1997). In addition, some studies consider a less stringent learning criterion. For example, Sullivan and Lewis (2003) used a 15% learning criterion in their study with 4- and 5-month-old infants. Whether infants with SB would have learned the contingency to the same level as control infants given a longer acquisition phase is unknown. In this respect, it is worth noting that although school-age children with SB take longer to learn a motor skill such as mirror drawing, they do learn the skill to the same level as controls and are similar to controls in retaining the skill over time (Edelstein et al., 2004).

Our findings for motor contingency learning at 6 months have some features in common with those we obtained when learning was measured using habituation and attention shifting at 18 months. Learning in a habituation paradigm is completely stimulus-driven and requires no integration of information. Although the mobile task also requires attention to a cognitively interesting stimulus, learning of the contingency requires the integration of sensory and motor information, which is then reinforced by sensory feedback (the mobile moves and makes a sound). Infants with SB may have difficulty shifting attention between motor information and sensory feedback as they do with shifting attention in the habituation task (Taylor et al., 2010). Due to difficulties in attention shifting, infants with SB may demonstrate a disconnect between their arm movements and sensory feedback which may in turn interfere with learning. Difficulties learning the contingency in infants with SB may also be related to motor timing deficits that have been proposed to produce a temporal disconnect between sensation and movement related to an asynchrony in feed-forward processes important for receiving sensory consequences of motor acts (Dennis et al., 2004).

This study did not include a measure of infants' attention to the mobile which may have impacted learning. In approaching this task, infants received a variety of sensory and proprioceptive stimuli including tactile information caused by the tether on the infant's wrist, proprioceptive sensations when the tether would become taut, and auditory and visual sensations when the mobile moved and the bells jingled. Some infants appeared to visually attend to and focus on the mobile immediately and attempt to reach for the objects. Others appeared to take longer to notice the mobile and/or have more difficulty tracking and finding the mobile in their visual field. On occasion, infants did not appear to attend to the mobile at all but would move their arm or grab the tethered ribbon and bring it to their mouth to chew, subsequently noticing the mobile when it moved and jingled providing additional sensory feedback. Future studies should capture the ability of infants with SB to attend to a moving mobile as this may relate to learning the contingency.

Although infants were considered their own control by comparing their individual baseline performance to their acquisition performance, this may not have controlled for increases in movement in the TD group *versus* the group of children with SB related to other factors including potential differences in arousal. However, we think increases in the specific arm movement coded in this study were likely due to learning and retention of the contingency rather than infant arousal simply related to a moving mobile. This inference is based on studies showing that infants do not increase their response merely in the presence of a moving mobile (i.e., without the sensory feedback based on their own movements), suggesting that arousal alone does not account for the findings in these sorts of paradigms (Heathcock et al., 2004; Heathcock, Bhat, Lobo, & Galloway, 2005).

Consistent with what we hypothesized, arm waving for children with SB who had learned the contingency showed a steeper decline over time compared to controls during the immediate retention phase when the link between arm movement and sensory feedback was interrupted. We found that infants with SB performed similarly to control infants during the first block of the immediate retention phase, but their responses were much lower in the second block of the immediate retention phase compared to controls. These findings are in general agreement with recent proposals put forward by Dennis and colleagues (Dennis & Barnes, 2010; Dennis et al., 2010) about the nature of motor function in SB, including motor learning. In children and adults with SB, error-based motor adaptation and motor learning is generally intact (Colvin et al., 2003; Dennis, Jewell, et al., 2006; Edelstein et al., 2004) as is the ability to time movements in relation to an external stimulus, such as tapping in time to a computer generated rhythm (Dennis et al., 2004). In contrast, children with SB have difficulty with internally generated movements in the absence of external stimulation (Dennis et al., 2004), such as continuing to tap out a rhythm once the computer generated beat stops. It has been suggested that the cerebellar abnormalities associated with SB interfere with the ability to form sensory-motor representations that provide an internal copy of the motor command, and its predicted movement (efference copy) and sensory consequences (Dennis et al., 2010). With respect to the current findings, infants with SB who learned the motor contingency failed to continue to move their arms once they no longer received sensory feedback linked to their arm movements (sound and movement of the mobile). In contrast, the TD infants continue to move their arms in the immediate retention phase, perhaps using intact sensory-motor representations that allow for internally generated predictions about motor movements and their expected consequences.

The comparisons above concern the relation of a child's baseline performance to their performance during either acquisition or immediate retention. However, one can also ask what responding in the two groups looks like between the end of the acquisition phase and the beginning of the retention phase. A visual comparison of Figures 2 and 3 suggests that there is approximately a 50% decrease in arm waving for TD infants compared to fairly stable responses among infants with SB between the last min of acquisition (AQ5) and the first min of immediate retention (R1-1). A similar decrease in response from TD infants has been observed in other studies between acquisition and non-reinforcement phases (e.g., Haley et al., 2008). In general, this decrease suggests that TD infants may be sensitive to the change in contingency, however, their responses do not fall below the criterion for learning (≥ 1.5 baseline) and are sustained over the second min of R1 (R1-2). In comparison, infants with SB do not appear to change significantly from AQ5 to R1-1. By the second min of R1, however, they fall below the criterion for learning, close to their baseline level. More research is needed to shed light on these findings.

During the delayed retention phase (R2), infants in both groups who learned the contingency were more likely to exhibit movement compared to infants who did not learn the contingency, regardless of group. This was more apparent in block 1 with all infants becoming more similar in responding by block 2, regardless of previous contingency learning. The finding that infants with SB who learned the contingency performed similarly to the TD infants when presented with the mobile after a delay suggests that both groups show evidence for longer-term retention of the contingency when placed in the original learning context. In this way, infants with SB appeared to experience spontaneous recovery for the motor-contingency when presented with the visual cue of the mobile during the first-min of R2 (e.g., Rovee-Collier & Giles, 2010). This is common among infants and may indicate that memory of the motor-contingency was still in the infants working memory. However, by the second min of R2 this was not sustained and their responding dropped compared to TD infants, possibly suggesting difficulty maintaining the motor contingency.

Infants' successful motoric organization and exploration of the environment is essential for cognitive development (Thelen & Smith, 1995; Thelen & Ulrich, 1991). Infants require sensory stimulation to trigger processes of neural development that will then affect the development of motor control. Infants with SB appear to respond to this sensory feedback but lack the intact sensory-motor representations when feedback is absent. Further studies need to be conducted to determine if additional repetition and exposure improves learning means/ends relations for infants with SB. The importance of infants' perception of contingency information for later cognitive and social development is well established in the literature, indicating that contingency learning procedures might constitute one type of early intervention for infants with SB.

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