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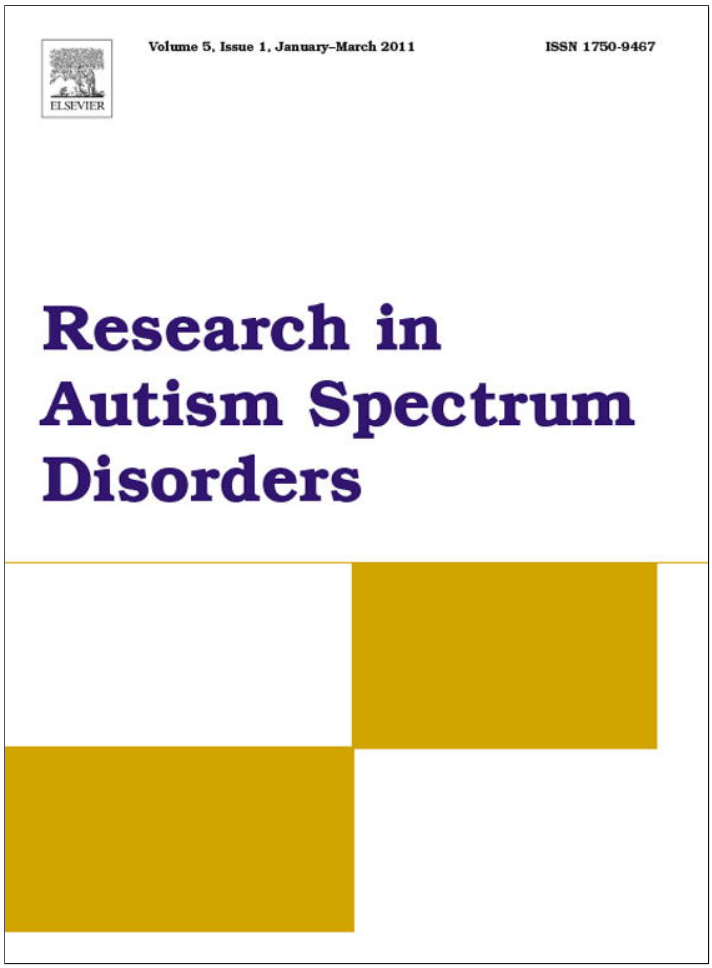

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Rhythmic bimanual coordination is impaired in young children with autism spectrum disorder

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ABSTRACT

Impairments in motor coordination are a common behavioral manifestation of autism spectrum disorder (ASD). We, therefore, used a drumming methodology to examine rhythmic bimanual coordination in children diagnosed with ASD ($M = 47.3$ months) and age-matched typically developing (TD) children ($M = 42.6$ months). Both groups were instructed to drum on a pad in two required phases: in-phase (drumsticks striking the pad simultaneously) and anti-phase (drumsticks striking in alteration). Analysis revealed that TD children were more able than children with ASD to stay in the required phase relationships for both in-phase and anti-phase coordination. Movement variability was higher for children with ASD than TD children. Imitation ability of the ASD group was somewhat related to their performance on the task. We discuss the implications that deficits in bimanual (intra-personal) coordination may have for social and interpersonal coordination in children with ASD.

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Our goal is to explore and quantify one class of coordination deficits in children diagnosed with autism spectrum disorder (ASD) using a modified version of the well-studied bimanual rhythmic coordination paradigm. Although the pervasiveness of motor deficits in ASD has been open to question, there has been substantial neurological (Mostofsky et al., 2009) and behavioral (Jansiewicz et al., 2006) research on the topic. A recent meta-analysis of forty-one studies involving motor coordination in ASD revealed that deficits in motor coordination are prevalent across many diagnoses of ASD (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010) including Asperger's Syndrome and High Functioning Autism. Other studies have found manual (upper extremity) coordination deficits in children with ASD (Dyck, Piek, Hay, Smith, & Hallmayer, 2006; Gernsbacher, Sauer, Geye, Schweigert, & Hill Goldsmith, 2008; Martineau, Schmitz, Assiante, Blanc, & Barthelemy, 2004), and children with ASD exhibit a lesser degree of handedness and hand preference consistency (McManus, Murray, Doyle, & Baron-Cohen, 1992). However, to date, no studies have examined rhythmic bimanual coordination in young children with ASD.

Bimanual coordination, the spatio-temporal locking of two limbs in the service of behavior, is utilized in many daily life skills and is recruited for more complex motor behaviors (e.g., reaching to grab an object with both hands simultaneously,

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clapping, tying shoe laces, and eating with a knife and fork). Adroit bimanual coordination involves a high level of rhythmicity and synchrony, and given that deficits in anticipatory timing adjustments (critical to the performance of bimanual tasks) have been documented in children with ASD (Martineau et al., 2004) explicitly examining coordination in this population with a rhythmic bimanual task is warranted.

Beneficially, the dynamics of rhythmic bimanual coordination are well understood. Numerous studies have revealed that rhythmic coordination can be understood in terms of the entrainment dynamics of coupled oscillators (Kelso, 1995; Kugler & Turvey, 1987). Specifically, the model of interlimb coordination proposed by Haken, Kelso, and Bunz (1985; HKB model) has provided an important methodological and theoretical framework to study bimanual coordination in adults (cf. Amazeen, Amazeen, & Turvey, 1998; Turvey, 1990) and children (Fitzpatrick, Lockman, & Schmidt, 1996; Lantero & Ringenbach, 2007; Robertson, 2001). The motion equation for the HKB model is usually presented as the following:

$$\dot{\phi} = \Delta\omega - a\sin\phi - 2b\sin 2\phi + \sqrt{Q}\xi_t \quad (1)$$

Relative phase (ϕ) is the collective variable that captures the spatio-temporal relationship between the two component oscillators (i.e., arms in the present study). $\dot{\phi}$ is the rate of change of relative phase. The sine functions ϕ and 2ϕ, along with their respective coefficients a and b, index the relative strength of the stable relative phase modes (when $\dot{\phi} = 0$) at $\phi = 0^\circ$ (in-phase coordination) and $\phi = 180^\circ$ (anti-phase coordination) of the oscillators. In-phase is stronger than anti-phase. $\Delta\omega$ is a detuning parameter and is a measure of the difference in the natural (and uncoupled) frequency of the two oscillators (Sternad, Collins, & Turvey, 1995). ξ_t is a Gaussian noise process that dictates a stochastic force of strength Q (Schöner, Haken, & Kelso, 1986).

Research examining rhythmic bimanual coordination in typically developing children on tasks as diverse as clapping (Fitzpatrick et al., 1996), circle drawing (Lantero & Ringenbach, 2007), and drumming (Brakke, Fragaszy, Simpson, Hoy, & Cummins-Sebree, 2007) has demonstrated results consistent with the predictions of a coupled oscillator model. Although the emergence of bimanual coordination in typically developing children occurs early, clapping during the first year (Kaye & Marcus, 1981) and drumming sometime between the first and second birthdays (Brakke et al., 2007), evidence suggests that adult level proficiency in terms of the coupling strength of entrainment does not appear until well into childhood (Fitzpatrick et al., 1996).

Given that coordination deficits appear to be important, yet underexplored, behavioral deficits of autism and that interlimb coordination is well understood and central to motor behavior, we investigate whether children diagnosed with ASD have deficiencies in rhythmic interlimb coordination. We anticipate that children with ASD will be less able than matched controls to maintain required coordination patterns during a bimanual drumming task for two reasons: (1) the prevalence of motor deficits associated with ASD is likely to detrimentally affect the precise control needed to successfully perform the task and (2) previous research reveals that rhythmic bimanual coordination follows a developmental trajectory (Fitzpatrick et al., 1996) which is likely impaired in ASD, as numerous developmental delays typify the disorder.

The two required coordination patterns we examine are the two stable states predicted by the HKB model, in-phase drumming—a relative phase (ϕ) of 0° with drumsticks striking the pad simultaneously—and anti-phase drumming—a relative phase (ϕ) of 180° with drumsticks striking the pad in alteration. Because previous research has demonstrated that in-phase bimanual coordination is more stable than anti-phase coordination (Kelso, 1984, 1995), we anticipate any differences between groups will be magnified during anti-phase coordination. Additionally, if children with ASD are less able to maintain the required phase relationships it is likely that their movements will be more variable than typically developing controls.

1. Method

1.1. Participants

Seven children with ASD and seven children with a history of typical development (TD) participated in the study after their parents' informed consent was attained. Children with ASD were recruited through an ongoing "Early Detection" study (where initial diagnosis was made) at the University of Connecticut (Kleinman et al., 2008), and a diagnosis of autism was confirmed using the *Autism Diagnostic Observation Scale* (ADOS; Lord, Rutter, DiLavore, & Risi, 1999) and the *Autism Diagnostic Interview, Revised* (ADI-R; Lord, Rutter, & Le Couteur, 1994). TD children were a convenience sample recruited from the local university community. Clinical judgment by experienced clinicians is the "gold standard" for autism diagnosis (Klin, Lang, Cicchetti, & Volkmar, 2000). Clinicians used the DSM-IV-TR criteria for Pervasive Developmental Disorders (APA, 2000) as the basis for their clinical judgments and a diagnosis of ASD was given if the licensed clinician determined that the child met the necessary diagnostic criteria. Both a licensed clinician at the University of Connecticut and a doctoral student completed the ADOS and ADI-R.

Both the groups of participants were administered the *Mullen Scales of Early Learning* (Mullen, 1995) by the same licensed clinician and doctoral student that completed the ADOS and ADI-R. The two groups were matched on scores from the *fine motor* subscale of the Mullen and TD children were run until suitable matches (within 6 months per pair) were obtained for each child in the ASD group. The Mullen is a measure of intellectual development for children up to 68 months of age that includes items that measure skills on five scales: *gross motor*, *visual reception*, *fine motor*, *receptive language*, and *expressive*

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language. The *gross motor* subscale is only applicable to children birth through 33 months and therefore could not be used for age-matching the participants. However, the *fine motor* subscale is justifiable for age-matching, given the motor precision required to control the spatiotemporal aspects of the endpoint trajectories of each drumstick to successfully perform the task. The median split-half reliability for the *fine motor* subscale is 0.75.

The ADOS (Lord et al., 1999) is a semi-structured standardized assessment of communication, social interaction, and play behaviors. The instrument consists of planned social interactions that are presented by a trained evaluator in order to encourage the child to initiate and respond to interactions in a naturalistic setting. The ADOS has four modules corresponding to varying expressive language levels ranging from pre-verbal/single words to fluent speech. The ADOS algorithm provides diagnostic cutoffs for Autistic Disorder, ASD, and non-ASD.

The ADI-R (Lord et al., 1994) is a structured interview with the parent or caregiver who is familiar with the developmental history of the individual being evaluated. It focuses on behaviors that are uncommon in unaffected individuals and targets eight relevant content areas. The interviewer records and codes the responses according to standardized procedures. The ADI-R includes a question on imitation ("Does [subject] imitate you or other people in the family? How about when you are not trying to get him/her to do so?) and, therefore, use of this instrument allowed quantification of imitation ability (detailed in Section 2).

None of the TD children showed developmental delays in any domain. TD children ranged from 28 to 55 months in chronological age ($M = 42.6$; SD Y = 11.7) and achieved scores on the fine motor subscale of the Mullen indicating adaptive motor functioning in the range of 27 to 59 months ($M = 39.1$; $SD = 11.2$). Three TD participants were female, the other four were male; TD participant characteristics are provided in Table 1. Children with ASD ranged from 45 to 49 months in chronological age ($M = 47.3$; $SD = 1.5$). Their scores on the fine motor subscale of the Mullen indicated adaptive functioning age equivalents between 24 to 57 months ($M = 37.9$; $SD = 12.0$). One ASD participant was female, the other six were male; ASD participant characteristics are provided in Table 2. Participants received a children's book or equivalent monetary compensation for their participation.

1.2. Apparatus

Children were seated in front of a small (25 cm × 25 cm) wooden pad that was covered with cork material. Children held a drumstick (27 cm in length) in both of their hands. The movements of the drumsticks were recorded at 60 Hz using a magnetic tracking system (Polhemus Corporation, Colchester, VT) and 6-D Research System software (Skill Technologies, Inc., Phoenix, AZ). Sensors were attached to each drumstick such that the thumbs of each child rested on the sensors when the drumsticks were grasped.

1.3. Design and procedure

Before the experimental trials, the experimenter demonstrated in-phase and anti-phase drumming patterns to the child using the pad and drumsticks. In order to avoid a potential confound the drumming demonstration was conducted by the same experimenter for each participant. Each child practiced the task three times per phase for approximately 15 s at a time

Table 1
Characteristics of TD children.

Child	Gender	Mullen mental age (years)	Mullen fine motor (months)
1	F	3	37
2	M	4.66	59
3	M	4.25	47
4	F	2.75	32
5	M	2.17	27
6	F	3.5	42
7	M	1.83	30

Table 2
Characteristics of children with ASD.

Child	Gender	Mullen mental age (years)	Mullen fine motor (months)	ADI-R age parent first concerned (months)	ADI-R spontaneous imitation in the home
1	M	3	36	22	Limited
2	M	3.75	57	17	Spontaneous imitation
3	M	3.5	47	12	Limited
4	F	3.25	31	15	Some spontaneous
5	M	1.66	24	22	Rare
6	M	2.75	44	13	Some spontaneous
7	M	1.83	26	18	Spontaneous imitation

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to ensure near-continuous drumming. Differences in practice time between children and groups were kept as minimal as possible. The child was then instructed to drum continuously on the pad in either in-phase (both drumsticks down and up at the same time) or anti-phase (one drumstick down, the other up) for 45 s at his or her own preferred pace. The order of trials was balanced across participants.

2. Results

Drumming movements of children were self-paced, so we examined the tempo of drumming by calculating the average period (seconds/cycle between consecutive drumstick-to-pad contacts) of the motions of both sticks (Table 3). The low standard deviation of period in Table 3 reveals that the drumming task produced reliable data across participants in both groups.

A 2 (Phase: In or Anti) × 2 (Hand: Left or Right) × 2 (Group: ASD or TD) mixed ANOVA was conducted to determine if there were any differences in the average period of drumming movements. In-phase movements were faster than anti-phase movements, $F(1, 12) = 13.93$, $p < .01$, $\eta_p^2 = .54$. Participants' right hands moved slightly faster than their left hands, $F(1, 12) = 7.11$, $p < .05$, $\eta_p^2 = .37$. There was no effect of Group ($F < 1$); however, there was a marginally significant Phase × Group interaction, $F(1, 12) = 4.29$, $p = .06$, $\eta_p^2 = .26$. The difference between in-phase and anti-phase period was somewhat greater for the TD group than the ASD group.

In order to assess the tempo variability, we calculated the intra-trial standard deviation of the drumming movement periods. A second 2 (Phase: In or Anti) × 2 (Hand: Left or Right) × 2 (Group: ASD or TD) mixed ANOVA was conducted to determine if there were any differences in the variability between the groups. There were no differences between Phase or Hand ($Fs < 1$), nor were there any significant two- or three-way interactions; however, there was a main effect of Group, $F(1, 12) = 4.84$, $p < .05$, $\eta_p^2 = .29$. The ASD group had higher movement variability in their drumming motions, as quantified by the standard deviation of period, than the TD group.

To examine degree of success the children had in producing and maintaining the required coordination, the relative phasing of the drumstick motions was analyzed. Relative phase allows us to examine how closely and how often the child's drumming reflected an in-phase or anti-phase pattern. The percentage of time spent at relative phase angles between in-phase and anti-phase was measured using phase regions 10° on either side of 10° (with 0° = in-phase), 30°, 50°, 70°, 90°, 110°, 130°, 150°, 170° (with 180° = anti-phase), for each drumming trial.

To determine the degree to which children drummed in the required phase relation (i.e., in-phase and anti-phase), two separate 2 (Group: ASD or TD) × 9 (Phase Region from 0° to 180°) mixed ANOVAs were performed for each required phase. As seen in Fig. 1A, the patterns of coordination differed between groups, with TD children spending more time in-phase than children with ASD (Group × Phase Region: $F(8, 96) = 4.51$, $p < .01$, $\eta_p^2 = .28$). Follow-up t-tests verified that TD children displayed significantly more of the required in-phase coordination (at phase bin 0°) than children with ASD, $t(12) = 2.22$, $p < .05$.

Table 3
Average period and standard deviation of period for left and right hand drumstick movements of TD children and children with ASD.

Group	Required phase	LH period	RH period	LH SD	RH SD
TD	In-phase	.36 s (.04)	.35 s (.04)	.11 s (.05)	.09 s (.06)
	Anti-phase	.56 s (.07)	.54 s (.08)	.09 s (.04)	.08 s (.03)
ASD	In-phase	.46 s (.13)	.45 s (.12)	.18 s (.09)	.20 s (.16)
	Anti-phase	.49 s (.11)	.47 s (.10)	.13 s (.06)	.12 s (.07)

Note: Between trial standard deviations are in parentheses. LH SD = left hand intra-trial standard deviation of period. RH SD = right hand intra-trial standard deviation of period.

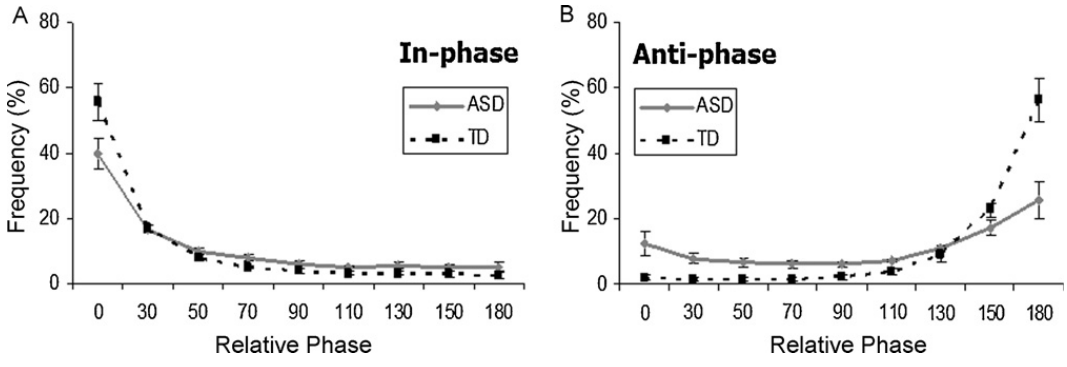

Fig. 1. (A) Average percentage of time children diagnosed with ASD and age-matched TD children spent in different relative phases when in-phase was required and (B) when anti-phase was required. Error bars indicate the standard error of the mean.

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Similarly, the patterns of anti-phase coordination differed between groups (Fig. 1B) with the TD children spending more time in anti-phase than children with ASD (Group × Phase Bin: $F(8, 96) = 10.23$, $p < .001$, $\eta_p^2 = .46$). Once again follow-up *t*-tests confirmed that TD children displayed significantly more of the required anti-phase coordination (at phase bin 180°) than children with ASD, $t(12) = 3.49$, $p < .01$. Because in-phase has been shown to be more stable in bimanual coordination tasks than anti-phase, we examined coordination at the in-phase (0°) bin for both groups of children when *anti-phase* was the required drumming phase. Children with ASD displayed significantly more in-phase coordination than TD children $t(12) = 2.80$, $p < .05$, indicating that children with ASD were less able to maintain the required phase and were more likely than their TD counterparts to revert to the more stable in-phase coordination pattern.

Lastly, we compared the imitation ability of each child with ASD with their performance of in-phase and anti-phase coordination. Imitation ability (Table 1) was coded from parents' response to the imitation question on the ADI-R ("Does [subject] imitate you or other people in the family? How about when you are not trying to get him/her to do so?). Parents give open-ended answers to these questions, which are then coded by the clinicians as "very rare" spontaneous imitation (3), "limited" spontaneous imitation (2), "some" spontaneous imitation (1), or an answer indicating an amount of spontaneous imitation typical for a child of the same age (0). For the purposes of this study, these scores were inverted, at which point Spearman's rank order test was used to correlate these values with the rank order of the frequency (the average of which is represented on the y-axis of Fig. 1) each child spent in the 0° (in-phase) bin ($\rho = .66$, $p = .11$) and the 180° (anti-phase) bin ($\rho = .42$, $p = .35$). Combining in-phase and anti-phase coordination data in a second rank-ordering, and using Spearman's test on all 14 drumming trials elevated the correlation to significance ($\rho = .55$, $p < .05$). Imitation ability, therefore, may be somewhat positively related to how well children with ASD performed the rhythmic drumming task.

3. Discussion

Using a simple, age-group and clinical population appropriate task, the current study is the first to report rhythmic bimanual coordination differences between children diagnosed with ASD and TD controls. Consistent with our predictions, children diagnosed with ASD were less able to maintain required phase relationships, both in-phase and anti-phase, than age-matched TD children on a drumming task. As indicated by differences in the effect sizes of the in-phase and anti-phase Group × Phase Region interactions, children with ASD had a harder time maintaining anti-phase coordination than in-phase coordination. Additionally, they were more likely to revert to in-phase coordination during anti-phase trials. These results are consistent with previous research that has shown that in-phase entrainment is stronger than anti-phase entrainment across non-clinical populations (Kelso, 1984, 1995).

Analysis of movement tempo revealed that self-paced in-phase drumming movements were faster than anti-phase movements: In-phase entrainment is stronger than anti-phase and is therefore easier to produce, and to produce more quickly. This difference was magnified in the TD group relative to the ASD group: Not only were TD children better able to produce the required phases, but they also differentiate these phases with distinct self-paced tempos. Across children, right hand movements were slightly faster than left hand movements. We assume this is a handedness effect given the prevalence of right handers; however, we did not document handedness to corroborate our suspicions (see Section 3.1). Moreover, the variability of the tempo of drumming movements was greater for children with ASD than TD children. As opposed to TD children who tended toward steady-state drumming behavior, children with ASD tended to speed up and slow down more within a trial.

Our results are important because they quantify and begin to explore a novel class of motor deficits in young children with ASD: those of bimanual rhythmic coordination. Such motor deficits have implications for understanding other ASD deficits, as they reveal that children with ASD are differently embodied (i.e., different action capabilities) than TD children. The body has an important role in shaping the development of the mind, and research has found that early motor abilities correlate with later cognitive abilities, such as: math, writing, and reading capabilities (Bobbio, Gabbard, Goncalves, Filho, & Morcill, 2009), categorization and executive function (Murray et al., 2006), and working memory and processing speed (Piek, Dawson, Smith, & Gasson, 2008). Furthermore, theories of embodied cognition speculate that our understanding of others as emotional beings with feelings and desires that differ from our own may be fundamentally intertwined with having sensory, motor, and neural capabilities that allow us to respond to the physical states of another.

Therefore, differences in embodiment in children with ASD may have profound implications for the development of proficient social interaction, as coordination underlies this activity (Marsh, Richardson, Baron, & Schmidt, 2006). Our claim that embodiment differences may underlie development of social interactions is bolstered by the fact that the same underlying coordinative processes apparent in bimanual interlimb coordination (within a single individual) are also found to constrain the rhythmic coordination between an individual and either an environmental rhythm (Schmidt, Richardson, Arsenault, & Galantucci, 2007) or another individual (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt & O'Brien, 1997) whether or not there is an intention to coordinate. In other words, if an individual cannot coordinate their own limbs, how can they possibly coordinate with their physical and social environment? In the context of autism research, TD children show spontaneous entrainment of their postural sway motions to oscillatory stimuli presented on a screen; whereas, children with ASD fail to show such spontaneous coupling (Gepner & Mestre, 2002; Gepner, Mestre, Masson, & de Schonen, 1995). Similarly, TD children show spontaneous in-phase entrainment of rocking chair movements with their parents; whereas, children diagnosed with ASD show no such spontaneous social entrainment (Marsh et al., 2011). The current study suggests that not being as readily able to coordinate movements intra-personally—whether by verbal instruction or

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imitation—in a prescribed fashion may be a reason that children with ASD do not synchronize their movements with other individuals or environmental stimuli.

Social entrainment in TD children has recently been examined using a joint drumming methodology (Kirschner & Tomasello, 2009; Kleinspehn, 2008), with results suggesting a reciprocal relationship between movement entrainment and positive social feelings. Other research has shown that participation in joint action results in the development of social connection (Marsh, Richardson, & Schmidt, 2009; Sebanz, Bekkering, & Knoblich, 2006). Applying a joint-drumming methodology to examine interpersonal coordination in ASD and TD children may not only reveal illuminating differences in social synchrony, but also allow a better understanding of the social connection deficit of children with ASD. Furthermore, the current drumming methodology could easily be applied toward investigating coordination in older children with ASD, though the relative young age of our sample is noteworthy. Indeed, assessment of rhythmic motor coordination may facilitate very early screening of ASD, (cf., Teitelbaum, Teitelbaum, Nye, Fryman, & Maurer, 1998), as cognitive and linguistic development is not a prerequisite for its measurement. Importantly, our findings may be of benefit to those seeking to improve coordination in the ASD population. For example, practice with drumming in-phase and anti-phase alone and with other individuals could be incorporated into occupational and physical therapies.

We are circumspect as to the mechanisms that underlie the differences reported here; however, imaging studies reveal that premotor, supplemental motor, primary motor, and primary sensory cortexes, and the cerebellum are all involved in producing both in-phase and anti-phase coordination patterns (Mayville, Jantzen, Fuchs, Steinberg, & Kelso, 2003). Abnormalities in these brain areas and in the pathways that connect them have been extensively documented in ASD research (Allen, 2006; Mostofsky, Burgess, & Gidley Larson, 2007; Mostofsky et al., 2009; Muller, Cauch, Rubio, Mizuno, & Courchesne, 2004; Oberman et al., 2005). Our results are therefore consistent with evidence of neurobiological deficits relating to the planning and coordination of movement.

3.1. Limitations

Sex differences between children of the same chronological age on *the Mullen Scales of Early Learning* have been documented (Carter et al., 2007); however, according to these findings boys tend to be developmentally ahead of girls on the fine motor subscale. Because our sample of children with ASD included more boys, if anything, our results should be strengthened if we had run proportionately more TD boys to sex-match the groups. An additional limitation of the generalizability of the present study is the relative homogeneity of the races of the children involved. We did not record the race of the participants, although it is known that participants from both groups were predominantly Caucasian. Importantly, though, we did not expect to find any racial differences between children's coordination abilities, as this has not been a topic of study in coordination dynamics literature and no previous research has reported racial differences in coordination ability or development. Future research could aim to determine if racial differences are present in coordination abilities.

We acknowledge the small sample as a possible limitation of the generalizability, but not the value, of the present study. We duly note that our sample size is consistent with many previously published studies of rhythmic bimanual coordination in non-clinical populations (Kelso, 1995; Kugler & Turvey, 1987). The high degree of regularity in the mechanisms producing bimanual coordination allows meaningful results to be attained with few participants. However, future research should be conducted to reveal if larger sample sizes yield similar results and to increase the generalizability and validity of the study.

Additionally, although we report deficits in bimanual coordination in children with ASD, these reported deficits could be due, in part, to differences in IQ/DQ, motivation, and imitation ability. Future extensions of this work should make note of the handedness of the participants. More importantly, clinical evaluations run on children with ASD should likewise be run on TD children to increase the generalizability and validity of the study.

4. Conclusions

The current study is the first to report rhythmic bimanual coordination differences between children diagnosed with ASD and TD controls. Children diagnosed with ASD were less able to maintain required in-phase and anti-phase relationships than age-matched TD children on a drumming task, and this effect was magnified when anti-phase (the more difficult of the two coordination patterns) was required. Additionally, the variability of the tempo of drumming movements was greater for children with ASD than TD children. Quantifying intra-personal coordination deficits, such as these, has implications for understanding social coordination deficits in ASD.

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