Master's Theses

University of Connecticut Graduate School

7-11-2013

The Effects of Robot-Child Interactions on the Bilateral Coordination Skills of Typically Developing Children between 4 and 11 years of age

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B.Ph.T., Post Graduate Institute of Medical Education & Research (India), 2009.

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

At the

University of Connecticut

2013

APPROVAL PAGE

Masters of Science Thesis

The Effects of Robot-Child Interactions on the Bilateral Coordination Skills of Typically

Developing Children between 4 and 11 years of age

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University of Connecticut

2013

Acknowledgements

Thanks to my Committee members:

Anjana N. Bhat

Deborah J. Bubela

Kerry L. Marsh

Thanks to my fellow graduate students:

Sudha Srinivasan

Isabel Park

Thanks to all the undergraduates who worked on the project:

Kathleen Lynch

Carolyn Susca

Hannah Hester

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Abstract

Background: Coordination develops gradually over development with younger children showing more unstable coordination patterns compared to older children and adults. In the present study, we examined whether robot-child interactions could improve bilateral coordination skills of typically developing (TD) children through imitation of whole body actions. **Methods**: Twenty four TD children between 4 and 11 years of age were non-randomly assigned to training and control group. Training group children received twelve training sessions across six weeks in a robot imitation context involving whole body and drumming actions. Children were assessed pre- and post-training on standardized tests of motor performance, and task-specific dual-limb and multilimb actions within a solo and social context. **Results:** Training group children improved their bilateral coordination following training compared to the control group children. Specifically, training group showed greater improvements in task-specific actions versus standardized tests of motor performance. In addition, TD children performed better in the solo versus the social context of task-specific actions. **Conclusions:** Robot-child interactions could potentially facilitate bilateral coordination and be a promising intervention tool for children with significant coordination impairments such as children with Autism Spectrum Disorders (ASDs). The present study served as a foundation for future group studies in children with ASDs.

Keywords: Dual-limb, Multilimb, Motor, Coordination, Social, Autism

Chapter 1: Introduction

Several daily activities such as walking and reaching require coordination between various body segments. These activities may involve dual-limb coordination (using two limbs) such as buttoning one's shirt or multilimb coordination (using more than two limbs) such as walking while bouncing a ball. Coordination improves gradually over development with younger children showing more variable dual-limb and multilimb coordination patterns compared to older children followed by adults (Getchell, 2006, 2007; Muzii, Warburg, & Gentile, 1984). The broad goal of this research is to develop novel movement-based interventions to facilitate dual and multilimb coordination in school-age children.

Humanoid robots have been used to facilitate social communication skills such as imitation and social attention in children (Kozima, Nakagawa, & Yasuda, 2007; Robins, Dautenhahn, te Boekhorst, & Billard, 2004). However, there are practically no studies examining the effects of robot-child interactions on the motor coordination skills of children. Results of our recent study showed small increases in bilateral coordination following a short period of robot-child interactions with a low-end robot, Isobot (Kaur, Gifford, Marsh, & Bhat, 2013). In this project, we used a high-end robot called Nao (Aldebaran Robotics, Inc.) to teach children rhythmic actions such as drumming, marching, and tapping. Moreover, we introduced a controlled experimental design, which was lacking in our previous study. Below, we review the literature on how robots have been used to facilitate social and motor skills in children and to better understand the development trajectories for dual-limb and multilimb coordination in typically developing children.

Use of robots in children

The field of assistive robotics has rapidly advanced over the last decade and robots are being frequently used to aid clinicians in adult and pediatric rehabilitation. There are hands-on, socially non-interactive robots such as the 'MIT-Manus' and the 'Lokomat', which provide assistance to patients with motor deficits through physical contact (Hidler et al., 2009; Kwakkel, Kollen, & Krebs, 2008). In addition, there are hands-off, socially interactive robots such as the 'Keepon' and the 'Robota' that have been used to facilitate social and motor behaviors in children with autism (Kozima et al., 2007; Robins et al., 2004). Children with autism showed some improvements in social interactions and communication following an extended protocol involving imitation games with a humanoid robot, Robota (Robins et al., 2004). In addition, children with autism paired with the mobile robot, Tito showed greater shared attention including visual contact and physical approach towards the robot compared to children with autism paired with an adult experimenter (Duquette, Michaud, & Mercier, 2008). Both typically developing children and children with autism engaged in spontaneous social interactions and self-initiated imitation of the creature-like robot Keepon, during dyadic (robot-child) and triadic (robot-adult-child or robot-child-child) social interactions (Kozima et al., 2007). In terms of motor skills, robotic arms are better at facilitating simple reaching motions in children with Autism Spectrum Disorders (ASDs) compared to human models which are better at facilitating reaches in typically developing children (Pierno, Mari, Lusher, & Castiello, 2008). Children with ASDs may have an easier time perceiving and responding to the simple, predictable, and repeatable movement patterns of a robot compared to humans (Dautenhahn & Werry, 2004; Robins et al., 2004). Overall, robots could be a promising tool for children with ASDs to improve their motor coordination as well as social communication skills. However, a recent systematic review on the

clinical use of robots in subjects with ASDs revealed that the majority of the evidence is anecdotal. It is also difficult to make generalizations due to the methodological limitations of the different studies such as variability in the abilities of the participating children, small sample sizes, and lack of standardized tests (Diehl, Schmitt, Villano, & Crowell, 2011). Furthermore, there is a clear lack of normative data on robot-child interactions in healthy typically developing children. Therefore, the first aim of the present study was to conduct a systematic study evaluating the effects of a novel movement-based intervention, i.e. robot-child interactions on the dual and multilimb coordination skills of children from 4 to 12 years of age. This study has served as a foundation for our ongoing randomized controlled trial on the effects of robot-child interactions on the social and motor skills of children with ASDs.

Dual- and Multilimb coordination in children

Healthy adults are consistent and stable while performing coordinated motor actions. During multilimb actions such as walking and clapping, the majority of adults (78%) consistently clapped once on every other step (67%) or clapped once on every step when instructed to perform the walking and clapping action at variable speeds (11%) (Muzii et al., 1984). In addition, adults were able to flexibly adapt their multilimb actions to changes in step length, clap width, and clap/walk frequency (Whitall & Getchell, 1996). In contrast, children demonstrate difficulty while performing complex multilimb actions compared to simpler dual-limb actions (Getchell, 2006). Children from 4 to 10 years of age showed stable and consistent performance during dual-limb actions of clapping only or walking only compared to the multilimb action of clapping and walking simultaneously (Getchell, 2006). Moreover, multilimb actions of younger school-age children are more inconsistent than those of older school-age children and adults. Specifically, in a multilimb action such as clapping and walking, 4-year olds had the most

difficulty synchronizing their claps with steps compared to 6-, 8-, and 10-year olds (Getchell, 2007). Taken together, we can summarize that children gradually improve coordination with age with dual limb coordination emerging earlier than multilimb coordination.

Bilateral coordination in children

Bilateral coordination or the ability to move two sides of the body together is demonstrated during dual-limb actions such as hopping as well as multilimb actions performed in various sports and functional activities. Studies examining the bilateral coordination skills of adults such as finger tapping, pendulum swinging, clapping, or circle drawing demonstrate that adults can perform both, stable bilaterally symmetrical (in-phase), and asymmetrical (anti-phase) movements (Brakke, Fragaszy, Simpson, Hoy, & Cummins-Sebree, 2007). During a bimanual circle drawing task, adults were able to perform stable symmetrical and asymmetrical arm movements at self-preferred speeds (Semjen, Summers, & Cattaert, 1995). The preference for bilateral movements emerges in the second year of life with two-year-old children showing a preference for bimanual drumming, compared to the unimanual drumming observed in one-year-olds (Brakke et al., 2007). However, the timing and regulation of the bimanual drumming varies considerably at two years of age with few children producing stable drumming patterns (Brakke et al., 2007). During bimanual crank rotations, 5 to 7-year-old children found in-phase motions involving homologous muscles easier compared to anti-phase motions involving non-homologous muscles, whereas 9-year-olds were equally competent doing both motions (Fagard, 1987). Hand-hand bilateral movements become stable by 5 to 7 years of age; however ipsilateral (same-sided) or contralateral (opposite-sided) hand-foot movements are unstable until 6 years of age and improve from 7 to 10 years of age (Volman, Laroy, & Jongmans, 2006). Overall, there

are clear developmental trajectories for dual-limb and multilimb, bilateral coordination skills in school-age children.

Solo versus social coordination in children

Socially embedded motor activities such as sports, choir performances, and dancing require an individual to coordinate their movements with others. Solo context refers to a child's action performed on his/her own whereas social context refers to a child's actions performed with another partner. In a social context, intrapersonal synchrony refers to intra-limb coordination of the child while moving with the other child whereas interpersonal synchrony is the inter-limb (i.e. moving limb of one child coordinating with the moving limb of other child) coordination of the two children moving together. Coordination in a social context has different constraints compared to solo coordination. Specifically, social context has an added constraint of perceiving the visual information received from the social partner and synchronizing with them. While the aforementioned studies examined coordination in solo context in children and adults, few studies have examined coordination in social context in adults and children. When adult pairs were moving together in rocking chairs, they demonstrated synchronous rocking while they were facing side-by-side (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007). In contrast, when children were paired with their parents during the rocking chair experiment they showed weaker spontaneous interpersonal synchrony compared to the adult pairs (Marsh et al., 2013). In a recent study, adult-adult pairs showed better interpersonal synchronization during bilateral drumming actions compared to child-child pairs (Kleinspehn-Ammerlahn, Riediger, Schmiedek, Oertzen et al., 2011). Better perceptual awareness and advanced motor skills may have contributed to the greater interpersonal synchrony observed among the adult-adult pairs (Kleinspehn-Ammerlahn, Riediger, Schmiedek, von Oertzen et al., 2011). Moreover, co-acting

adults may capitalize on the reduced variability of their own movements or increased predictability of their partner's movements as a coordination strategy to improve their interpersonal synchrony (Vesper, van der Wel, Knoblich, & Sebanz, 2011). In other words, we could infer that the ability to reduce variability of intrapersonal synchrony (intra-limb) in a social context in adults is closely associated with improved interpersonal synchrony (inter-limb). In fact, pairing an adult and a child improved the performance of children during the social bilateral drumming task because of adults ability to predict and adjust their performance based on the variability in child's performance (Kleinspehn-Ammerlahn, Riediger, Schmiedek, von Oertzen et al., 2011). Our recent paper showed that among pairs of children, reduced intrapersonal synchrony was observed for a complex multilimb action performed in the social context versus solo context (Kaur et al., 2013). Hence, the second aim of this project was to further investigate differences in coordination in the solo and social context during dual-limb and multilimb actions among children in this study.

Statement of Purpose

The purpose of the present study was to examine the effects of six weeks of robot-child interactions on the dual-limb and multilimb, bilateral coordination skills of typically developing children between 4 to 11 years of age. Secondly, we examined the differences in coordination in the solo and social context during dual-limb and multilimb actions in typically developing children. This study had a controlled quasi-experimental design with non-random assignment of children to the training and the control group. Children in the control group did not receive six weeks of robot-child interactions thus serving as a control for any changes in performance due to maturation or familiarization with the testing measures over the six week period.

We evaluated training-related changes using standardized tests of motor performance, i.e. Bruininks-Oseretsky Test of Motor Proficiency (BOTMP) and the Sensory Integration and Praxis Tests (SIPT). We also evaluated the variability of moving limbs for two task-specific actions, i.e. hand variability for a dual-limb drumming action, and arms and legs variability for a multilimb march-clap action following six weeks of training. In addition to training-related changes, context-related differences (solo versus social context) were evaluated for the dual-limb and multilimb actions in children. For context-related differences, the intrapersonal synchrony i.e. intra-limb coordination of the child was assessed in the solo and social context of dual-limb and multilimb actions.

Aims and Hypotheses

Aim 1: To evaluate the effects of six weeks of robot-child-child interactions on the motor coordination skills of children between 4 and 11 years of age using (1) standardized tests of motor performance, BOTMP and SIPT, and (2) variability of task-specific dual-limb drumming and multilimb march-clap action.

Hypothesis 1.1: The training group children will show improvements in motor coordination as evaluated by the standardized tests of motor performance, BOTMP and SIPT following training. However, the control group children will fail to show similar improvements.

Hypothesis 1.2: The training group will reduce the variability for the dual-limb drumming and the multilimb march-clap action following training by a greater magnitude compared to the control group.

Aim 2: To compare the variability of dual-limb drumming and multilimb march-clap action within a solo and a social context in children between 4 and 11 years of age.

Hypothesis 2: In general, we expect the children to show higher variability of moving limbs within a social versus a solo context for both the task-specific actions. Specifically, the variability of hands during the drumming action, and the variability of arms and legs during the march-clap action will be higher within the social context compared to the solo context for children

Chapter 2: Methods

Participants

Twenty four typically developing children in the age group of 4 to 11 years were assigned either to the training group (n=12, mean age± SE=6.72±0.43 years) or the control group (n=12, 6.88±0.69 years). Training group comprised seven males and five females whereas the control group included eleven males and one female. Two children, one from each group, were excluded from the statistical analysis either due to non-compliance or inability to participate in the posttest session. The children were recruited from the university listserv, local day care centers and public schools in the Storrs, Mansfield region. Parents/caregivers of all the participating children signed a consent form approved by the University of Connecticut Institutional Review Board before participation in the study. The Institutional Review Board approval # is H09-113, and is valid until April, 2014. The inclusion criteria for children were absence of any developmental disorders and age-expected typical motor performance as demonstrated on the short form version of the standardized test of motor performance, the Bruininks-Oseretsky Test of Motor Performance (BOTMP-SF). Out of the 24 families, 16 were Caucasian American in origin, six were Asian, and two were (biracial) European.

Procedural Overview

The testing and training sessions were delivered over eight weeks. The pretest and posttest sessions were conducted in the first and the eight week of study participation respectively and included two standardized tests of bilateral coordination, the Bruininks-Oseretsky Test of Motor Proficiency (BOTMP) and the Sensory Integration and Praxis Test (SIPT). In addition, we evaluated coordination within two task-specific test actions, dual-limb drumming and multilimb march-clap. In between the testing weeks, 12 training sessions were delivered to the training

group children over six weeks with two sessions per week (see Table 1 for study timeline). The children in the control group did not receive any training sessions between the pretest and the posttest assessments. All the testing and the training sessions were videotaped.

Table 1: *Study Timeline*

Pretest session (Week 1)	Training sessions (Week 2-7)	Posttest session (Week 8)
1. Bilateral Coordination subtest and short form version of BOTMP	Total # and duration of sessions 12 training sessions with 2/week Each session lasted 30-45 minutes.	1. Bilateral Coordination subtest and short form version of BOTMP

2. Bilateral Motor Coordination subtest of SIPT	Session theme
	
	    (a) Moving on steady beat
	
	    (b) Turn taking
	
	    (c) Moving on count
	
	    (d) Slow and fast
	
	    (e) Small and large
		2. Bilateral Motor Coordination subtest of SIPT

3. Two task-specific actions: dual-limb drumming and multilimb march-clap.	Training conditions
	
	    (a) Introduction
	
	    (b) Warm up
	
	    (c) Action game
	
	    (d) Drumming game
	
	    (e) Farewell
		3. Two task-specific actions: dual-limb drumming and multilimb march-clap.

Testing measures

1. Bruininks-Oseretsky Test of Motor Performance (BOTMP)

BOTMP is a reliable and valid measure that assesses the fine and gross motor skills of individuals from 4 to 21 years of age (Bruininks, 1978). The Short form of the BOTMP (BOTMP-SF) was administered in the pretest to determine typical motor performance of children in the training and the control group. The BOTMP-SF percentile scores for both groups were in the typical range (Training group = 66.10±6.35, Control group = 61.64±6.37). In addition, both the training and the control group children showed similar baseline percentile scores on the BOTMP-SF (p=0.53).

The bilateral coordination subtest of BOTMP (BOTMP-BC) was used to assess the training-related changes in bilateral motor coordination following training. BOTMP-BC has seven actions with two dual-limb and five multilimb actions. In the testing session, children were asked to perform ten action cycles for each action of this subtest. The standardized scoring scheme of BOTMP-BC is not based on the evaluation of all the ten action cycles performed for an action in our testing session. Therefore, apart from the standardized scoring scheme for BOTMP-BC, we devised our own qualitative scoring scheme to provide a more detailed analysis of the quality of bilateral coordination demonstrated during the BC subtest of BOTMP (see Appendix 1 for scoring sheet). Each action cycle was scored as correct or incorrect based on the presence of the following errors:

i. Magnitude/Modulation errors were coded for actions that were either insufficient or exaggerated in magnitude, for example insufficient arm movements during the touch your nose action or additional head rotations to accomplish the touch your nose action.

ii. Timing errors were errors in the temporal synchronization of moving limbs during dual and multilimb actions, for example failure to simultaneously move legs and arms during jumping jacks.

iii. Pattern errors were errors where children substituted complex coordination patterns with simpler motor patterns or strategies, for example contralateral tapping of fingers and feet substituted with ipsilateral tapping of fingers and feet.

2. Sensory Integration and Praxis Tests (SIPT)

The Sensory Integration and Praxis Test (SIPT) is a comprehensive assessment tool for evaluating praxis in children between 4.0 and 8.11 years of age (Ayres, 1996). The bilateral motor coordination subtest of SIPT (SIPT-BMC) was administered during the pretest and the posttest to assess training-related changes in the bilateral motor coordination skills of children in the study. The SIPT-BMC has 18 test items that require the child to imitate the bilateral hand, leg, and foot actions performed by the tester. We coded the following spatio-temporal errors for each action of the SIPT-BMC (see Appendix 2 for the scoring sheet).

i. Sequence (or sequencing) errors were errors in the order of the bilateral action including errors due to any addition, omission or merging of movement.

ii. Rhythmicity errors were errors where the child had difficulty distinguishing and imitating speed changes within a demonstrated rhythmic pattern.

iii. Mirroring errors were errors where the child was unable to mirror the tester's actions. If the child started with the wrong arm, then it was coded as a mirroring error.

iv. Movement overflow errors included any extra movements performed by the child at the end of the action beyond what the tester performed.

v. Time to best effort was the total time taken in seconds taken by the child to finish an action i.e. the time from the start to the end of the child's imitation of the demonstrated action.

3. Task-specific actions

Children performed two task-specific actions, a dual-limb drumming and a multilimb march-clap action during the pretest and the posttest sessions within a solo (moving on your own) and a social (moving with another child) context. Movement speeds were controlled using a metronome beat of 80 Hz frequency. Drumming action was performed on a quarter-eighths note, such that two hits by one hand were followed by one hit with the other hand, and the march-clap action involved simultaneous marching and clapping. In the solo context, the tester demonstrated the two actions to the child and provided a brief practice bout. Children were then instructed to perform the actions while coordinating their movements with the metronome beat. In the social context, the two children were positioned in front of each other. The tester again demonstrated the actions to the children and instructed them to coordinate their movements with each other while moving to the metronome beat. Within the social trials, each child was provided an opportunity to be the leader for one trial. The second child had to match up the movements of the leader. Children were asked to perform each action (i.e. multilimb march-clap and dual-limb drumming) twice within the solo context followed by twice within the social context. The order of the actions was fixed with solo trials always followed by social trials. Total of eight trials were collected for each child for the pretest/posttest session with each trial lasting 22 seconds. We used the OpenSHAPA software to code for the task-specific actions performed in the solo and social contexts.

OpenSHAPA is an open source video coding software that can be used to code for frequencies or durations of different behaviors. For drumming trials, we coded for the duration of time between two successive drum hits by the same hand. Similarly for march-clap trials, we coded for the duration of time between two successive clap events and two successive stomp events. The coded files were run through a custom-made MATLAB program to calculate the

inter-event duration (in seconds) or in other words the total time between two successive events such two successive drum hits during the dual-limb drumming trials and two successive claps or stomps during the multilimb march-clap trials. We used the inter-event durations to calculate the coefficient of variation (COV) of each trial using the following equation:

COV= SD/Mean

where COV = Coefficient of variation of a trial, SD = standard of deviation of inter-event durations of a trial, Mean = average of inter-event durations for a trial

COV analysis is a statistical measure used to calculate the dispersion or the variability of given data points in a sample across the mean (Vereijken, 2010). We used COV analysis to calculate the variability of the hand during the dual-limb drumming actions and the arms and legs during the march-clap motion within the solo and social contexts. The COV data from two trials of each kind such as two solo trials of dual-limb drumming action were pooled during statistical analysis. Note that intrarater and interrater reliability of above 85% was established for all the testing measures after coding 20 % of the entire dataset

Training Protocol

Training group children received 12 sessions of robot-child-child interactions across six weeks with two sessions per week. Training group children were divided into six pairs and training was delivered to a pair together. A highly sophisticated robot, Nao (Aldebran, see Figure 1) controlled by a laptop-based custom built software DRCS (Dynamic Robot Controller System) was used to deliver the training. Both the children were positioned side by side; the trainer and the robot were positioned in front of the children (see Figure 1). The trainer triggered the robot to perform bilateral, gross motor and drumming actions, while children were instructed to imitate the robot. In terms of training principles, we promoted discovery learning without

excessive explicit feedback by the trainer about the form of the children's actions. An accurate visual reference was provided by the robot's actions. The trainer also facilitated the verbal interactions between the children and the robot.

Figure 1: Training set-up with the Nao robot

Each session lasted for 30-45 minutes and comprised of the following conditions:

1. Introduction (2 minutes): The robot greeted the children and involved them in a conversation by asking questions such as "How are you?" or "How was school today?" This condition did not involve any movement imitation.

2. Warm up game (5-7 minutes): In this condition, the two children and the robot performed various rhythmic actions together. The trainer instructed the children to copy the robot's actions. Two warm up actions were performed in each session.

3. Action game (10-12 minutes): Children performed various rhythmic, bilateral gross-motor actions that varied in the type and complexity of the coordination pattern. Majority of the training actions involved symmetrical or asymmetrical dual-limb coordination with few

multilimb actions. The training actions were based on various themes such as start and stop, moving on a steady beat, slow and fast, moving on a count, turn taking, and small and large; every session included one of these themes. Three to four actions were performed per session with each action repeated thrice. In the first trial, children were instructed to copy the robot, in the second trial they were asked to demonstrate the action to the robot while matching with the other child, and in the third trial children were instructed to move together with the other child while matching up to the robot as well. The trainer provided feedback to the children if they clearly missed some components of the action. Within each session, children were also provided time for free exploratory gross motor play.

4. Drumming game (10-12 minutes): Children performed various drumming actions that varied in the type and complexity of coordination pattern. The drumming actions involved unilateral and bilateral drumming patterns with increasingly complex patterns such as symmetrical and asymmetrical bilateral movements performed in the later training sessions. Session themes were paralleled between the action and the drumming games. Three to four drumming actions were practiced in each session with each drumming action repeated thrice. Similar to the action game, during the first trial we instructed the children to "copy the robot", in the second trial we asked the children to "demonstrate action to the robot while matching with the other child", and in the third trial we instructed them to "move together with each other while copying the robot". Children were given time for free play within the drumming context.

5. Farewell (2 minutes): The robot ended the session with farewell statements such as "Goodbye! See you next time". Similar to the introduction, this context did not involve any movement imitation.

At the end of each session, children were given small toys. Training group children received $50 and control group children received $20 as participation reimbursement at the end of the study. Two pairs of training group children missed four and two sessions respectively due to scheduling conflicts.

Statistical Analysis

We conducted paired t-tests, Wilcoxon's signed rank tests, and repeated measures ANOVA to assess training-related changes (pre-posttest changes) and context-related differences (solo-social differences) in bilateral coordination. Paired t-tests and repeated measures ANOVA were done for continuous dependent variables, and Wilcoxon's signed rank tests were done for categorical dependent variables. Post hoc analyses with Bonferrori corrections were done in case of multiple comparisons. Significance level was set a priori at 0.05, and p values between 0.1 and 0.05 were considered as statistical trends. We checked our data for assumptions of parametric statistics including assumptions of normality and homoscedasticity. The Kolmogorov-Smirnov Tests were conducted to check for violations of normality for paired t-tests, and the Levene's Tests and the Mauchly's test of Sphericity for violations of homoscedasticity for independent T-tests and repeated measures ANOVA. Corrected t-values have been reported in case of violations of the assumption of normality and homoscedasticity. Missing values in our data have been replaced by group average.

Specifically, the following tests were done to test each of the proposed hypotheses:

Hypothesis 1.1: The training group children will show improvements in motor coordination as evaluated by the standardized tests of motor performance, the BOTMP and the SIPT following training. Two paired t-tests were conducted for the continuous dependent variable-- number of incorrect action cycles in the BC subtest of BOTMP. Eight Wilcoxon's signed rank

tests were conducted for the categorical variables-- different error types and two paired t-tests were conducted for the continuous dependent variable-- time to best in the BMC subtest of SIPT.

Hypothesis 1.2: The training group will reduce the variability for the dual-limb drumming and the multilimb march-clap action following training by a greater magnitude compared to the control group. Three separate repeated measures ANOVAs were conducted for the three different dependent variables of task-specific actions, i.e. hand COV during dual-limb drumming, arm COV and leg COV during multilimb march-clap. The within subjects factors for the ANOVAs were context (solo, social), test (pretest, posttest) and the between-subjects factor was group (training, control).

Hypothesis 2: In general, we expect the children to show greater variability of moving limbs within a social versus a solo context for both the task-specific actions. Specifically, the variability of hands during the drumming action, and the variability of arms and legs during the march-clap action will be greater within the social context compared to the solo context for children. A repeated measure ANOVA was conducted for solo-social comparisons with context (solo, social) and task (arm COV, and leg COV during multilimb march-clap, hand COV during dual-limb drumming) as within-subjects factors. We pooled the pretest data of the training and the control group for this analysis in order to increase the sample size.

Chapter 3: Results

Training-related changes in bilateral coordination of children during standardized tests of motor performance and task-specific actions

We evaluated the first aim of our study i.e. training-related changes in bilateral coordination skills of training and control group children using standardized measures of motor performance, the BOTMP-BC and the SIPT-BMC, as well as by assessing the variability of two task-specific actions. The dependent variables for the BOTMP-BC and the SIPT-BMC were the number of incorrect action cycles, and the number of errors and time to best effort respectively. The dependent variables for the task-specific actions were hand COV during the dual-limb drumming, and arm COV and leg COV during the multilimb march-clap action.

1. Incorrect action cycles in the BC subtest of BOTMP:

Paired t-tests of the raw scores and age-appropriate performance for the BOTMP-BC showed statistical trends for training-related improvements in the training group (posttest=21.82±1.23, pretest=20.18±1.17; p=0.08 & posttest=9.81±0.66, pretest=8.78±0.76; p=0.11 respectively) versus the control group (p=0.38 & p=0.26 respectively). However, the magnitude of improvement or the difference in posttest versus pretest performance in the training group was just by one point and was thus insufficient to comment on any training-related changes in the training group. Therefore, we performed a more refined qualitative analysis for the BC subtest of BOTMP by scoring each action cycle as incorrect or correct based on the presence or absence of errors. Paired t-tests for the total number of incorrect action cycles indicated that the training group showed reduction in the number of incorrect action cycles following training (p=0.008, see Figure 2), whereas the control group failed to show similar reductions (p=0.13, see Figure 2). In

terms of individual data, 9 out of 11 training group children showed improvement in performance in the posttest compared to the pretest.

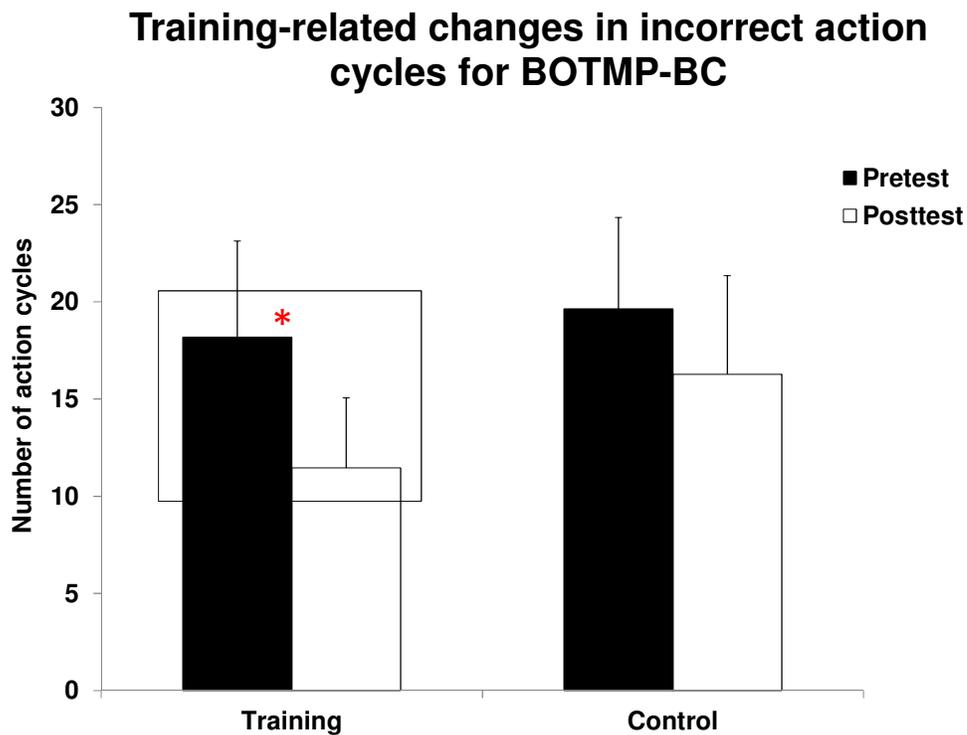**Training-related changes in incorrect action cycles for BOTMP-BC**

Figure 2: Training-related changes in the total number of incorrect action cycles during the BOTMP-BC in the training and the control groups. The training group significantly reduced the total number of incorrect action cycles in the posttest compared to the pretest.

2. Total number of errors and time to best effort in the BMC subtest of SIPT:

Wilcoxon's signed rank tests for the total number of errors during SIPT-BMC indicated that the training group significantly reduced the total number of sequencing (Z=-2.83, p=0.005, see Table 2) and overflow errors (Z=-2.81, p=0.005, see Table 2) in the posttest compared to the pretest. However the control group did not reach statistical significance for any of the error types (p≤0.006, after Bonferrori corrections); statistical trends for reduced number of total sequencing

(Z=-2.67, p=0.008, see Table 2) and rhythmicity (Z=-2.69, p=0.007, see Table 2) errors were observed in the control group. In addition, the magnitude of improvements (posttest-pretest, see Table 2) for sequencing and rhythmicity errors was almost similar across the training and control group. Paired t-tests for time to best effort of SIPT-BMC showed a statistical trend for the training group with reduction in total time taken in the posttest compared to the pretest (p=0.08, see Table 2). No similar training-related improvements were seen in the control group (p=0.59, see Table 2). In terms of individual data, 7-10 out of 11 training group children followed the group trends.

Table 2: *Number of errors in the BMC subtest of SIPT*

Note: For error type, α was set at 0.006 after Bonferrori corrections.

Error type	Training			Control		
	Pretest	Posttest	p	Pretest	Posttest	p
Sequencing	5.27±1.22	3±1.31	0.005*	5.55±1.06	2.80±1.13	0.008†
Rhythmicity	4.37±1.34	2.81±1.48	0.021	4.82±1.43	2.50±1.17	0.007†
Mirroring	2±0.86	0.45±0.37	0.019	2.10±0.72	1.20±0.57	0.147
Overflow	7.20±1.04	2.81±0.62	0.005*	5.37±1.34	4.79±0.77	0.79
Time (sec)	4±0.32	3.54±0.20	0.08†	3.81±0.19	3.65±0.36	0.59

3. Variability (COV) of task-specific actions:

a. Hand COV for dual-limb drumming

Repeated measures ANOVA of hand COV during the dual-limb drumming indicated a statistically trend for main effect of context (F (1, 86) =3.11, p=0.08, ηp2=0.04) and a significant test*group interaction (F (1, 86) =5.82, p=0.02, ηp2=0.06) and context*group interaction (F (1,

86) =6.27, p=0.01, ηp2=0.07). Post-hoc analysis for the relevant test*group interaction revealed that the training group decreased the hand COV during the dual-limb drumming in the posttest compared to the pretest (p=0.03, see Figure 3) whereas the control group failed to show similar improvements (p=0.32, see Figure 3). In terms of individual data, 7 out of 11 training group children followed the group trends.

Training-related changes in hand COV during dual-limb drumming
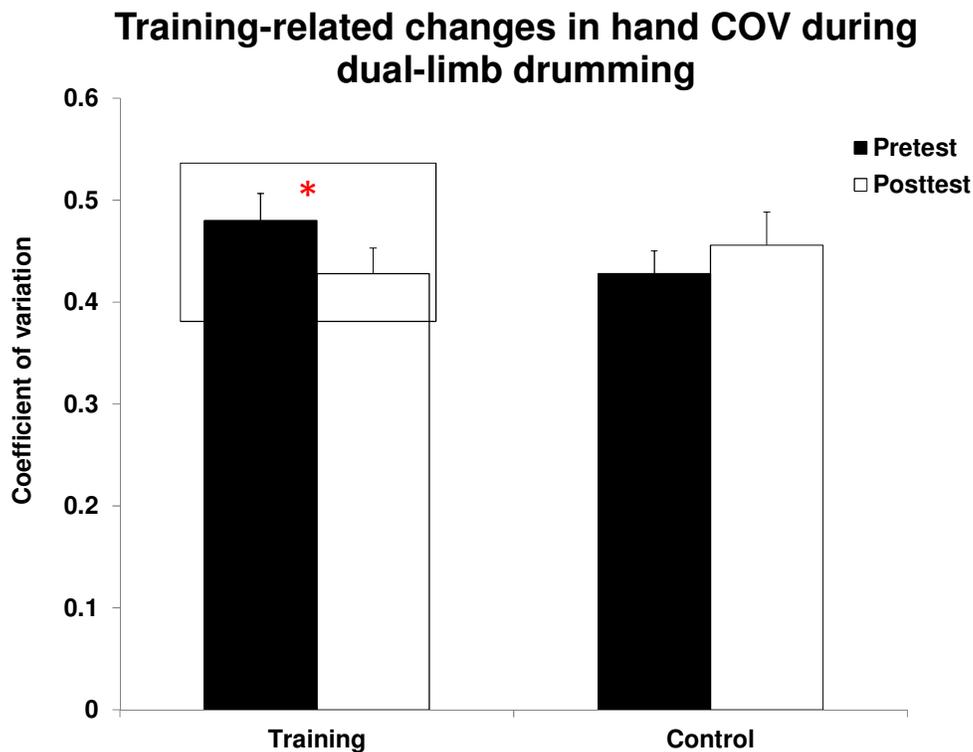
Figure 3: Training-related changes in hand COV during dual-limb drumming in the training and the control groups. The training group significantly reduced hand COV during the dual-limb drumming in the posttest compared to the pretest, whereas the control group did not show similar changes.

b. Leg COV and arm COV for multilimb march-clap

Separate repeated measures ANOVA were conducted for leg COV and arm COV during the multilimb march-clap action. ANOVA of leg COV during multilimb march-clap showed a

significant main effect for context (F (1, 42) =13.40, p=0.01, ηp2=0.24) and statistical trend for test*group interaction (F (1, 42) =3.19, p=0.08, ηp2=0.07) and test*context*group (F (1, 42) =3.77, p=0.06, ηp2=0.08). Post hoc analysis for the two relevant test*group interactions, revealed that the training group showed a trend for reduction in their leg COV during the multilimb march-clap action in the posttest compared to the pretest (p=0.13, see Figure 4), whereas the leg COV for the control group did not vary across the posttest and the pretest (p=0.22, see Figure 4). No pre- posttest changes were observed for arm COV in the training and the control groups.

Training-related changes in leg COV during multilimb march clap

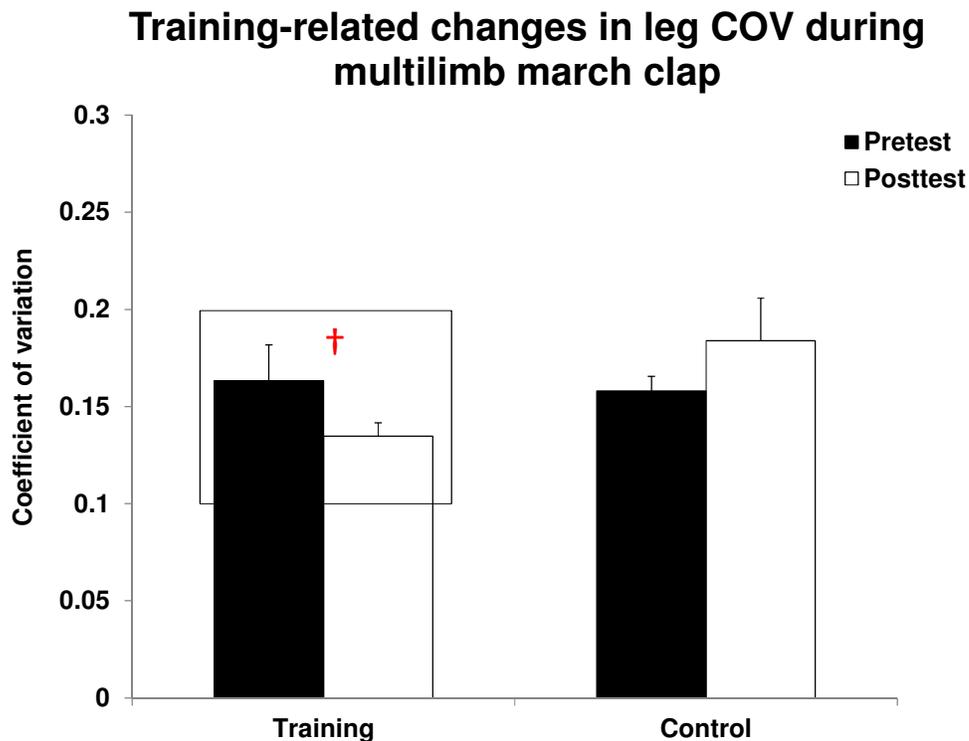
Figure 4: Training-related changes in leg COV during multilimb march-clap action in the training and the control groups. The training group reduced their leg COV in the posttest compared to the pretest whereas the control group did not show similar changes.

Context-related differences in bilateral coordination of children during performance of task-specific actions

We evaluated the second aim of our study i.e. context-related differences in bilateral coordination of children through two task-specific actions, dual-limb drumming and multilimb march-clap. The dependent variable for this comparison was the COV of the moving limb segment, i.e. hand COV during dual-limb drumming, and leg and arm COV during multilimb march-clap. The pretest data for the training and the control group was pooled for this analysis in order to increase the sample size. ANOVA showed a significant main effect for context (F (1, 43) =5.51, p=0.02, ηp2=0.11), task (F (1, 43) =401.58, p<0.01, ηp2=0.91), and a statistical trend for context*task interaction (F (1, 43) =2.62, p=0.11, ηp2=0.05). Post hoc analysis for significant main effect of task showed that the hand COV was significantly higher than the arm followed by the leg COV (p<0.05 for all three comparisons, see Figure 5). Post hoc analysis for the context*task interaction showed that the leg COV (p=0.03, see Figure 5) and arm COV (p=0.02, see Figure 5) during the multilimb march-clap were significantly more variable within the social versus the solo context. The COV during the dual-limb drumming action showed no differences between the social and the solo contexts (p=0.91, see Figure 5).
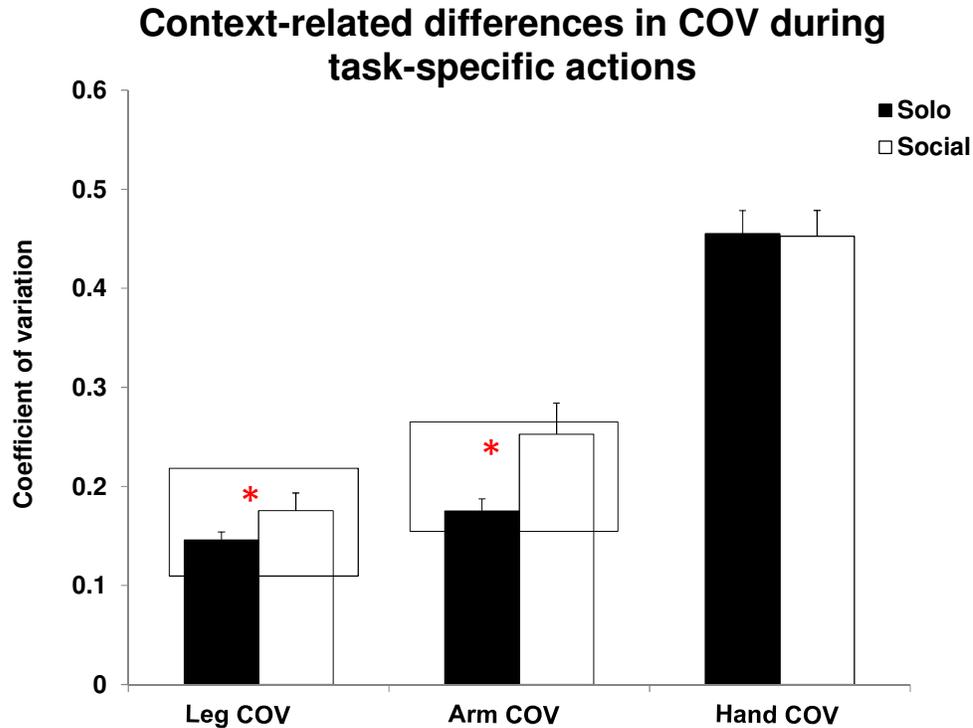
Figure 5: Context-related differences in leg and arm COVs during multilimb march-clap action and hand COV during dual-limb drumming action pooled across both training and control group children. The leg COV was lowest followed by the arm and then the hand COVs. However, context-related differences of increased COV in the social context compared to the solo context were obtained for leg and arm COVs during the multilimb march-clap action.

Note: * indicates a significant trend ($p \leq 0.05$) and † indicates a statistical trend ($0.05 < p < 0.10$)

Chapter 4: Discussion

Summary of results

      This study aimed to examine the effects of robot-child-child interactions on the bilateral coordination skills of children between 4 and 11 years of age. We used a controlled experimental design with non-random assignment of children to the training and control group. The training group children received six weeks of robot-child interactions. Training-related changes were assessed using standardized tests of motor performance- the BC subtest of the BOTMP and the BMC subtest of the SIPT as well as COV analysis of two task-specific actions within a solo and social context. In terms of training-related changes in the standardized tests, the training group improved their bilateral coordination in the posttest by reducing the number of incorrect moves and errors within the BC subtest of the BOTMP and the BMC subtest of the SIPT. The training group also showed reduced COV for task-specific actions, whereas the control group failed to show similar changes. In terms of context-related differences in bilateral coordination during the performance of task-specific actions, children increased their leg and arm variability during the social context compared to the solo context for the multilimb march-clap action. Next, we further review these findings and provide support from the current literature. We will also discuss implications of these findings for children with autism and directions for future research.

Training-related changes in bilateral coordination of children during standardized tests of motor performance and task-specific actions

    Training group children reduced the number of incorrect actions and errors post-training in the BC subtest of the BOTMP and the BMC subtest of the SIPT compared to the control group children. In addition, training group children reduced the variability in task-specific actions of multilimb march-clap and dual-limb drumming in the posttest compared to the pretest. The

improvements in the standardized tests and the task-specific actions in the training group could be attributed to the repeated motor practice during the robot-child interactions. The majority of the training actions were asymmetrical in nature and facilitated bilateral coordination in the training group. These results concur with the findings of our recent study where we showed that a small 7-inch robot, Isobot could improve the bilateral coordination of typically developing children between 4 and 7 years of age during complex multilimb actions (Kaur et al., 2013). Greater improvements in the task-specific drumming actions could be directly related to the practice of various simple and complex drumming actions practiced with the Nao robot. In contrast, the smaller improvements in the task-specific multilimb action could be associated with the limited ability of the robot to perform complex multilimb actions such as balancing or complex coordination. For example, the Nao robot had significantly poor postural control and dynamic balance for complex multilimb actions. Hence, a variety of movements requiring complex multilimb coordination could not be practiced over the training weeks. The training group children showed little improvements in the standardized scoring of BC subtest of BOTMP in the posttest compared to the pretest; however a more qualitative scoring of test actions showed a considerable reduction in the number of incorrect actions in the training group compared to the control group (see Figure 2). Similarly, the training group failed to show considerable amount of improvements for the BMC subtest of the SIPT compared to the control group (see Table 2). The lack of sufficient improvements in the standardized tests of motor performance in the training group children could be attributed to the relatively short duration of our training protocol. Twelve sessions of training for children may have been sufficient to improve performance of various task-specific dual and multilimb actions but may not be sufficient to result in significant generalized improvements in motor coordination. Moreover, as discussed above the training

actions were not complex enough to challenge the high levels motor performance observed in typically developing children, thus limiting their posttest improvements. In terms of social attention, children spent significant portion of the various training activities focusing on various social cues such as the robot, the other child partner and the trainer. Based on coding of social attention, we know that children spent the majority of time observing the robot versus the other child or the trainer. While children observed motions of their partner more during the "move together" conditions, overall, they spent a significant portion of the training monitoring the robot's actions. Together, these may have contributed to improved social monitoring in the training group children. Indeed, our data confirm that training group children significantly reduced their hand variability during the drumming in the posttest compared to the pretest within the social context and similar training-related improvements were not seen for the solo context of drumming. Overall, significant improvements in task-specific actions during the posttest for the training group children could be attributed to both, enhanced motor practice and social monitoring during training.

Context-related differences in bilateral coordination of children during performance of task-specific actions

Children showed greatest variability in the hand movements during the drumming compared to the arm and leg movements during the march-clap action. In terms of context-related differences, children showed greater leg and arm variability within the social context compared to the solo context for the march-clap action but such differences were not observed for the drumming action. The greatest hand variability during drumming could be explained by its task complexity. The drumming pattern involved drum hits to the beat of a combination of quarter and eighth notes and was possibly the most complex pattern the children performed leading to

high movement variability. This fits with what we know about increased variability due to inconsistent task performance (Vereijken, 2010). Moreover, greater variability of arms compared to legs during the march-clap action could be due to the type of limbs involved i.e. arm movements such as clapping are mechanically more complex and challenging than leg movements due to the greater degrees of freedom involved.

Children performed similarly within the solo and social context of drumming with high levels of variability. As discussed above, the drumming pattern was highly complex and difficult to master for the school-age children in this study. We noticed that children spent the majority of the time observing their own movements and paid little attention to their social partner. However, for actions such as march-clap, which may be relatively easy for children to master within the solo context but difficult to perform within a social context due to its visual demands of observing four moving segments of the social partner, children showed greater variability within the social versus the solo context. These findings of task-related differences in motor performance across the solo and social context were also present in our recent paper (Kaur et al., 2013). Younger children between 4 to 6 years of age had poor motor coordination in the social context compared to the solo context during complex multilimb actions but no differences in performance during the simple symmetrical dual-limb actions (Kaur et al., 2013). Together, these studies extend the past findings on interpersonal synchrony in adults and children to suggest that differences in solo and social coordination are a function of task complexity.

Social coordination relies on the ability to perceive the visual information available from the social partner and modify one's own actions based on the actions of the social partner (Richardson et al., 2007; Richardson, Marsh, & Schmidt, 2005). Adult experiments on social coordination have also shown that decrements in visual information about motions of a social

partner can reduce interpersonal synchrony between moving partners (Ouillier, DeGuzman, Jamtzen, Lagarde, & Kelso, 2008). For example, during a rocking chair experiment, adults showed greater in-phase coordination when they were looking at each other compared to when they were looking at the wall or looking away from each other (Richardson et al., 2007; Richardson et al., 2005). On the other hand, during a joint drumming task, pairs of children were less coordinated compared to pairs of adults when visual information from the social partner was available (Kleinspehn-Ammerlahn, Riediger, Schmiedek, von Oertzen et al., 2011). Within our studies, we have noted that children may not attend to the motions of their social partner as well as adults because they shift back and forth from observing the actions of the social partner to observing their own actions to ensure accurate motions. During complex actions children may also have difficulties reducing the variability of their actions to match that of the social partner (Kleinspehn-Ammerlahn, Riediger, Schmiedek, von Oertzen et al., 2011). On the other hand, adults have the ability to spontaneously modify their behavior such as reducing the variability or increasing the predictability of their own actions in response to the movements of their social partners (Vesper et al., 2011). Taken together, we believe that the differences in motor coordination in children within a solo versus a social context interact closely with task complexity. For highly complex tasks such as drumming, children show high levels of variability in both, solo and social contexts. For semi-complex tasks such as march-clap actions in this study or asymmetrical maraca shake and march actions in our previous study (Kaur et al., 2013), children are able to perform consistently in the solo context whereas social context appears challenging and movement variability increases. However, for simple tasks such as bilateral symmetrical actions (Kaur et al., 2013), or unilateral actions such as handshaking, children will

not show differences in solo and social motor coordination because these activities are mastered and stable for the age group across both the contexts.

Clinical Implications

Our study showed that typically developing children improved their bilateral coordination performance following six weeks of robot-child interactions. Specifically, greater magnitudes of improvements were seen in the task-specific actions compared to the standardized tests of motor performance. To date, robot-child interactions have not been used to enhance the motor performance of typically developing children as well as children with ASDs. However, there is some evidence for use of robots in enhancing social interactions and imitation skills of children with ASDs. In addition to social impairments, motor impairments such as incoordination, difficulties in gait, impaired balance and posture are also prevalent in children with ASD. The results from our present study suggest that robot-child interactions may be a promising tool to enhance coordination in children with impairments with motor incoordination, including children with ASDs.

Study Limitations

Our preliminary study is limited by a (i) convenience sample selection, (ii) a short duration of training, and (iii) a limited motor repertoire of the robot contributing to progressive boredom with the context. In this study, we had a convenience sample of children who were non-randomly assigned in the training and the control groups. We did not match children on their motor abilities before assignment into the two groups. We had a relatively short training period of six weeks which was insufficient for generalized improvements in motor performance of children. Moreover, training group children seemed to get bored in the later training sessions which was probably due to the limited repertoire of the robot and the and lack of adequate

complexity of training actions. The training sessions were devised according to the abilities of children with ASDs, therefore children might have found these actions very simple and not challenging enough. The current study was a proof-of-concept study in healthy school-age children and did not involve special populations. Our future studies will use a combination of various sophisticated and toy-like robots with different capabilities to increase both the level of engagement and the robots' repertoire of motor and social behaviors. Currently, we are conducting a randomized controlled trial in children with ASDs using multiple robots, an extended training protocol, and prior matching of motor repertoires of children with ASDs to further extend our preliminary findings to this population.

Conclusions

The primary purpose of our study was to evaluate the efficacy of robot-child-child interactions on the bilateral coordination skills of children between 4 and 11 years of age. We found greater improvements in bilateral coordination during task-specific actions in the training group compared to the control group children. Robot-child interactions may have facilitated motor practice of symmetrical and asymmetrical bilateral actions which in turn might have enhanced coordination, and/or social monitoring in the children. Taken together, socially embedded motor activities using robots might be a valuable context for improving motor coordination of children. Therefore, robot-child interactions could be a promising tool for clinicians working with children who have motor coordination deficits including children with ASDs.

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Appendix

a. Scoring sheet for BC subtest of BOTMP

ID #: _____   Circle one: Pretest/Posttest   Coder's initials_____

#	Test move	# of correct movement	# of incorrect movement	Error Type
1.	Touch your nose			# of halts Target error Excursion error Head rotation error Lack of alternating movements Opens eyes A combination of errors
2.	Jumping Jacks			# of halts Only arm moves Only leg moves No synchrony between arms and legs A combination of errors
3.	Ipsilateral Jumping in place			# of halts Fails to simultaneously move leg and arm of same side Takes extra steps/loses balance
4.	Contralateral Jumping in Place			# of halts Fails to move leg and arm of opposite side Takes extra steps/loses balance
5.	Pivoting thumb & index fingers			Unable to pivot (Correct but disjoint) # of halts Improper placement of thumb & index finger
6.	Ipsilateral tapping feet and fingers			# of halts Fails to simultaneously tap foot and finger of same side
7.	Contralateral tapping feet and fingers			# of halts Fails to simultaneously tap foot and finger of the opposite side

Notes: 1. Code the motions performed and not the postures attained. Therefore, even if the child is able to correctly attain the starting posture, it does not count.
2. The first two attempts of the child are coded. Each attempt consists of 10 movement cycles. If the child performs well in the first attempt, then the second attempt is not coded.

b. Scoring Sheet for BMC subtest of SIPT

ID #: _____   Circle one: Pretest/Posttest   Coder's initials_____

	Rhythmicity errors	Sequencing errors – Omit/Merge/Add	Mirroring errors	Movement overflow errors	Time to Best Effort (sec)
1.	Y / N	O / M / A	Y / N	Y / N	
2.	Y / N	O / M / A	Y / N	Y / N	
3.	Y / N	O / M / A	Y / N	Y / N	
4.	Y / N	O / M / A	Y / N	Y / N	
5.	Y / N	O / M / A	Y / N	Y / N	
6.	Y / N	O / M / A	Y / N	Y / N	
7.	Y / N	O / M / A	Y / N	Y / N	
8.	Y / N	O / M / A	Y / N	Y / N	
9.	Y / N	O / M / A	Y / N	Y / N	
10.	Y / N	O / M / A	Y / N	Y / N	
11.	Y / N	O / M / A	Y / N	Y / N	
12.	Y / N	O / M / A	Y / N	Y / N	
13.	Y / N	O / M / A	Y / N	Y / N	
14.	Y / N	O / M / A	Y / N	Y / N	
15.	Y / N	O / M / A	Y / N	Y / N	
16.	Y / N	O / M / A	Y / N	Y / N	
17.	Y / N	O / M / A	Y / N	Y / N	
18.	Y / N	O / M / A	Y / N	Y / N	

Note: Y stands for Yes (or presence of errors)
       N stands for No (or absence of errors)