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Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat

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ABSTRACT

In prior work (Corriveau et al., 2007), we showed that children with speech and language impairments (SLI) were significantly less sensitive than controls to two auditory cues to rhythmic timing, amplitude envelope rise time and duration. Here we explore whether rhythmic problems extend to rhythmic motor entrainment. Tapping in synchrony with a beat has been described as the simplest rhythmic act that humans perform. We explored whether tapping to a beat would be impaired in children for whom auditory rhythmic timing is impaired. Children with SLI were indeed found to be impaired in a range of measures of paced rhythmic tapping, but were not equally impaired in tapping in an unpaced control condition requiring an internally-generated rhythm. The severity of impairment in paced tapping was linked to language and literacy outcomes.

There is considerable evidence that children with speech and language difficulties (Specific Language Impairment or SLI) have co-occurring motor problems. Although SLI is defined on the basis of expressive and receptive language deficits that interfere with the educational achievement and communication ability of the child, many studies report co-morbidity with motor co-ordination deficits. For example, Robinson (1991) found that 90 per cent of his sample of children with speech and language difficulties had motor impairments. There are reports of difficulties with both gross motor skills such as balance (Hill, 1998) and with fine motor skills such as bead-threading and speeded tapping (Bishop, 2002; Bishop and Edmundson, 1987; Dewey et al., 1988; Owen and McKinlay, 1997; Preis et al., 1997; see Hill, 2001 for a review). In a review of the literature, Hill (2001) found that most children with SLI also have a diagnosis of developmental coordination disorder (DCD). DCD is defined in terms of movement difficulties out of proportion with general development and intelligence.

Despite the variety of motor tasks that have been given to children with language difficulties, the literature is very inconsistent. For example, the peg-moving task is frequently employed to examine fine motor abilities in children with SLI. In this task, children are required to move pegs from one end of a board to the other and are timed while (1) using their dominant hand only, (2) using their non-dominant hand only, and (3) using both hands together. Although many studies have found that children with SLI take longer to complete this task than age-matched, normally-developing children (Bishop, 2002; Bishop and Edmundson, 1987; Owen and

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McKinlay, 1997; Powell and Bishop, 1992; Preis et al., 1997), several others have failed to find a significant difference on this same measure (Archer and Witelson, 1988; Bradford and Dodd, 1996; see Hill, 2001 for a review). One explanation for this inconsistency may be poor matching of the children with SLI to the typically developing children who usually comprise the control group. Most of the research on motor impairments in SLI to date has failed to match groups for nonverbal IQ. Further, many studies have failed to include a younger, language age-matched control group to control for linguistic development (with the exception of Bishop and Edmundson, 1987; see Hill, 2001 for a review). Nevertheless, poor control group matching alone is not sufficient to explain the variability in the motor abilities of children with SLI that is observed across studies.

An alternative possibility is that the motor skills of children with SLI are not globally impaired. Rather, the motor difficulties observed may be specific to certain tasks. Although children diagnosed with speech and language difficulties usually exhibit no obvious neurological dysfunction, our interest here is whether there are subtle neural impairments that affect both language and motor development. One possible candidate is an impairment in the neural mechanisms for the perception and expression of rhythm and timing. For example, children with SLI do seem to have difficulties with auditory cues to the rhythmic timing of language. Corriveau et al. (2007) tested children with SLI along with language age (LA)-matched and chronological age (CA)-matched controls using non-speech auditory discrimination tasks that isolated two rhythmic cues important for speech segmentation: amplitude envelope rise time and duration. Corriveau et al. found that children with SLI were significantly impaired in their discrimination of these rhythmic cues, but were not impaired on two non-speech auditory tasks that were not tied to rhythm (intensity and temporal order judgements). Furthermore, performance on the auditory rhythmic processing measures accounted for a significant amount of unique variation in language and literacy ability after controlling for age, IQ and task demands. One possibility is that the rhythmic processing deficit observed by Corriveau et al. (2007) in the auditory realm extends across receptive and expressive modalities.

In this study, we explore possible links between motor and auditory rhythmic timing in children diagnosed with SLI. Our motor timing task was tapping a finger in synchrony with a metronome beat. This task has been widely used in explorations of adult human rhythmic and timekeeping behaviour. In a recent study with 88 children aged 4–12 years, McAuley et al. (2006) reported that the range of accessible tapping rates widened during childhood, with older children able to tap accurately to a wider range of rates. The preferred spontaneous tempo between ages 8–12 years was around 500 msec (2 Hz). Correlational analyses carried out by McAuley et al. (2006) showed that children with higher nonverbal IQ could synchronize their tapping accurately to a wider range of rates. This latter finding illustrates the importance of controlling for non-verbal IQ in developmental studies of motor abilities. Tapping to a beat combines auditory and motor rhythms, and hence was expected to be impaired in our sample of children with SLI. It is often noted that timing, duration perception and rhythm perception and production activate the same brain areas, notably premotor and supplementary motor areas, the cerebellum and the basal ganglia (see Grahn and Brett, 2007). Although many studies of children with SLI have used *repetitive* tapping measures (in which children are asked to tap as fast as they can; Archer and Witelson, 1988; Bishop, 2002; Dewey et al., 1988; Hughes and Sussman, 1983), to date rhythmic tapping tasks have not been administered to an SLI population.

Some of the motor tasks used in previous studies of children with SLI have required expressive rhythm abilities, but these requirements have been indirect. An example is Powell and Bishop's (1992) throw-clap-catch task, in which children threw a ball, clapped, and then caught the ball again. Wolff and colleagues (Waber et al., 2000; Wolff, 2002; Wolff et al., 1990) have examined rhythmic finger tapping in children with developmental dyslexia, and some of these children may have also had language impairments. Wolff and colleagues have found consistently that children with reading problems have trouble with rhythmic finger tapping, using both unimanual and bimanual tapping tasks. For example, using a task requiring children to tap to a cued beat, Wolff (2002) found that children with dyslexia tended to overanticipate the cued stimulus by as much as 100 msec, unlike their CA-matched peers. Wolff interpreted this overanticipation as indicative of a deficit in an internal timing mechanism in children with developmental dyslexia. Meanwhile, Goswami and colleagues have reported deficits in tasks measuring sensitivity to auditory cues to rhythmic timing in children with developmental dyslexia (Goswami et al., 2002; Muneaux et al., 2004; Richardson et al., 2004).

Additional studies of rhythmic finger tapping in both children with developmental dyslexia (Wolff et al., 1990) and learning impaired children (Waber et al., 2000) have reported that in each case the clinical population showed increased variability (a greater standard deviation) in the time interval between finger taps (inter-tap interval – ITI). Furthermore, Waber et al. (2000) found that the children who exhibited reading problems were also the children with the greatest variability in ITI, and that variability in ITI predicted achievement in reading, spelling, and maths for both learning impaired and control children, even when non-verbal IQ was controlled. However, this study measured tapping ability by summing across paced tapping (for 10 sec to a metronome beat) and unpaced tapping (continuing to tap to the beat for a further 20 sec when the metronome had stopped). Hence both entrainment and tapping to an internally-generated rhythm were conflated in the analyses relating tapping performance to academic performance.

Similar impairments in auditory and motor rhythm abilities were found in a recent study of adults with developmental dyslexia by Thomson et al. (2006). They examined auditory and motor rhythm abilities in college students with dyslexia and age- and IQ-matched controls. Participants were asked to tap to a metronome beat both in the presence and the absence of a cue; data from these two conditions were analyzed separately. The students with developmental dyslexia showed reliably greater ITI variability at rates of both 1.5 and 2 Hz when tapping to a metronome beat, and at the 2 Hz rate when tapping in the absence of a beat. Partial correlations controlling for non-verbal IQ showed that ITI variability in synchronized tapping was related to reading development in this adult sample, and also to duration perception. Unpaced tapping was related to rise time perception and to digit span, but not to literacy. In summary, four recent findings are consistent with the hypothesis that rhythmic motor entrainment deficits may be present in children with SLI. Firstly, an estimated 90 per cent of children with SLI have some sort of motor impairment (Hill, 2001). Secondly, auditory deficits in rhythmic perception have been found both in children with SLI (Corriveau et al., 2007) and in children with developmental dyslexia (Goswami et al., 2002; Richardson et al., 2004; Muneaux et al., 2004). Thirdly, children and adults with developmental dyslexia have both auditory rhythmic deficits and motor rhythmic deficits (Thomson et al., 2006; Wolff, 2002). Finally, there is some co-morbidity between developmental dyslexia and SLI, with reported rates varying from a low of 10% (Bishop and Snowling, 2004) to estimates as high as 50% (McArthur et al., 2000). Hence relations between auditory and motor rhythmic performance found in participants with dyslexia may extend to participants with speech and language difficulties.

In the current study, we set out to explore the expressive motor abilities of children with SLI on motor tasks requiring rhythmic processing and on motor tasks lacking a rhythmic component. We gave a selection of the expressive motor tasks used by Thomson et al. (2006) to a group of children with SLI and to matched CA- and LA-controls. These were the same children studied in Corriveau et al. (2007), known to have difficulties in auditory rhythmic processing. It was expected that the children with SLI would also show difficulties with motoric rhythms, particularly in paced conditions (tapping to a metronome beat). Furthermore, based on previous findings indicating that auditory rhythmic processing abilities are related to phonological awareness and literacy skills in children with SLI, it was expected that performance on the expressive rhythm task would be related to some developmental variation in language and literacy.

1. Method

1.1. *Participants*

Sixty-three 7–11-year-old children participated in this study. No child had a diagnosis of an additional learning difficulty (e.g., ADHD, autistic spectrum disorder, dyslexia), and all children had a nonverbal IQ above 80 and spoke English as their first language. Twenty-one subjects (13 male, 8 female; mean age 10 yrs 2 months, SD, 11 months) had a statement of specific language impairment (SLI) from their local education authority. Twenty-one subjects were CA-matched controls (CA group: 9 male, 12 female; mean age 9 yrs 9 months, SD 2;4). Twenty-one subjects were language ability-matched controls (LA group: 11 male, 10 female; mean age 7 yrs 8 months, SD 8 months). These subjects were matched to SLI subjects using raw scores from an expressive vocabulary (WISC vocabulary) and a receptive vocabulary measure (BPVS). Scores were matched to within 5 points (±2 S.E.). Participant characteristics are described in more detail in Corriveau et al. (2007) and are displayed in Table 1.

Table 1 – Mean (standard deviation) participant characteristics for the standardized tasks.

Group	SLI	CA match	LA match	*F*(2,60)
N	21	21	21	
Age[a,b] (SD)	10;2 (0.94)	9;9 (2.38)	7;8 (0.67)	66.69^{***}
Nonverbal IQ[c] (SD)	92.14 (11.75)	97.29 (10.08)	104.09 (8.67)	1.37
BPVS raw[b,d,e] (SD)	78.43 (7.48)	104.19 (8.89)	79.19 (11.39)	50.76^{***}
WISC vocab. raw[b,d,f] (SD)	20.15 (2.64)	28.7 (6.33)	20.67 (4.15)	23.10^{***}

$^{***}p < .001$.
a SLI > LA, $p < .001$.
b CA > LA, $p < .001$.
c Nonverbal IQ estimated from the Block Design and Picture Arrangement subtests ($M = 100$, SD 15).
d CA > SLI, $p < .001$.
e Raw score calculated using standard ceiling-floor guidelines of the BPVS (max = 144).
f Raw score calculated using the WISC vocabulary procedures (max = 40).

1.2. *Tasks*

1.2.1. *Psychometric tests*

All children received standardized tests of receptive vocabulary (British Picture Vocabulary Scales; Dunn et al., 1982) single word and nonword reading (Test of Word Reading Efficiency; Torgesen et al., 1999), reading comprehension (Wechsler Objective Reading Dimensions – Comprehension subtest; Rust et al., 1992), spelling (British Ability Scales; Elliott et al., 1996), rapid color naming (CELF-3 rapid color naming subtest; Semel et al., 1995), word recall (Working Memory Test Battery for Children; Pickering and Gathercole, 2001), and nonword repetition (Children's Test of Nonword Repetition; Gathercole and Baddeley, 1996). Children also were given experimental measures of phonological awareness (phoneme deletion and rime oddity). Finally, all children received four subtests of the Wechsler Intelligence Scale for Children (WISC-III): block design, picture arrangement, similarities, and vocabulary. IQ scores were then prorated for each child from these subtests following the procedure adopted by Sattler (1982).In addition, all children with specific language impairment received two receptive subtests (Concepts and Directions, Semantic Relations) and two expressive subtests (Formulating Sentences, Sentence Assembly) of the Clinical Evaluation of Language Fundamentals-3 (CELF-3; Semel et al., 1995).

1.3. *Motor tasks*

1.3.1. *Expressive rhythmic timing (metronome)*

This task was modeled after work on paced finger tapping in children with dyslexia by Wolff and colleagues (Rivkin et al., 2003; Waber et al., 2000; Wolff, 2002; Wolff et al., 1990). It was designed to compare rhythmic motor ability in paced settings (in time to a metronome beep) with rhythmic motor ability in unpaced settings (without a metronome beep). Beeps at the rate of 1.5 Hz (666.66 msec), 2 Hz (500 msec), and 2.5 Hz (400 msec) were created using an 800 Hz pure tone of 10 msec in duration. The experiment was created using Presentation software and was presented on a laptop computer, with the sounds presented through headphones at 73 dB SPL. Each metronome speed was presented for 30 sec (paced), followed by a 30 sec block of silence (unpaced). The task lasted for a total of 3 min, and the blocks of sounds were always presented in the following order: 2 Hz paced, 2 Hz unpaced, 2.5 Hz paced, 2.5 Hz unpaced, 1.5 Hz paced, 1.5 Hz unpaced. Children's responses were recorded using the spacebar, which was pressed with the index finger of the child's dominant hand.

Prior to the test procedure, all children completed a practice block lasting 30 sec, with 10-sec blocks of 2 Hz paced, 2 Hz unpaced, and 1.5 Hz paced. Children were told that they were going to hear a rhythm on the computer, and were asked to use the spacebar to tap to the rhythm. They were told that the beeps would sometimes go away, but to keep tapping at that same rhythm. When they heard a new rhythm, they were to tap to that new rhythm. For both the practice and test procedure, the time between taps (inter-tap-intervals), and time between the expected and actual response (anticipation time – AT) were recorded (at .1 msec resolution) and analyzed offline.

1.3.2. *Pegboard*

The Purdue Pegboard Battery (Tiffin, 1999) was used to establish the child's dominant hand and also provided a measure of non-rhythmic motor dexterity for both hands. The pegboard had two rows of 30 holes. Children took pegs of 1 cm in diameter and 5.2 cm in length from a bowl at the top of the pegboard and placed them in the holes of the row indicated by the experimenter. Children first practiced placing pegs in the holes with each hand individually, and then with both hands together. Children then completed 3 trials of 30 sec each for each of the three conditions (9 trials total) in the following order: dominant hand only, non-dominant hand only, both hands together. The score reported was the average of the three trials for the dominant, non-dominant, and both hands conditions.

2. Results

2.1. *Language and reading measures*

Results of the language and reading measures are displayed in Tables 1 and 2 and are described in detail in Corriveau et al. (2007). One-way between-subjects ANOVAs by group (SLI, CA, LA) were conducted for all of the tasks given. The ANOVAs revealed significant group differences for all psychometric measures. Post-hoc Bonferroni tests revealed that children with SLI were significantly impaired as compared to their CA and LA control groups on every measure except for CELF RAN colors. For this task, the children with SLI were only impaired relative to the CA controls.

2.2. *Metronome*

In the metronome task, children were asked to tap to one of three rhythms (1.5, 2, 2.5 Hz), in both a paced condition (where they heard a beep) and an unpaced condition (where they did not hear a beep). Two measures were calculated in the metronome task: ITI in both the paced and the unpaced conditions, and AT in the paced condition only.

The ITI measured the rate of a participant's tapping, and was measured by calculating the difference between the participant's responses (response 2–response 1, response 3–response 2, response4–response 3, etc.). An ITI of zero indicates tapping exactly as the metronome beeps. The AT measured the timing accuracy of each tap produced by the participant relative to the target beep, and was calculated by taking the difference between the paced beep and the participant's response (beep 1–response 1, beep 2–response 2, etc.). Negative anticipation scores indicate that the participant responded before the beep occurred (e.g., AT_1 in Fig. 1); positive responses indicate a response after the beep was played (e.g., AT_2 in Fig. 1). An anticipation score of zero indicates a response at exactly the same time that the beep was played. Fig. 1 is a schematic description of the method used to calculate the ITI and the AT in a hypothetical paced condition.

2.2.1. *Paced condition*

In the paced condition, subjects were asked to tap to the rhythm of the metronome beeps. To determine whether the time interval between the subject's responses was similar to the time interval between the metronome beeps, the ITI was

Table 2 – Mean performance (standard deviation) in the reading, memory, and rapid naming tasks by group (SLI, CA, LA).

Group	SLI	CA match	LA match	$F(2,60)$	Effect size (η^2)
Working memory^{a,b}	77.43	94.24	103.00	14.23***	.44
(SD)	(9.52)	(13.37)	(13.56)		
Nonword repetition (max = 30)^{a,b}	18.28	25.42	22.62	16.81***	.36
(SD)	(3.30)	(4.11)	(4.54)		
TOWRE word^{a,b}	88.81	107.91	114.95	25.09***	.46
(SD)	(15.51)	(11.37)	(9.45)		
TOWRE nonword^{a,b}	85.09	104.47	109.85	30.31***	.50
(SD)	(11.23)	(13.65)	(12.34)		
BAS spelling^{a,b}	84.09	113.43	118.05	39.76***	.56
(SD)	(14.04)	(11.10)	(12.14)		
Reading comprehension^{a,b}	76.52	96.95	105.57	48.36***	.61
(SD)	(8.51)	(11.02)	(9.78)		
CELF RAN colors (s)^{a}	32.15	22.19	26.25	8.24***	.22
(SD)	(11.92)	(3.77)	(6.07)		

$^{***}p < .001$.
a SLI < CA.
b SLI < LA.

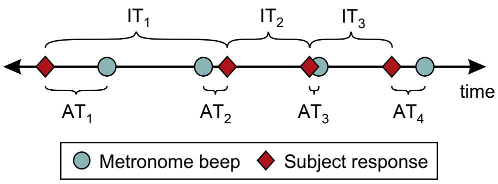

Fig. 1 – Schematic depiction of ITI and AT calculation.

calculated for all three rhythm speeds (1.5, 2, 2.5 Hz; see Fig. 1). To ensure that the child was automatically tapping to the correct rhythm, only the middle 15 beeps were analyzed. Outlying ITIs (for example, intervals in which children skipped a beep) were removed if the ITI fell outside 3.27 standard deviations of the group mean (90% confidence interval). In order to create a measure of the extent to which each child produced appropriate ITIs, the absolute value of the difference between the target ITI and the child's mean ITI was calculated (e.g., for 2 Hz a child with a mean ITI of 450 would have an ITI difference score of $|500–450\ \text{msec}| = 50$ msec). Note that as these are absolute values they do not indicate whether the child was trailing the beat or systematically tapping early. Table 3 displays the mean ITI difference scores for each of the three rhythms.

One-way ANOVAs by group (SLI, CA, LA) were conducted for each tapping rate. Significant group differences were found when subjects tapped at rates of 2 Hz $[F(2,60) = 5.71, p < .01, \eta^2 = .16]$ and 1.5 Hz $[F(2,60) = 8.01, p < .001, \eta^2 = .21]$, but not at rates of 2.5 Hz. Post-hoc Bonferroni tests revealed that children with SLI produced tapping rates that were significantly different from both the CA and LA control groups when tapping at a rate of 1.5 Hz and 2 Hz.

To determine whether SLI children's comparatively poor performance as represented by the ITI difference score was due to inconsistent tapping rates or to consistent but inaccurate tapping rates, the inter-subject variability of the paced ITI was examined. For example, a child who consistently tapped at a rate of 3 Hz when asked to tap at a rate of 1.5 Hz would have a large ITI difference score, but a relatively small inter-subject variability score. In contrast, a child tapping inconsistently at a mean rate of 1.5 Hz would have a small ITI difference score but a relatively large inter-subject variability score. We used the standard deviation of each subject's paced ITI scores as a measure of inter-subject variability. As in the paced ITI, only the middle 15 beats were examined, and outliers were removed. One-way ANOVAs with group (SLI, CA, LA) revealed significant group differences in inter-subject variability in the 1.5 Hz $[F(2,60) = 4.86, p < .01, \eta^2 = .14]$ and 2 Hz conditions $[F(2,60) = 14.11, p < .001, \eta^2 = .32]$, although no group difference was found in the 2.5 Hz condition. Post-hoc Bonferroni tests revealed that the inter-subject variability of the SLI group differed significantly from both the CA and LA control groups on the 2 Hz condition, and from the CA group on the 1.5 Hz condition. Table 4 displays the inter-subject variability for each group for the three tapping rates.

As described above, the extent to which each child anticipated the metronome beat was also measured (see Fig. 1). Mean AT scores (standard deviations) for each tapping rate are displayed in Table 5. One-way between-subjects ANOVAs with group found a significant group difference in the 1.5 Hz condition only $[F(2,60) = 5.52, p < .01, \eta^2 = .16]$. Post-hoc Bonferroni tests revealed that, on average, children in the SLI group tapped earlier than children in both the LA and CA control groups.

2.2.2. *Unpaced condition*

In the unpaced condition, the subject was asked to continue tapping at the same rate without the help of a metronome beep. ITI difference scores and inter-subject variability were measured in order to determine if the time interval between the subject's responses was similar to the time interval expected if there were a metronome beep, and to determine the variability of the subject's responses, respectively. Both the ITI difference scores and the inter-subject variability scores were calculated using the same method as in the paced condition. Table 6 displays the mean ITI difference scores for each of the three rhythms in the unpaced condition. One-way ANOVAs by group (SLI, CA, LA) were conducted for the ITI difference scores at each tapping rate. No significant group differences were found. However, note that the mean ITI difference scores in the unpaced condition are relatively large as compared to the ITI difference scores in the paced condition. Thus, the lack of group differences on this measure may have been due to all children performing poorly in the unpaced condition.

Table 3 – Mean (standard deviation) ITI difference scores in milliseconds for the 1.5 Hz, 2 Hz, 2.5 Hz paced condition.

Group	SLI	CA match	LA match	*F*(2,60)
1.5 Hz (666.66 msec)[a,b] (SD)	95.2 (142.10)	6.78 (7.82)	13.14 (29.21)	8.01***
2 Hz (500 msec)[a,b] (SD)	46.12 (75.25)	5.99 (8.28)	5.99 (5.78)	5.71**
2.5 Hz (400 msec) (SD)	34.90 (49.13)	15.59 (32.81)	16.50 (21.42)	1.89

$^{*}p < .05$, $^{**}p < .01$.
[a] SLI > CA, $p < .05$.
[b] SLI > LA, $p < .05$.

Table 4 – Mean (standard deviation) inter-subject variability in milliseconds for the 1.5 Hz, 2 Hz, 2.5 Hz paced condition.

Group	SLI	CA match	LA match	*F*(2,60)
1.5 Hz (666.66 msec)[a] (SD)	58.51 (33.03)	42.26 (9.12)	61.46 (15.16)	4.86**
2 Hz (500 msec)[a,b] (SD)	51.44 (25.86)	29.08 (8.91)	27.99 (5.82)	14.11***
2.5 Hz (400 msec) (SD)	37.24 (16.23)	38.47 (19.59)	51.44 (25.86)	.35

$^{**}p < .01$, $^{***}p < .001$.
[a] SLI > CA, $p < .01$.
[b] SLI > LA, $p < .01$.

Table 5 – Mean (standard deviation) AT scores in milliseconds for the 1.5 Hz, 2 Hz, 2.5 Hz paced condition.

Group	SLI	CA match	LA match	F(2,60)
1.5 Hz (666.66 msec)[a,b] (SD)	45.08 (66.18)	89.37 (53.46)	98.47 (45.47)	5.52**
2 Hz (500 msec) (SD)	−53.74 (38.28)	−50.35 (50.44)	−42.25 (46.60)	.36
2.5 Hz (400 msec) (SD)	−33.24 (42.87)	−19.22 (42.45)	−27.35 (34.79)	.65

$^{**}p < .01$.
a SLI < CA, $p < .05$.
b SLI < LA, $p < .01$.

Table 7 displays the inter-subject variability scores in the unpaced condition. Inter-subject variability was high for all three groups, indicating that all children performed inconsistently on the unpaced tapping task. One-way between-subjects ANOVAs with group were conducted for the inter-subject variability scores. A significant group difference was found for the 1.5 Hz condition only [$F(2,60) = 4.17$, $p < .05$, $\eta^2 = .12$]. Post-hoc Bonferroni tests revealed that the SLI group performance was significantly more inconsistent than CA control group performance.

2.3. *Composite scores*

In order to increase the predictive power of the rhythmic measures to explore relations with language and literacy, composite variables were created by collapsing across the three rhythm speeds. For both the paced and unpaced condition, composite variables were created for the ITI difference and inter-subject variability scores. A composite AT score was also created for the paced condition. Thus, each child was assigned a total of five composite scores.

Before creating the composite variables, mean scores for each metronome speed were divided by the length of the time interval. For example, in the 2 Hz condition, each subject's scores were divided by 500. In order to reduce the number of outliers, the natural log of each normalized score was calculated, except in the AT condition, where this step was unnecessary. The log transformation resulted in negative scores: more negative scores indicated better performance than less negative scores. Because the AT scores were not log-transformed, negative scores continue to represent anticipatory taps, while positive scores represent taps that occurred after the metronome beep. Finally, in order to determine whether scores from all three metronome rhythms should be included in each composite variable, Chronbach's alpha was calculated for the sum of the three normalized scores, and for each possible pair of these scores. For each of the five measures (paced ITI difference, unpaced ITI difference, paced inter-subject variability, unpaced inter-subject variability, and AT) the combination of normalized scores yielding the highest Chronbach's alpha were included in the composite variable. Table 8 displays mean (standard deviation) composite scores for these five composite measures.

Table 6 – Mean (standard deviation) ITI difference scores in milliseconds for the 1.5 Hz, 2 Hz, 2.5 Hz unpaced condition.

Group	SLI	CA match	LA match	F(2,60)
1.5 Hz (666.66 msec) (SD)	93.01 (85.98)	76.24 (130.42)	120.58 (138.66)	.72
2 Hz (500 msec) (SD)	89.31 (104.38)	48.70 (55.33)	49.62 (41.15)	2.17
2.5 Hz (400 msec) (SD)	40.39 (39.98)	38.88 (38.54)	57.52 (85.49)	.65

Table 7 – Mean (standard deviation) inter-subject variability in milliseconds for the 1.5 Hz, 2 Hz, 2.5 Hz unpaced condition.

Group	SLI	CA match	LA match	F(2,60)
1.5 Hz (666.66 msec)[a] (SD)	121.99 (121.84)	50.64 (21.31)	86.85 (56.31)	4.17*
2 Hz (500 msec) (SD)	78.01 (59.06)	64.05 (104.01)	54.19 (39.61)	.56
2.5 Hz (400 msec) (SD)	73.69 (115.93)	55.83 (76.12)	50.48 (36.93)	.45

$^{*}p < .05$.
a Asterisks indicate significant differences between control and SLI performance.

One-way ANOVAs with group (SLI, LA, CA) as the between-subjects variable were conducted for the five composite scores, and post-hoc Bonferroni tests were used to determine the locus of significant group differences. In the paced condition, these analyses revealed that the children with SLI had an ITI difference score that was significantly larger than that of the two control groups. This indicates that motor rhythm production to an auditory stimulus by children with SLI was significantly less accurate than that of either control group. In addition, inter-subject variability in the paced condition was significantly greater for children with SLI than

Table 8 – Mean composite scores by group for the five metronome measures.

	SLI	CA match	LA match	F(2,60)
Paced condition				
ITI difference (SD)	−7.69 (3.97)	−10.38 (2.19)	−9.76 (2.04)	5.08**
Inter-subject variability (SD)	−4.80 (.935)	−5.68 (.482)	−5.32 (.320)	10.15***
AT (SD)	−.040 (.149)	.033 (.154)	.063 (.140)	2.68∼
Unpaced condition				
ITI difference (SD)	−5.59 (2.42)	−5.87 (1.53)	−5.24 (1.38)	.64
Inter-subject variability (SD)	−4.16 (1.29)	−5.12 (.767)	−4.61 (.867)	4.82**

$\sim p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

for children in either of the two control groups. This indicates that the motor rhythms produced by the children with SLI were more inconsistent than those produced by the control groups. There was a trend for anticipation scores to be more negative in the children with SLI than in the CA control group, indicating that the group with SLI was more likely than the CA controls to tap before the beep was played. Hence in all measures of auditory entrainment, the children with SLI were performing more poorly than controls. In the unpaced condition of the metronome task, the children with SLI did not differ from either control group in their ITI difference scores. However, inter-subject variability was significantly greater for the children with SLI than for both the CA controls and for the younger LA controls.

In summary, we created five measures of interest in the metronome task: paced ITI difference, unpaced ITI difference, paced inter-subject variability, unpaced inter-subject variability, and AT. Children with SLI differed significantly from one or both control groups in 3 of these measures: within-subject variability, paced ITI difference scores, and unpaced inter-subject variability. They did not differ significantly from controls in the unpaced ITI difference scores. The difference for AT approached significance. Table 8 summarizes performance in these five measures by participant group.

2.3.1. *Pegboard*

The pegboard task measured the children's motor dexterity. Four scores were calculated for this measure. First, the average number of pegs completed in 30 sec by group was calculated for each of the 3 subtasks (dominant hand, non-dominant hand, both hands). Second, a total score combining the mean scores from the three subtasks (dominant + non-dominant + both) by group was computed. For each of these measures, one-way ANOVAs with group as the between-subject variable were conducted. A main effect of group was found for the non-dominant hand, both hands, and total score, but not for the dominant hand score. Post-hoc Bonferroni tests were conducted to determine the locus of significance in each case. The children with SLI did not differ significantly from the two control groups on either the dominant hand measure, the "both hands" measure or the total measure. However, the CA group scored significantly higher than the LA group on both the total measure and the "both hands" measure. On the non-dominant hand task, children with SLI inserted significantly fewer pegs than CA controls. This was the only deficit found. Table 9 displays the average number of pegs inserted in 30 sec for each of the four conditions (dominant, non-dominant, both, total) by subject group.

Table 9 – Mean number of pegs inserted in 30 sec for pegboard by subject group.

	SLI	CA match	LA match	$F(2,60)$
Dominant hand (SD)	12.73 (1.79)	13.11 (1.36)	12.01 (1.69)	2.47
Non-dominant hand[a] (SD)	11.38 (1.68)	12.48 (.99)	11.36 (1.14)	4.99**
Both hands[a] (SD)	9.56 (1.56)	10.34 (.98)	9.38 (1.17)	3.50*
Total[a] (SD)	33.97 (4.13)	35.87 (2.38)	31.97 (3.82)	6.42**

$^*p < .05$, $^{**}p < .01$.
a CA performance was significantly greater than LA performance ($p < .05$).

Exploration of partial correlations controlling for age showed that several of the metronome variables were related to measures of phonological awareness and reading (see Table 10). The paced metronome composite variable was related to measures of phonological awareness, and both the paced metronome and the paced inter-subject variability composite variables were related to all measures of reading and spelling. In contrast, the unpaced tapping measures were not related to language or literacy. The pegboard non-dominant hand measure was related to phoneme deletion and rime oddity, but not to reading and spelling.

In order to determine whether there was a connection between motor performance as measured by the metronome and pegboard tasks and children's performance on the language and literacy tasks, a series of fixed-order multiple regressions were conducted. The entire group of 63 subjects was included in order to examine developmental relationships. For each regression, the Cook's distance metric was calculated. Data points with Cook's distance scores of above 1.0 were excluded from the regression (Tabachnik and Fidell, 2001). The dependent variables used were the different measures of language, phonological awareness, memory and literacy. The independent variables were (in a fixed order): 1. Age, 2. WISC Performance IQ, 3. An additional rhythm and motor measure (paced ITI difference composite, paced inter-subject variability composite, unpaced ITI difference composite, unpaced inter-subject variability, AT composite, pegboard non-dominant hand). The resulting equations are displayed in Table 11 in terms of the unique variation accounted for by each variable (change in R-squared).

The analyses showed that the paced motor measures of rhythmic timing were related to variability in language and literacy, whereas the unpaced measures and motor dexterity (the pegboard measure) were not. The paced ITI difference score accounted for a significant amount of unique variation in all language and literacy measures, and for as much as 13 per cent unique variation in the Rime Oddity task. The paced inter-subject variability measure explained additional variation in spelling and single word and nonword reading. AT explained unique variance in vocabulary and the phonological awareness measures, and in spelling. The unpaced ITI difference score and the unpaced inter-subject variability measure did not predict any unique variation in any of the language and literacy measures. The pegboard task did not predict any unique variation in the language and literacy measures, with the exception of the Phoneme Deletion task, for which the non-dominant pegboard score accounted for 7.8 per cent of unique variation.

To determine the extent to which the pegboard task accounted for unique variance after controlling for the paced metronome task, and the extent to which the paced metronome task accounted for unique variation after controlling for the pegboard task, two stepwise regression models were created with the independent variables: 1. Age, 2. Performance

Table 10 – Partial correlations (*r*) of intelligence, language, reading and motor measures, controlling for age (months).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Nonverbal IQ[a]	–	.134	.183	.041	.105	.076	.073	.051	.098	.285*	.252*	.164	.173	.003	.269*
2. Verbal IQ[b]		–	.719***	.593***	.553***	.351**	.388**	.453***	.631***	−.112	−.178	−.036	−.136	−.273	.206
3. Receptive vocabulary[c]			–	.605***	.637***	.393**	.364**	.485***	.639***	−.247	−.160	−.284*	−.112	−.071	.210
4. Phoneme deletion				–	.701***	.631***	.638***	.691***	.622***	−.262	−.109	−.333*	−.041	−.068	.294*
5. Rime oddity					–	.477***	.400**	.527***	.637***	−.353**	−.210	−.317*	−.082	−.091	.264*
6. Word reading[d]						–	.844***	.827***	.530***	−.293*	−.298*	−.124	−.059	−.063	.137
7. Nonword reading[e]							–	.825***	.481***	−.286*	−.301*	−.198	−.198	−.118	.203
8. Spelling[f]								–	.494***	−.287*	−.322*	−.266*	−.073	−.128	.101
9. Reading comprehension[g]									–	−.236∼	−.214∼	−.116	−.044	−.012	.211
10. Met. Paced										–	.508***	.450***	.354**	.189	.033
11. Met. paced variab.											–	.348**	.390**	.427***	−.174
12. AT												–	.143	.000	.143
13. Met. unpaced													–	.440***	.179
14. Met. Unpaced Variab.														–	−.091
15. Pegbord non-dominant															–

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

a Nonverbal IQ estimated from the block design and picture arrangement subtests ($M = 100$, SD = 15).

b Verbal IQ estimated from the similarities and vocabulary subtests ($M = 100$, SD = 15).

c British picture vocabulary test ($M = 100$, SD = 15).

d Test of word reading efficiency – sight word subtest ($M = 100$, SD = 15).

e Test of word reading efficiency – non-word subtest ($M = 100$, SD = 15).

f British ability scales – spelling subtest ($M = 100$, SD = 15).

g WORD – reading comprehension subtest ($M = 100$, SD = 15).

IQ, 3. Metronome paced ITI difference measure and 4. Pegboard non-dominant hand measure; versus 1. Age, 2. Performance IQ, 3. Pegboard non-dominant hand measure and 4. Metronome paced ITI difference measure. Changes in R^2 values for these models are displayed in Table 12. With the additional metronome step included, the pegboard task accounted for nearly the same amount of unique variation as when the metronome measure was not included, and change in R^2 values also changed only slightly after controlling for the pegboard measure. Thus, the results from these two models indicate that the metronome and pegboard measures account for separable, unique variation in the language and literacy

Table 11 – Stepwise regressions exploring the unique variance (change in R^2) accounted for by the rhythm and motor measures in the language and literacy tasks.

	Vocabulary		Phon. awareness		Reading and spelling				RAN and working memory		
	WISC vocab	BPVS	Phon deletion	Rime	Single word	Single nonword	Reading comp.	Spelling	RAN colors	NW rep	WM word
Step 1: age	.181**	.222***	.023	.000	.040	.001	.035	.066*	.000	.001	.026
Step 2: performance IQ	.027	.019	.007	.012	.006	.002	.005	.003	.035	.009	.002
Step 3: paced ITI difference	.018	.083**	.079*	.130**	.096*	.091*	.065*	.088*	.072*	.092*	.024
Step 3: paced inter-subject variability	.016	.026	.009	.022	.080*	.091*	.039	.095*	.021	.032	.010
Step 3: unpaced ITI difference	.004	.003	.001	.004	.005	.043	.003	.007	.003	.000	.012
Step 3: unpaced inter-subject variability	.032	.008	.005	.007	.004	.035	.000	.015	.022	.006	.027
Step 3: AT	.001	.063*	.102*	.083*	.012	.037	.010	.063*	.023	.052	.044
Step 3: pegboard non-dominant hand	.012	.023	.078*	.059	.014	.040	.038	.007	.010	.055	.045

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Note: WISC vocab = WISC vocabulary, BPVS = British picture vocabulary scales, Phon deletion = Phoneme deletion total, Rime = Rime oddity, Single word = TOWRE words, Single nonword = TOWRE nonwords, Reading comp = WORD-comprehension subtest, Spelling = British ability scales-spelling subtest, RAN colors = CELF-rapid color naming, NW Rep = children's test of nonword repetition, WM word = working memory test for children-word subtest.

Table 12 – Stepwise regressions exploring the unique variance (change in R^2) accounted for by both the rhythm and motor measures in the language and literacy tasks.

	Vocabulary		Phon. awareness		Reading and spelling				Ran and working memory		
	WISC vocab	BPVS	Phon deletion	Rime	Single word	Single nonword	Reading comp.	Spelling	RAN colors	NW rep	WM word
Step 1: age	.181**	.222***	.023	.000	.040	.001	.035	.066*	.000	.001	.026
Step 2: performance IQ	.027	.019	.007	.012	.006	.002	.005	.003	.035	.009	.002
Step 3: paced ITI difference	.018	.083**	.079*	.130**	.096*	.091*	.065*	.088*	.072*	.092*	.024
Step 4: Pegboard non-dominant hand	.010	.020	.073*	.053	.011	.036	.035	.006	.009	.051	.042
Step 3: pegboard non-dominant hand	.012	.023	.078*	.059	.014	.040	.038	.007	.010	.055	.045
Step 4: paced ITI difference	.016	.080**	.074*	.125**	.094*	.087*	.061*	.086*	.070*	.088*	.022

Note: WISC vocab = WISC vocabulary, BPVS = British picture vocabulary scales, Phon deletion = Phoneme deletion total, Rime = rime oddity, Single word = TOWRE words, Single nonword = TOWRE nonwords, Reading comp = WORD-comprehension subtest, Spelling = British ability scales-spelling subtest, RAN colors = CELF-rapid color naming, NW Rep = children's test of nonword repetition, WM word = working memory test for children-word subtest.
*$p < .05$, **$p < .01$, ***$p < .001$.

measures, with the rhythmic timing measure showing the majority of significant relationships.

3. Discussion

The central question of interest in this paper was whether children with SLI would exhibit difficulties in tapping in synchrony with the auditory rhythm provided by a metronome beat. Tapping to a rhythm without an auditory entrainment stimulus was also measured. The data show that the children with SLI were significantly impaired in the metronome (paced) tapping conditions, exhibiting poorer performance than both age-matched and younger language-matched control children when tapping at the slower rates of 1.5 and 2 Hz. The children with SLI also displayed more inter-subject variability than both control groups for paced tapping, and showed significantly different ATs for the slowest rate (1.5 Hz), tapping earlier than both age-matched and younger language-age matched children. In contrast, when the metronome beat was turned off and the children were asked to keep tapping at the same rate according to an internally-generated rhythm, no significant group differences were found in ITIs (although all children performed poorly in this task). The only difference found in unpaced tapping was for the slowest 1.5 Hz rhythm, for which the children with SLI showed significantly greater inter-subject variability than age matched controls only. We have therefore demonstrated that children with SLI and with established auditory rhythmic difficulties (Corriveau et al., 2007) are also impaired in paced tapping tasks requiring them to tap in time with an auditory stimulus. These findings are consistent with the possibility that at least part of the comorbidity between language and motor impairment found in some children with SLI results from a rhythmic processing deficit.

Most reports of motor impairment in children with SLI do not rely on rhythmic motor tasks, however. We therefore included a standard measure of motor performance in our study, the pegboard task, as an index of general motor dexterity. The children with SLI were not impaired in the pegboard task in comparison to either age-matched or younger language-age matched controls, apart from on one measure involving the non-dominant hand. Motor dexterity was not related to language nor literacy in multiple regression analyses controlling for age and IQ. In contrast, paced tapping was related to all measures of language and literacy in the same multiple regression analyses. The composite measures of paced ITI and anticipation of the metronome beat accounted for unique variance in vocabulary, phoneme deletion, rime awareness and spelling, with the paced ITI measure also predicting unique variance in word and nonword reading, RAN, nonword repetition and reading comprehension. The unpaced measure of ITI did not account for any significant variance in the phonology, language or literacy measures. Motor dexterity was related to one measure of phonological awareness, namely phoneme deletion.

In the introduction, we predicted difficulties in tapping to a beat in our sample on the hypothesis that children with SLI may have subtle impairments in the neural mechanisms for the perception and expression of rhythm and timing that affect both language and motor development. In the wider literature on rhythm and beat perception, there is considerable debate about what the neural structures underpinning motor and timing abilities might be. For example, Grahn and Brett (2007) note that perception of a beat in a musical stimulus frequently causes spontaneous synchronized motor movement such as toe tapping, suggesting an intimate neural connection. In musical stimuli the beat is conveyed by temporal properties of the music, and depends on the organization of auditory cues that may themselves be non-rhythmic, such as pitch and volume. It is these properties of temporal organization to which we synchronize our motor behaviour. As noted earlier, the classical view is that both motor structures and the cerebellum and basal ganglia are involved in timing and rhythm perception and production. However, in their fMRI study of adults, Grahn and Brett (2007) found that the cerebellum and premotor areas were not differentially active for beat-inducing rhythms compared to rhythms that did not induce a beat. They argued that the cerebellum did not play a specific role in beat-based timing.

This argument is consistent with a series of experiments reported by Molinari and his colleagues. They demonstrated that rhythmic motor entrainment (tapping to a beat) depends on neural excitation patterns in the auditory nerve, rather than on the cerebellum (Molinari et al., 2003). Molinari et al. (2003) reported that patients with cerebellar pathology could tap in synchrony to a metronome, and could modify their tapping to variations in the metronome beat as well as control subjects, despite having an impaired conscious ability to detect rhythmic variation. Molinari et al. (2003) suggested that time coding in the auditory nerve may transfer directly into adjacent motor structures. If this idea is correct, it would explain why our participants with impaired auditory rhythmic timing also had difficulty in rhythmic motor entrainment tasks. It might also help to explain why individual differences in motor entrainment tasks predicted language and literacy development. On this account, the primary low-level deficit would depend on auditory processing and not on cerebellar dysfunction (see Nicolson and Fawcett, 1999 for a cerebellar account of developmental dyslexia). It is interesting to note that in their study of learning-impaired children, Waber et al. (2000) drew similar conclusions. They speculated that degraded connectivity could impede motor system access to a working memory representation of the auditory signal (working memory is a phonological system).

In Corriveau et al. (2007), we argued that the auditory rhythmic processing deficits that we had uncovered supported the possibility that SLI could be caused by lower-level processing difficulties in the auditory domain. We suggested that early difficulties, present from infancy, in processing accurately auditory rhythmic cues to prosody could impair the acquisition of language, for example by disrupting the suprasegmental processing required to extract words and syllables from the speech stream. As caretakers communicate with infants in a special prosodic register (called infant-directed speech or Motherese, Fernald and Mazzie, 1991), an early insensitivity to auditory cues to rhythm and stress could have profound and lasting consequences on the development of the language system. In fact, a recent review of work in language development suggested that young children attend primarily to global spectral structure arising from relatively slow modulations of the vocal tract (Nittrouer, 2006), which would fit this view of a primary impairment in suprasegmental processing.

However, rhythm and beat perception are also central to the appreciation of music. This has led to vigorous interest in the possibly shared neural bases of music and language (e.g., Patel, 2006; Peretz and Coltheart, 2003;). Clearly, a subtle neural impairment in the perception and expression of rhythmic timing could affect both language and music. A fruitful approach to exploring this hypothesis might be to take the modular framework for music and language processing proposed by Peretz and Coltheart (2003, see Fig. 2), and analyse potential difficulties in the sub-components of acoustic analysis with respect to language- and literacy-impaired children. Taking a wider perspective across all of our studies (which have included other measures of tempo as well as tapping), we can propose that the parts of the model that are proposed to be specific to pitch organization (shown in blue) do not appear to be impaired in children with language and literacy problems (Goswami, 2007). In contrast, those parts of the model that are proposed to comprise temporal organization, namely rhythm and meter analysis, do appear to be impaired in children with language and literacy problems. These aspects of musical processing are shown in yellow in the model, along with other

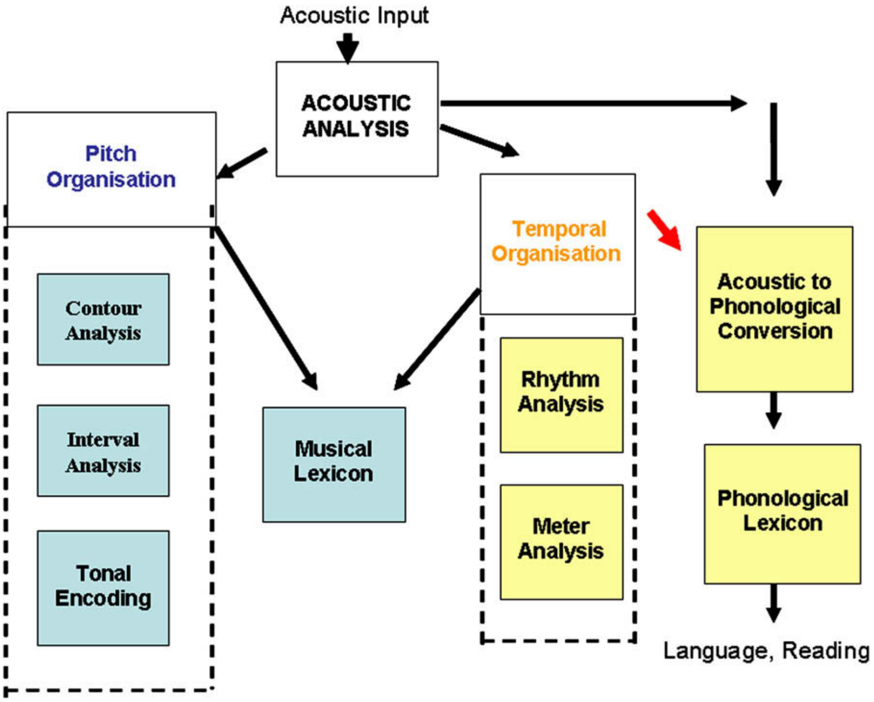

Fig. 2 – An adaptation of the modular framework for music processing proposed by Peretz and Coltheart (2003). Boxes shown in yellow are hypothesized to be impaired in children with language and literacy difficulties. The impairment in temporal organization (rhythm and meter) is hypothesized to be causal in the phonological problems shown by these children (red arrow). Further research is required to see whether boxes shown in blue are preserved.

aspects of acoustic analysis that are impaired in children with language and literacy difficulties. To paraphrase a review by Hyde and Peretz (2004), brains with amusia are out of tune but in time. It may be that brains with developmental dyslexia are in tune but out of time. Intriguingly, if amusic adults are asked to perform pitch organization tasks such as pitch contour tasks using syllables instead of tones, they can now succeed in these tasks. Whether children with language and literacy impairments can succeed in rhythmic and metrical tasks when they are given musical stimuli remains to be established.

It certainly seems worthwhile to explore the use of rhythmic training interventions with speech and language impaired children (Overy, 2000). Simple activities such as singing to music or playing a drum in time with the stressed syllables in nursery rhymes (HUMP-ty DUMP-ty SAT on a WALL) may have previously unsuspected benefits for the development of language, phonology and literacy. Although this idea may appear speculative, it is of note that patients with movement disorders such as Parkinson's disease can be helped by auditory rhythms (e.g., Thaut et al., 1996). If auditory rhythms can be used to rehabilitate motor problems, then there is some plausibility in the reciprocal idea that motor rhythms might be able to help in the development of better auditory rhythmic sensitivity in children with auditory processing problems and poor language. The production of structured rhythmic and temporal language patterns is a crucial part of language acquisition. For example, when babies are born deaf, these rhythmic structures have a motor basis. Petitto et al. (2004) studied the rhythmic hand movements of two groups of babies, deaf babies born to deaf parents (who were learning to sign), and hearing babies born to hearing parents (who were not learning to sign). Pettito et al. reported that the deaf babies ''babbled'' with their hands. This ''hand babble'' was produced repetitively in accord with the general prosodic contours of natural sign languages, duplicating the rhythmic timing and stress of hand shapes in natural signs. The hearing babies did not produce manual babbling. These data suggest that babbling is not simply motoric rhythmic behaviour, but is specifically linguistic. If infants are exposed to spoken language, they will babble sounds. If infants are exposed to sign language, they will babble signs. For hearing babies, the sounds that they babble reflect the prosodic properties of the native language: adults listening to taped infant babble from French, Cantonese and Arabic infants could distinguish each ''language'' (De Boysson-Bardies et al., 1984). Both hearing and deaf babies are hence discovering and producing the most rudimentary structures of the natural language to which they are exposed. These rudimentary structures are rhythmic ones, in both the auditory and motor realms. Hence motor and language play focused on rhythm seems likely to be beneficial for the development of speech and language.

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