SAPIENZA
UNIVERSITÀ DI ROMA

PhD Program in Neurophysiology

XXVI cycle

Development of motor cooperation through joint-action in middle childhood: A behavioral study

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PhD Dissertation

December 2013

INDEX

ABSTRACT

The development of the abilities to behave in a joint-action so far has been investigated only in infants and preschoolers (Tollefsen, 2005; Brownell et al. 2006). To our knowledge, no experiments have been carried out yet to investigate how and when the ability related to successfully perform a joint-action does develop during middle childhood. Since this developmental period is critical for the large changes in motor dexterity, cognition, and sociality (Hartup, 1984; Fischer & Silvern, 1985; Hale, 1990), we thought that it would have been also crucial for the refinement of those skills required for complex forms of motor coordination, such as those required during joint-action. Thus, we tested couples of age- and gender-matched children (5-9 years) and adults while they performed a center-out videogame, in which the same action (moving a cursor on a screen through an individual isometric joystick) could be performed *i)* alone, *ii)* in a coordinate fashion with the partner (joint-action task), *iii)* coordinating with a computer, which reproduced the partner's trajectories. It was found that the performance in the joint-action task improved during development, but that there was a critical "jump" between 7-8 years, in which the performance during the joint-action improved rapidly, reaching for most parameters the level of adults at 9 years. Importantly, the increase in the joint-action performance did not simply reflect the maturation of the motor skills underlying single-action. Since 7-8 years, the performance benefited from the presence of an interaction with a real partner ("cooperation benefit"), as compared to the simple coordination with the computer. The analysis of spatial-temporal parameters of behavior showed the presence of a shift in the strategies for the movement control during the joint-action, from feedforward (around 6 years) to feedback-based (around 9 years). We thought that older children gradually learned to adjust their movements with respect to those of their partners through the use of feedback corrections, which allowed them to perform an online control of their partners' trajectories, a strategy made possible by the long movement times that characterized the task performance. The cognitive development and the changes in motor control occurring around 7-8 years are discussed as possible factors mediating the growth in the fine motor adjustment responsible of the improvement in the joint performance.

Introduction

1- Joint-action in childhood: state of the art

1.1 Development of joint-action

Cooperation between individuals is the best known determinant for the transmission of the human culture, and joint-action is a simple form of *hic et nunc* social interaction and cooperation in which two or more individuals coordinate their actions in space and time as to produce a change in the environment (Sebanz et al. 2006). Current research in social and developmental psychology indicates that joint-action in young children is based on a variety of social cognitive capacities, which start emerging around the age of 9 months.

The first, fundamental ability consists in sharing representations with others (Sebanz et al. 2006), which happens primarily through joint-attention (the ability to direct one's attention to where an interactive partner is attending). Since 9 months of age infants are able to follow the gaze of caregivers and peers, and act on objects by imitating the adults' actions on them (imitative learning) (Tollefsen, 2005). As a basic mechanism for sharing representations, joint-attention creates a kind of "perceptual common ground", necessary for coordinating the actions. Since 9 months, infants are also able to understand the goals underlying other's actions (Behne et al. 2005), but, even if they are able to play with peers alongside one another, they do not interact to any great extent with each other (Tollefsen, 2005).

From the completion of the 1st year, a major awareness of the actions of others, including not only the others' goals, but also their plans for actions and the means the others will use to reach the desired end states starts to emerge (Gergely et al. 2002). One-year-olds seem to have some rudiments of "common knowledge" with the caregiver, i.e. the knowledge which has developed between them (Liszkowski et al. 2008). Very interestingly, this is also the age at which infants are not just capable of helping others, but are also very motivated to do so: their help is spontaneous, without the need for an external request (Warneken & Tomasello, 2006, 2007). The completion of the 1st year is also a hallmark for the starting of a real peer cooperation, since infants at this age begin to engage in more cooperative behaviors (e.g. make puzzles with others). In fact, it is between the 1st and the 2nd year of life that the capability to coordinate with peers starts a steep growth. In particular, it seems that the coordinated acts between peers grow three fold between

16 and 28 months, with a sharp increase between 24 and 28 months (Holmberg, 1980; Eckerman et al. 1989; Brownell & Carriger, 1990).

By reaching 24 months of age, children have finally learned to coordinate their behavior with one another quickly and effectively (Brownell & Carriger, 1990; Brownell et al. 2006).

However, interesting studies on older children suggest that the understanding of a common ("we") intentionality is far from complete at two years. In fact, it is only from the 3rd year that children start to recognize both when an adult is committed and when they themselves are committed to a joint-activity, and do exhibit surprise if the adult does not respect the common goal, showing a new awareness of what obligations such committed activities engender (Gräfenhain et al. 2009). By this time, children are also beginning to engage in much more complex joint-actions, even imaginary, as the joint-pretense with peers (e.g. serving pretend tea, with empty cups). In this kind of joint-action, children not only coordinate their overt actions, but they also maintain and coordinate their "pretend world" (Tollefsen, 2005).

Moreover, since this age, the development of the play with peers becomes highly segregated by gender. Observational studies suggest that, from 3 to 6 years, 50-60% of peer interactions happen with same-gender peers (Martin et al. 2011). Between 4 and 6 years, boys start to interact more in same-gender groups and less in dyadic relations than girls (Benenson et al. 1997). Likely, the major engagement in group interactions can account for the finding that boys imitate and are imitated more than girls. Very interestingly, this is true especially for the so called "dominant" boys (as valued by teachers and by the occurrence of the peers' gazes directed on them) (Abramovitch & Grusec, 1978).

It has been suggested that the first form of peer cooperation is the imitation of the non-verbal actions of the peers (Eckerman et al. 1989). At any rate, peer imitation seems to decrease with age (Abramovitch & Grusec, 1978), possibly because the growth of more mature cognitive functions could help children to cooperate also in complementary, non imitative, ways.

Since '70s, the development of the cooperation during scholar years has been abundantly studied from a qualitative point of view, with an emphasis for the development of the attitude for cooperation. Some authors have shown that, when required to make a choice, old children (from 10 years) seem more predisposed to competition with respect to cooperation, as compared to younger children (5 years) (Nelson, 1970; Kagan & Madsen, 1971; Ribes-Iñesta et al. 2003), while others have shown that fifth-graders, but not younger children, almost always tend to respond cooperatively (Brady et al. 1983). Some researchers found conspicuous sex-differences in the tendency to cooperate in 8-year-olds, showing that boys are more competitive than girls (Skarin & Moely, 1974; Moely et al. 1979), while others pointed out that these differences are culture-dependent (Kagan & Madsen, 1971; Cárdenas et al. 2011; for a review see Hartup, 1984). Moreover, it has been shown that the choice to cooperate can be manipulated, and is reward-dependant in children since 7 years of age (Azrin & Lindsley, 1956, Mithaug, 1969).

In any case, to my knowledge, no study has yet been carried out aiming at the study of ontogeny of cooperative joint action, with special attention to the ways by which the developing motor system is able to adjust to the requirements of a joint-action, when it is requested to cooperate with a peer.

1.2 Action prediction and integration during joint-action

It has been suggested that successful joint-actions require the capability to take into account the actions of the partner, in order to predict when they will happen in time and space (Sebanz et al. 2006).

There is a evidence, from studies on adults that not only the understanding, but also the prediction of the others action are obtained through a sort of inner motor resonance or simulation in the observer (Kilner et al. 2004; van Schie et al. 2004). The degree of the motor resonance in the observer depends on his implication in the other's action, and in particular whether he is engaged or not in a joint-action with him (Sebanz et al. 2006, 2006b).

One recent electrophysiological study has demonstrated that children aged three years exhibit an enhanced motor involvement during action observation of an adult performing a button-pressing game when they were engaged in a joint-action, as compared to the condition in which they were not engaged, and, moreover, the extent of children motor involvement has been associated with their performance during the joint-action (Meyer et al. 2011). This motor system involvement might play an important role for children's joint-action performance.

It is very likely that the cerebral areas involved in motor simulation found in children (when they observed the action of the co-actor) were part of the putative mirror neuron system (pMNS) - as inferior frontal gyrus (IFG) and inferior parietal lobule (IPL)- since pMNS has been correlated with action observation and execution in many joint-action tasks (Ramnani & Miall, 2003; Sebanz et al. 2006b; Newman-Norlund et al. 2008).

However, engaging in joint-action additionally requires the partners to integrate the observation of the partner's action with solo execution. This process seems to rely on other cerebral areas, some of which partly forming the pMNS, as the bilateral IFG, precentral gyrus, superior parietal lobule (SPL), IPL, middle and temporal occipital gyri, left thalamus, and cerebellum. There is some evidence that successful joint-actions require one specific information flow in the brain, which is directed from anterior to posterior areas, involving two anatomically separated networks: (1) the action prediction network, and (2) the integration network (Kokal & Keysers, 2010).

2- Development in childhood: state of the art

2.1 Brain development

In a classic experiment using Positron Emission Tomography (PET), some researchers determined the presence of high rates of local cerebral metabolic glucose consumption in various gray matter regions of the children's brain from 2 years until 9 years. After 9 years, rates of glucose utilization started to decline, and finally reached the adult values only during the second decade of life, with the exception of the cerebellar cortex, whose glucose rate was similar between adults and children older than 9 years (Chugani et al. 1987).

The request for glucose or oxygen in the brain depends from the number of cerebral processes (number of neurons, synapses), which require energy. Therefore, the evidence for a constant high level in the rate of glucose during childhood is in line with the well-known age-related overproduction of neurons, synapses, and dendritic spines (Huttenlocher et al. 1982). For example, at age 7, when the child's brain is almost identical to that of the adult in terms of size and weight, the average synaptic density in frontal cortex is about 1.4 times the adult value (Peter, 1979). On the other side, the decline of the rate of local cerebral metabolic glucose in the brain found from 9 years on is consistent with the elimination of the majority of synaptic processes, due to the general selective principle of the brain maturation (and plasticity), which tend to reinforce only the strongest processes (Huttenlocher et al. 1982).

The process of myelination occurs regionally beginning with the brainstem at 29 weeks during the gestation, and generally proceeds from inferior to superior and from posterior to anterior, with proximal pathways myelinating before distal pathways, sensory pathways myelinating before motor pathways, and projection pathways myelinating before associative pathways (Volpe, 2000). Although most major tracts are significantly myelinated during the first 2-3 years of life, axons within the cortex continue to myelinate into the second and third decades of life (Yacovlev and Lecours, 1967).

In a more recent MRI study, some researchers explored cortical grey matter (GM) changes in a group of 13 subjects scanned from 5 years at approximately 2-year intervals. The developmental trajectory of cortical GM seems to follow an inverted U-shaped profile, with an increase until the reaching of a peak, and a subsequent decrease, with peaks depending on the specific cerebral region. In particular, the authors suggested that the increase of the cortical GM follows the functional maturation sequence, with areas subserving primary functions, such as motor and sensory systems, maturating earliest, while higher-order association areas, such as superior temporal cortex, maturating last. Dorsolateral prefrontal cortex seems the latest to reach adult levels of cortical thickness, in line with its higher order role, as in decision control (Gogtay et al. 2004).

Like the cortical GM**,** the subcortical GM development follows an inverted U-shape profile, which differs for males and females. There is some evidence that the amygdale volume increases with age significantly only in males, while hyppocampal volume increases with age significantly only in females; among the basal ganglia, the caudate nucleus volume peaks at age 7.5 years in girls and 10 years in boys (Giedd et al. 1999; see Lenroot & Giedd, 2006 for a review).

Differently to the GM, the development of cortical white matter (WM) seems to follow a linear pathway, and does not begin to decrease until the fourth decade of life. Also, unlike the lobar differences seen in GM, the WM slopes are similar in the various regions of the brain (Bartzokins et al. 2001).

Total cerebral volume peaks at 14.5 years in males and 11.5 years in females. By the age of 6 years the brain volume is at approximately 95% of these values (Giedd et al. 1999).

2.2 Cognitive development

Although there is large variability in terms of age-related performance, likely dependent on specific tasks used, the main literature of the 20th century addressed to the cognitive development in middle childhood adopted Piaget's concepts of stages of development, that are related to an increase in complexity of the logical organization of the thought.

Based on studies focused on middle-class children in Western cultures, these developmental stages can be summarized as follows:

1) 6-8 years of age: development of thought through the emergence of concrete operations. Children become able to combine multiple representations to form a complex construct, so that they can understand many of the complexities characteristics of concrete objects and events. The emergence of an "higher level of thought" would occur at the age of 7 (White, 1970).

2) 10-12 years of age: emergence of formal operations, which encompass the ability to abstract, and to create hypothetical ideas (Inhelder & Piaget, 1958; White, 1970; Siegler, 1981; see Fischer & Silvern, 1985 for a review).

During these stages, the starting year marks the onset of the competence that belongs to the stadium and the final year signs the successful acquisition by all subjects.

The speed of processing presents a linear developmental trend with age, which is known as the "global trend hypothesis", and which reflects a general speeding with age of many measures, such as reaction times (Hale, 1990; Kail, 1991).

However, it has been suggested that neurocognitive development is steeper between 5 and 8 years, relative to the transition period occurring between 9 and 12 years (Korkman et al. 2001).

The "cognitive jump" found around 7 years of age has been also documented for some parameters of executive functions. The capability of inhibiting irrelevant behaviors to optimally perform a goal-directed action is crucial for executive functions. These skills seem to improve significantly during middle childhood around the ages of 7-9 years (Levin et al. 1991; Williams et al. 1999).

Also working memory and the speed of information processing are both thought to subtend executive functioning (Barkley, 1997). It has been found that these two important dimensions present a steep development around the ages of 7 and 9 years (Brocki & Bohlin, 2004). Since executive functions are linked to the frontal cortex, it is very likely that the comparatively late development of the frontal lobes during cerebral development is central to the slow emergence of certain key abilities, such as goal selection, strategy planning and behavioral inhibition, all fundamental for goal-directed behavior (Dempster, 1992).

2.3 Motor control development

Motor behavior can occur along a continuum of control, ranging from feedback to feedforward. Feedforward movements can be defined as the movements made without the *online* control based on sensory feedback evolving during the action, and require an internal model of accuracy (Kawato, 1999). Such actions occur rapidly, as there is no need to account for the temporal delay of feedback loops. Feedback control, in contrast, involves modification of the ongoing movement using information from sensory receptors. This type of control allows for a high degree of accuracy, as well as for error detection and correction, but is necessarily slow.

The degree of motor planning and error correction has been associated with distinct dissociable networks of cerebral activation. Planning (feedforward) movements have been correlated with the cerebellum, the occipital and the premotor cortex, primary motor cortex, and basal ganglia, while feedback-based movements have been correlated with occipital, parietal, premotor, and supplementary motor cortex, ipsilateral sensorimotor cortex, cerebellum, and the thalamus (Winstein et al. 1997; Seidler et al. 2004; Bastian, 2006).

Movement control changes from feedback to feedforward during the course of skill acquisition. Movements become faster and more accurate as a function of practice, and the learner becomes less reliant on feedback control.

There are several behavioral studies that have defined the steps of acquisition of different movement strategies for performing reaching movements during ontogenesis. Initially (at about 5 years) feedforward mechanisms predominate, then (at about 7 years) feedback mechanisms take over, and finally (at about 9-11 years) an integration of both mechanisms occurs (Hay, 1979). The amplitude of the hand movement toward a visual target shows a critical age of development at 8 years of life, when children seem to rely on a feedback-based control strategy of their movement, while by age of 10 a feedforward mechanism is increasingly used (Bard et al. 1990). In line with these results, one study showed that children from 6 to 9 years become capable of quickly processing visual target information, and produce fast and uncorrected reaching trajectories (Favilla, 2006). Consistently, other studies have shown that the ability to exploit feedforward control in a dynamic tracking task improves significantly from 6 to 11 years of age (van Roon et al. 2008). Moreover, in an isometric force contraction task, it has been shown that the force output signal of children aged 6, 8, and 10 years exhibits a more broadband frequency profile with increases in age if children can monitor their force output through visual feedback (Deutsch & Newell, 2001).

3- Aims of the research

This research has been addressed to the mechanisms of behavioral development supporting joint-action during childhood. Since it is clear that even 2-year-old children are able to successfully cooperate, my research has been specifically aimed to the development of those fine motor skills adjustment that are required to cooperate. In particular, the differences in behavior during single-action as compared to joint-action have been explored during the development, with a particular emphasis on how the behavioral strategies employed during the joint-action with a peer do change during development.

To these goals, an *ad hoc* videogame has been created (see Methods) and adapted to a task which is presently used for the study of the neural basis of social cooperation in non-human primates at the Behavioral Neurophysiology Laboratory – Department of Physiology and Pharmacology, SAPIENZA, University of Rome.

We selected a specific developmental "window" for our research, which starts from 5 years and ends with the completion of 9 years, since the actions required in this task are all depending on fine motor skills fulfillment.

We hypothesized that the steep development that characterizes the life period tested here could influence the capability to coordinate actions with others. In particular, the increase in the speed of information processing, together with the increasing capability of self-inhibition could influence the cooperative play between peers, by allowing children to take into account the actions performed by their peers, in order to ameliorate the performance during joint-action. Since many authors found a steep cognitive "jump" at the age of 7, we expected the larger changes around this particular age, both in terms of coordination strategies applied and degree of awareness and attention during the task.

Moreover, we hypothesized that the maturation of feedforward mechanisms in the control of behavior, which is thought to happen from middle childhood until 11 years of age, could have a role in the joint-coordination required in our task. Since it has been shown that 7-year-olds predominantly use a feedback-based strategy for single-action movements, we thought that this ability could allow children from this particular age to better perform an *on line* control of the movement of their partners during joint-action, and this, in turn, could improve their performance as compared to younger children.

Methods

1- Participants

A total of 37 couples of typically developing children, aged 5-9 years and matched for age and gender, participated in the experiment (tot n. of males = 36; tot n. of left-handed = 3; see Table 1). All children were recruited from a public nursery school (5 years-olds) and a public elementary school (6-9 years-olds) located in a unique didactic plexus in the city of Rome. Subjects were paired with a maximum of 6-months-age difference, and in agreement with self-declared frequency of videogame playing. In most cases (81 %) classmates were matched. All children's parents provided written informed consent for the participation to the research. The control group consisted of 12 couples of healthy young volunteers, aged from 20-35 years, and matched for age and gender (tot n. males = 12; tot n. left-handed = 1; see Table 1). All participants had normal or corrected-to-normal vision. All experimental procedures were approved by the Ethical Committee of Department of Psychology – SAPIENZA University of Rome.

2- Apparatus, experimental setup and tasks

The task consisted in a cartoon-like videogame programmed in Matlab R2011b (Mathworks, Italy), executed on a 17'' portable PC, and projected on the wall of the science lab at the children's school, resulting in an image size of 180 cm in length and 135 cm in height. In each couple, subjects were comfortably seated side by side on adjustable chairs in front of the wall, which was located three meters away from their eyes, subtending 28 degrees of visual angle. Two isometric joysticks (Saitek X65F Control System) were used, as to prevent movements of hand or arm during the game. The joysticks were placed and holded in a comfortable position on a table located in front of the two subjects. Through the joystick, each subject moved one of two cursor-characters on the screen, which were visually identical except for the color (red or green), each associated to the action of an individual subject.

A typical trial started with the appearance of the red and green cursors inside a central window on the screen, respectively on the left and right side of the screen. The two subjects had to maintain their cursors in the central window, for a variable time interval (Center Holding Time, CHT; 1-1.5 seconds). Any cursor's movement outside the central window during CHT resulted in an error and consequent abortion of the trial. At the end of the CHT, the target (one black/white igloo, located at 45 degrees with respect to the central window, in one of the four quadrants of the screen randomly chosen), a path (extending from the central window toward the target-igloo), and a snow-shovel (located at the center of the path and near to the central window) were presented simultaneously (Fig. 1).

The task of each subject was to carry the snow-shovel toward the igloo, in order to remove the snow from it; the snow-shovel was bound to the cursor when this passed in its proximity (within a distance of 8.8 cm). The cursors could only be moved through the pre-defined path, from the central window to the target (within 105 cm in length and 53 cm in width), and an error occurred when they exited the path. No limits on reaction or movement times were imposed in the task.

In a first phase, two task conditions were presented:

- Self condition (SELF): each subject acted alone, while the other maintained its cursor in the central window. The cue to go for the red/green cursor was a red/green snow-shovel respectively. The goal was to carry its own cursor to the igloo to obtain a success (Fig. 2 a-b).
- Joint-action condition (JA): the two subjects acted together. The cue to go was a large, bicolored snow-shovel. The goal for the cursors was to carry together the snow-shovel toward the igloo, by maintaining the spatial and temporal proximity between each other during all the trajectory toward the final target destination (Fig. 2c).

A pilot study on some couples of children (age 5-6) was performed to define the maximum inter-cursors distance (ID; 26 cm) to be maintained during the JA condition. This was aimed at assessing that also younger children in the sample could perform the task; an error occurred when the cursors distances violated the predetermined threshold.

One replication was completed when a successful performance (arrival to the target) was obtained when moving both cursors toward the four targets for each of the three combinations (single red, single green, joint-action), for a total of twelve trials (4 trials x 3 combinations). Conditions were presented in a pseudo-random order. For each couple, we collected data from five replications, for a total of 60 successful trials.

Successes and errors were visually displayed to the subjects by increasing or decreasing the length of a red and green point bars, located in the down left and right angles of the screen, and associated to each subject within a couple. Before the experiment, subjects were trained in a short version of the task, which ended when 100% of success rate for one replication in SELF and JA conditions was reached, as to separate motor learning from motor execution, and to make sure that each subject executed the task at a very high level of performance.

The verbal instructions for the SELF condition were: “As soon as the red/green snow-shovel appears, you have to take it and reach the igloo with it, without go outside the path. Be as accurate and fast as you can!”. For the JA condition, instructions were: “As soon as the bicolored snow-shovel appears, both of you will have to carry it together toward the igloo, always keeping it within the path. Be as accurate and fast as you can!”.

After the end of the first phase of the experiment we presented the subjects a second brief task phase, which served as a control condition, relative to the JA condition:

- Simulation condition (SIM): each subject acted alone with his previously assigned cursor. After the appearance of a large and bicolored snow-shovel, the cue to go was the onset of the movements of the partner’s cursor, which was moved by the computer, and reproduced one of the 20 successful trajectories toward the target collected from the partner’s cursor during the JA. The goal of the acting subject was to carry the snow-shovel with the computer cursor toward the igloo in order to gain a success, by maintaining itself near the computer-moved cursor during the entire trajectory toward the target, without overcoming the threshold of maximum distance used in the JA condition (this condition is visually identical to the JA condition, see Fig. 2c).

A total of 20 successful trials was collected during the simulation condition (i.e. 4 trials -one for each target position- x 5 replications).

The verbal instructions for the SIM condition were: “As soon as the partner’s cursor starts to move, you have to follow it and reach the igloo with it, without leaving the pre-defined path. Be as accurate and fast as you can!”.

We did not provide any performance feedback to the subjects. In order to motivate the children to perform as better they could, they were informed that each subject’s final score in the experiment would have been summed to that of his couple mate, and the couple would have competed with all the classmates for a prize. At the end of the experiment, the “best” performers of a class received gold medals, and the others received bronze medals.

The control study was performed in a sound-proof room located at the Laboratory of Neurophysiology – Department of Physiology and Pharmacology, SAPIENZA University of Rome.

The entire experimental session lasted about half an hour. All subjects were free to pause or interrupt the game whether they felt tired or bored.

3- Dependent variables and statistical analysis

The 2D positional data of the joysticks were collected with a sampling rate of 100 Hz and were low-pass filtered with a cut-off frequency at 3 Hertz.

The dependent variables were success rates and spatial-temporal parameters of behavior (reaction times, movement times, trajectories' dispersion, inter-cursors distance, velocity peaks and number of velocity stops).

The success rates (SRs) were the percentage of the number of successes obtained by each subject relative to the total number of trials performed.

The reaction time (RT) was defined as the time interval between the presentation of the peripheral target (go-signal) and the initiation of the movement in both SELF and JA conditions, while in the SIM condition the RT was computed as the time interval between the movement onset of the partner's cursor and the initiation of the movement of the acting subject.

Outliers, calculated as the values whose standard scores were ±2.5 or beyond the average RTs at each age, were excluded from the data (3.1% of outliers on total data in the SELF condition, and 2.9% in the JA and SIM conditions).

The movement time (MT) was the time from the initiation to the end of a cursor movement (arrival of the cursor at the target). We excluded outliers MTs from the data (2.4% of outliers on total data in the SELF and JA, and 2.6% in the SIM condition), calculated with the same constraints used for the RTs.

The spatial dispersion of the cursor's trajectories in any given direction was calculated by dividing the trajectories in 50 equally spaced bins and for each bin the 95% confidence ellipse was calculated. We defined the index of spatial dispersion as the mean area of all ellipses for each target direction.

The inter-cursors distance (ID) was the distance between the two cursors during each trial in the JA condition given their coordinates during the movement toward the target (considering the start of the movement as the first cursor's movement onset), calculated bin by bin and then mediated for the all trials. The ID can be used as a measure of the spatial control of the two cursors' movement, since the lower is the ID, the more careful and matched is the control of the partner's cursor.

The velocity peak (VP) was defined as the maximum value in cursor's tangential velocity, while the number of velocity stops (nVS) was the number of times per second that the tangential velocity of a cursor was below 3.3 cm/s (van Roon et al. 2008).

The data were analyzed using Matlab (version R2011b, Mathworks, Italy). Statistical analysis consisted of analysis of variance and covariance (using Bonferroni post-hoc test for multiple comparisons, when appropriate), regression and correlation. Some couples of 5 years children (38%) did not pass the phase of initial training, due to an overall immature fine motor control. Among the remaining 5 couples of this age, only one couple performed the SIM condition; we therefore excluded this age-range from the data in the SIM condition, and in all the comparisons between the three conditions.

Results

1- Success rates (SRs)

To control the effects of gender on SR in the three conditions, a three-way ANOVA with the factors gender (2 levels), age (5 levels: 6 years to adults), and condition (3 levels) was run. It was found that the main effects of gender ($F_{(1,186)}$ = 7.97, p<.05), age ($F_{(4,186)}$ = 78.24, p<.000001), and condition ($F_{(2,186)}$ = 74.57, p<.000001) were significant, but neither the interaction between gender and age ($F_{(4,186)}$ = 2.1, p=.08), nor the interaction between gender and condition ($F_{(2,186)}$ =0.56, p=0.57) reached significance. The only significant interaction was found between age and condition ($F_{(8,186)}$ = 3.82, p<.001). Therefore, gender data have been collapsed in subsequent analysis.

Similarly, in order to study the effects of target side on SR in the three conditions, a three-way ANOVA with the factors target side (4 levels), age (5 levels: 6, 7, 8, 9 years and adults), and condition (3 levels) was run. The effect of target side ($F_{(3,796)}$ = 0.42, p=0.74) was not significant, while both the effects of age ($F_{(4,796)}$ = 132.04 p<.000001), and condition ($F_{(2, 796)}$ = 199.22, p<.000001) were highly significant. Neither the interaction between target side and age ($F_{(12, 796)}$ = 0.61, p=0.8), nor between target side and condition ($F_{(6, 796)}$ =0.95, p=0.46) reached significance. The only significant interaction was found between age and condition ($F_{(8,186)}$ = 14.27, p<.000001). Since no effect of target side on the SRs has been found, target side has been collapsed in subsequent analysis.

The effects of age on performance were tested through a one-way ANOVA on the SRs sorted for ages (Fig 3). In the SELF condition, the age effect was highly significant ($F_{(5, 92)}$ =15.88, p<.000001). Post-hoc analysis showed a clear age-related increase in performance, with significance between nonadjacent age-groups: SRs in 5- (54%), 6- (59%), and 7-year-olds (66%) were significantly lower than those at age 9 (90%) and in adults (92%), and SRs at ages 5 and 6 were significantly lower than 8 years (79%). At age 8, children reached maturity, since their SR was not significantly different from that of adults. Also in the SIM condition the age effect was highly significant ($F_{(4, 71) =}$ 22.2, p<.00001), with significant differences between nonadjacent age-groups: the performance during the SIM condition was significantly lower at age 6 (25%) and 7 (29%) as compared to age 9 (61%) and adults (75%), with 8-year-olds (46%) significantly worse than adults, while the adult level was reached at age 9. Yet, in the JA condition, the age effect was highly significant ($F_{(5, 43)}$ = 42.79, p<.00001), and the post-hoc analysis revealed that 5- (8%), 6- (11%), and 7-year-olds (28%)

performed significantly worse than 8- (54%), 9-year-olds (73%), and adults (86%); at age 8, the SR was significantly lower than that of adults, while, similarly to the SIM condition, at age 9 maturity was reached.

To test the differences in the SRs in the three conditions within each age (from 6 years to adults), a two-way ANOVA with the factors condition and age was run (Fig. 4). Both the main effects of condition ($F_{(2,193)}$ = 70.39, p<.000001) and age ($F_{(4,193)}$ = 73.68, p<.000001), as well as the interaction factor ($F_{(8,193)}$ = 3.65, p<.005), were significant. The post-hoc analysis revealed that at age 6, 7, and 8 the SRs during SELF condition were significantly higher than those during JA and SIM conditions at the respective ages; at age 9 and in adults, the SRs during SELF were higher than those during SIM condition.

The relationship between SRs and age was tested by a regression analysis (Fig. 5). The regression lines defining the development of SR with age (from 6 to 9 years) fitted a linear model for all the conditions (SELF: R^2 =0.97; SIM: R^2 =0.95; JA: R^2 = 0.94).

A one-way analysis of covariance (ANCOVA) was performed in order to compare the slopes of the regression lines resulting from each condition. The interaction between the independent variables (conditions) and the covariate (age) was significant ($F_{(2, 142)}$ = 4.48, p<.05). The post-hoc indicated that the slope of performance with age during the JA condition was significantly steeper respect to the SELF condition; no differences were found between JA and SIM, and between SELF and SIM conditions.

1.1 "Cooperation benefit"

In order to quantify the relation between the trend of the SRs across ages in the JA condition relative to the SIM condition, a linear correlation analysis was performed, and a significant correlation (R=0.98, p <.05) was found. The linearity of the relation between the SRs during JA and SIM conditions with growing ages was also tested by a regression analysis (Fig. 6). The differences between the SRs in JA and SIM conditions with age were fitted by a linear model (R^2 = 0.95, p < .0001).

The performance during JA condition overcame the performance during SIM condition from 8 years on. Thus, the presence of a real and interactive partner during the game advantaged the subjects in the cooperative task only starting from 8 years of age. This "cooperation benefit" reverses an opposite pattern seen at earlier ages.

2- Reaction times (RTs)

The effects of age on RTs were tested through a one-way ANOVA (Fig. 7). The RTs during SELF condition presented a highly significant effect of age ($F_{(5,1415)}$ = 53.44, $p<.0001$). The post-hoc analysis showed a clear age-related decrease of RTs, in line with the global trend hypothesis (Hale, 1990; Kail, 1991). In particular, RTs at age 5 and 6 were significantly higher than those at age 8 and 9, while those at 7 years were significantly higher than those at age 9; adults RTs were the significantly lowest. Similarly, RTs during the SIM condition presented a highly significant effect of age ($F_{(4,684)}$ =8.95, $p<.0001$) and post-hoc revealed that RTs at age 6 were significantly slower than those at age 8, 9 and in adults; RTs at 7 years were significantly slower than those in 9-year-olds and in adults; 8-, 9-year-olds and adults did not significantly differ between each other. Also during JA condition the RTs presented a highly significant effect of age ($F_{(5,1389)}$ =25.59, $p<.0001$), and adults RTs were the significantly fastest, but, differently from the SELF and SIM conditions, the other group ages did not significantly differ between each other.

Subsequently, the differences in the RTs at each age in the three conditions were investigated through a two-way ANOVA with condition (3 levels) and age (5 levels: ages from 6 years to adults) as factors (Fig. 8). The main effects of both condition ($F_{(2,3399)}$ = 12.24, $p<.00001$) and age ($F_{(4,3399)}$ = 77.21, $p<.00001$), as well the interaction between these two factors were highly significant ($F_{(8,3399)}$ = 5.79, $p<.00001$). A post-hoc analysis showed that the RTs during the JA at age 6 and 7 were significantly faster than those during the SELF condition within each age; in adults the RTs during the SELF condition were significantly faster than those at the same age during the SIM condition.

3- Movement times (MTs)

In order to test for an age effect on the MTs, we performed a one-way ANOVA on each condition separately (Fig. 9). In the SELF condition, the age effect on MTs ($F_{(5,1421)}$ = 71.63, $p<.00001$) was highly significant, and the post-hoc analysis showed that the MTs in adults were the fastest of all age-groups, at 5 years the slowest, and 6-year-olds were significantly faster than 7- and 8-years-olds; no differences were found between 7-, 8- and 9-years-olds. Similarly, in the SIM condition the age effect ($F_{(4,680)}$ = 24.58, $p<.00001$) was highly significant, and the post-hoc analysis showed that the MTs in adults were the fastest of all age-groups, while 6-, 7-, and 8-year-olds were faster than 9-years-olds. Also in the JA condition the age effect ($F_{(5,1390)}$ = 82.08, $p<.00001$) was significant, and the post-hoc analysis showed a clear age-related increase of the MTs: in particular, the MTs in adults were the fastest of all age-groups, at 5 years the slowest, at 6 and 7 years the MTs were significantly faster than those at 8 and 9 years, and at 8 years the MTs were significantly faster than those at 9 years.

The differences in the MTs for each age and across conditions were studied through a two-way ANOVA, with condition (3 levels) and age (5 levels: 6 years to adults) as factors (Fig. 10). Both the effects of condition ($F_{(2,3399)}$ = 51.77, p<.00001) and age ($F_{(4,3399)}$ =122.53, p<.00001), as well as the interaction factor ($F_{(8,3399)}$ =12.71, p<.00001) were significant. The post-hoc analysis revealed that at ages 7 and 8 the MTs during SELF condition were significantly slower than those during SIM condition; at ages 8 and 9 the MTs during JA condition were significantly slower than the MTs during both SELF and SIM conditions; finally, in adults, the MTs during JA condition were significantly slower than those in SIM condition.

4- Trajectories' dispersion

The trajectories tend to become more accurate and smoother with the development, in the all conditions (Fig. 11). The differences in the trajectories' dispersion for age and condition were tested through a two-way ANOVA with: condition (3 levels) and age (5 levels: 6 years to adults) as factors (Fig. 12). Both condition ($F_{(2,1225)}$ = 82.42, p<.00001) and age ($F_{(4,1225)}$ = 46.88, p<.00001), as well as the interaction factor ($F_{(8,1225)}$ = 5, p<.00001) were significant. The post-hoc analysis revealed that the spatial dispersion of the trajectories was significantly higher in SIM condition as compared to SELF condition at 8 years, and as compared to both SELF and JA conditions at 6 years, 7 years, and in adults.

5- Inter-cursors distance (ID)

The mean ID for all the trials in the JA condition has been plotted in function of time (for a duration of 2 seconds, starting from the movement onset of the faster cursor within each couple) across ages (Fig. 13a). In order to test the differences in the mean ID for age, a one-way ANOVA has been performed (Fig. 13b). The age effect was highly significant ($F_{(5,830)}$ = 21.61, p<.00001), and the post-hoc analysis showed a clear age-related improvement in the spatial control of the partner's cursor, characterized by a significant decrease in the mean ID which occurred between 6 years and 7 years, as well as between 7 and 8 years; after 8 years, the mean ID did not significantly change with age.

6- Feedforward or feedback mechanisms?

There is a large consensus in the literature on the prevalence of a feedforward (predictive) strategy in the performance of reaching movements and in the production of isometric force in young children, which gradually gives way to the use of feedback-based (or corrective) strategy around the age of 7 years, followed at the ages 9 and 11 by integration of both strategies (Hay, 1979; Bard et al. 1990; Deutsch & Newell, 2001; van Roon et al. 2008).

The presence of corrective actions during movement has been investigated by studying certain features of cursor's velocity profile, that is the velocity peak and the number of stops between peaks (Hay, 1979; van Roon et al. 2008).

The velocity peak seems to present an inverse relation with the feedback-based strategy, and a direct one with feedforward mechanisms, since the higher is the velocity peak, the more the movement is under predictive control. Conversely, the number of stops between peaks seems directly related to the feedback-based strategy, since the decrement of movement velocity between sub-movements (peaks) is necessary for the visual system to perform a sequential pursuit strategy (Mounoud et al. 1985; van Roon et al. 2008).

Therefore, it can be summarized that high velocity peaks and low number of velocity stops are representative of pre-programmed control of movement (feedforward), while low velocity peaks and high number of velocity stops are representative of corrective control of movement (feedback). A model that refers on how these two parameters are representative of different degrees of prediction in the control of movement is shown schematically in Fig. 14.

The velocity peaks (VPs) during the JA condition have been compared across ages through a one-way ANOVA (Fig. 15a). The age effect on the VPs was highly significant ($F_{(5,1666)}$ = 20.63, p<.00001), with an age-related decrease in the range between 6 and 9 years. Exceptions to this age-related trend of the VPs was observed at 5 years, when the VPs resulted significantly lower than those at 6 years, and in adults that performed their task with VPs significantly higher than 9 years.

The number of velocity stops (nVS) during the JA condition was statistically compared across ages through a one-way ANOVA (Fig. 15b). The age effect was highly significant ($F_{(5,1666)}$ =27.67, p<.00001), and a post-hoc analysis revealed that there was an age-related increase by 6 years on, although the nVS was significantly higher at 5 years as compared to 6 years, 7 years, and adults; the latter presented the lowest nVS as compared to all other ages, except the 6- and 7-year-olds. The VP and the nVS presented an opposite evolution with age, in a mirror fashion, from 6 to 9 years, since while the former decreases, the latter increases with age (Fig. 15c).

Discussion

Despite the fact that the development of the capabilities to behave in a joint-action has been investigated in infants and preschoolers in great detail (Tollefsen, 2005; Brownell et al. 2006), to our knowledge no experiments have been carried out yet to investigate how and when these capabilities do develop during middle childhood. Since this developmental period is critical for the acquisition of motor dexterity, cognition, and sociality (Hartup, 1984; Fischer & Silvern, 1985; Hale, 1990), we thought that it could be also crucial for the refinement of those skills required for motor coordination during joint-action.

Thus, this study has been aimed at investigating the development of the fine adjustments of those motor skills that are crucial to cooperate in the course of middle childhood. In particular, we explored the differences in behavior during single-action as compared to joint-action, and the behavioral strategies employed during joint-action through development.

To these goals, we tested couples of age- and gender-matched children (5-9 years) and adults performing a center-out videogame, in which the same action (moving a cursor on a screen through an individual joystick) could be performed: 1) alone (SELF condition); 2) with a couple-mate (joint-action condition, JA); 3) with the computer reproducing the trajectories of the couple-mate (simulation condition, SIM).

We hypothesized that the capability to coordinate actions with others could be influenced by the steep development that characterizes the life period tested here. In particular, the cooperative play between peers could be influenced by the improvements in executive functions, by allowing children to take into account the actions performed by their peers, as to increase the performance during the joint-action. We expected that the larger changes could occur around the age of 7, since many authors found a significant cognitive “jump” at this critical age (Inhelder & Piaget, 1958; White, 1970; Siegler, 1981).

Moreover, since it has been shown that children around the age of 7 do typically use a feedback-based strategy for single-action movements, we thought that this ability could allow children from this particular age to better perform an *online* control of the movement of their partner during the joint-action, and this, in turn, could improve their joint performance as compared to younger children.

In order to test these hypotheses, different measures of spatial and temporal parameters of behavior have been compared across ages.

As a first result, during the development we found a gradual maturation process, responsible of a significant improvement in performance in the all task conditions, although in the presence of a significant within-age high variability in performance.

The level of adults' performance was reached at 8 years in the SELF task, and at 9 years in the JA and SIM tasks. However, performance in the SELF condition was systematically better than that in the JA condition within each age until 8 years. Likely due to this difference, the trend of performance in the JA condition resulted steeper as compared to that in the SELF condition.

We conclude that the development of the performance during the joint-action does not only reflect the maturation of single-action skills (SELF task performance), but does require additional, and more specific capabilities.

We found that the JA task is executed better than the SIM task from 8 years on, a condition that we called "cooperation benefit", because the only real cooperation condition was the JA, while the opposite happened at earlier ages, where the performance during simulated joint-action was better that during real joint-action. It is possible that young children in the SIM task could have benefited from the explicit instruction to imitate the actions of their partners; conversely, no instructions relative to the strategies to apply were given for the JA condition. Thus, the absence of the "cooperation benefit" in young children could be due to their lower problem-solving capabilities. Interestingly, the "jump" in favour of the JA condition (the "cooperation benefit") occurred in children by overcoming 7 years, which is a well-known age of significant improvements in cognitive development (Inhelder & Piaget, 1958; White, 1970; Siegler, 1981).

The second part of this research was aimed at the study of some spatial and temporal variables of behavior which could explain the mechanisms at the basis of the "cooperation benefit" typical of the JA performance.

By studying the spatial relations between the two cursors when they were performing the JA task, starting from 7 years we found a significant decrease of the inter-cursors distance (ID), which reached the values of adults at the age of 8, suggesting that a general improvement in the visual-spatial processes that allow one subject to efficiently monitor the actions of his partner occurs at these critical ages. We thought that this capability could contribute, at least in part, to the "cooperation benefit" in the performance.

Moreover, we hypothesized that the predominance of corrective strategies in the control of movement, which is known to begin around these ages (Hay, 1979; Bard et al. 1990), would have helped these children in improving the spatial control of their partner cursor's movements.

Therefore, we studied velocity peaks (VP) and number of stops in velocity (nVS), which are thought to be informative of the strategies applied for the control of movement (Fig. 14). Although the age of 5 presented an idiosyncratic pattern, we found an age-related decrease of the VP, and an age-related increase of the nVS in the range 6-9 years, both consistent with the hypothesis of a shift during development from feedforward to feedback mechanisms of movement control. At the same time, the relatively high values in VP and low values in nVS found in adults are in line with adults' typical predominance in the use of feedforward strategy for the control of movement (Seidler et al. 2004). Coherently with the fact that the two principal mechanisms for movement control (feedforward versus feedback) are evolving throughout middle childhood and an integration between them has been described around 11 years of age (Hay, 1979), it is likely that the predominance of feedback control that has been found here at 9 years would be gradually replaced by a more mature feedforward strategy at successive ages.

It is likely that, through an increasing use of feedback-corrective strategies, older children can efficiently monitor *online* the trajectories of their partners, and therefore corrections can be made in order to maintain the own cursor as nearest as possible to the other's, which, in turn, could explain the decrease in the ID. Conversely, this capability is immature in youngest children, due to a general tendency to perform in a pre-programmed way, a major load in the information processing, and a general immaturity of the visuo-motor system. At the same time, adults are able to perform the joint-action smoothly and efficiently, and it is probable that they have quickly acquired an internal model of their partners' trajectories in order to move in synchrony with them. Differently from young children, they can perform their movements during the JA in a pre-programmed way with high success.

Therefore, it seems that the development of movement control can significantly contribute to the improvement in performance observed around 7-8 years in the JA task.

However, it is plausible that the use of corrective movements at these ages is accompanied by a more general problem-solving improvement, by understanding that cooperation is better achieved if the degree of reciprocity increases. Related to this issue, we found that the movement times (MTs) in the JA task do increase with age at 8 and 9 years. We consider this finding as sign of a significant change in the cognitive strategies employed in the joint-action. In fact, since older children learned to monitor *online* their reciprocal trajectories, they waited for each other in order to move the cursor toward the common target in a coordinated fashion, with the consequent slowing-down of their movements.

The large changes in terms of motor and problem-solving strategies during the cooperation, that seem to occur around 7-8 years, are probably linked to the development of higher order association areas of the brain (in particular prefrontal cortex), which is thought to happen around, and continue beyond, this critical period (Gogtay et al. 2004; Lenroot & Giedd, 2006).

Another analysis concerned the reaction times (RTs), which presented, as all the other variables, a certain degree of within-age variability. We found that RTs decreased with age throughout the development in the single-action conditions (SELF and SIM conditions), with the lowest RTs found in the adults. This result is in line with the global trend hypothesis, which states that there is a general increase in the speed of processing due to the maturation of the central nervous system (Hale, 1990; Kail, 1991). In our study, the RTs did not differ between children in the JA condition, and further analysis are needed to clarify this point.

However, the comparisons within each age across task conditions showed a significant shortening of the RTs during the JA condition with respect to the SELF condition occurring at 6-7 years. It is possible that the preparatory phase of the movement was fastened during the JA task in these young children due to the emergence of a sort of competitiveness, which forced them to reduce their timings with respect to the baseline (SELF task).

The general increase in the motor skills throughout development is evident when looking at the trajectories performed by the subjects, which became smoother with age in all task conditions. Consistently, the trajectories' dispersion tended to decrease with age, which indicates a gradual reduction in the behavior variability. Moreover, we found higher trajectories' dispersion during the SIM condition, as compared to the other conditions in almost all within-age comparisons, which is likely to reflect the necessity to modulate its own behavior with respect to that of the partner. This might be due to the fact that this adaptation reaches the maximum level during the SIM condition, as in this condition the partners' movements are unchangeable by definition, because generated by a computer. Also, the difference in the trajectories' dispersion in the SIM condition with respect to the other conditions was higher in younger as compared to older children, which probably reflects a greater difficulty encountered by young children in adapting their movement to the extremely variable movements of their peers.

Conclusions

In conclusion, the present study indicates that the development of joint-action do not only reflect the maturation of single-action skills, but do require additional, and more specific capabilities.

The ages of 7-8 years are a "critical period" for the development of cooperative joint-action. In fact, at these ages children start to adjust their movement with respect to that of their couple-mates as efficiently as adults.

Moreover, it is at 8 years that a "cooperation benefit" emerges when the cooperative joint-action occurs in the presence of a real interaction, or mutual cooperation.

We interpreted these findings on the basis of brain development, in particular in cognitive and motor domains, both of which present a considerable change around the age of 7. In line with the results of studies on single-action motor development, we found that successful joint-action is achieved through the use of different motor strategies during the course of middle childhood, which seem to shift from pre-programmed to feedback-based (or corrective) control. The increasing use of feedback-based control of movement is likely to explain the significant improvement in the accuracy of the *online* monitoring of joint movements that emerged at around 7-8 years. On the other side, the cognitive "jump" described by many authors around these ages is able to explain, at least in part, the changes in the cognitive strategies employed during joint performance, characterized by an increase in interaction and reciprocity.

We do believe that the task of this study captures those skills involved in the fine coordination during joint-action, and has the merit to be simple enough to allow the comparison between single- and joint-action. More important, the task has been appreciated by children as a real videogame.

In the future, it would be very interesting to study in deep some aspects of motor cooperation through the development. For example, a future investigation could concern whether and how different gender-matched couples are able to accomplish the joint-action. It is possible that the segregation by gender, which typically starts to increase during the course of middle childhood (Benenson et al. 1997), could influence children cooperation, due to an inner prejudice on the capabilities of the partner. In line with this hypothesis certain studies have investigated the relation between the perceived similarity with the partner and the outcomes in a joint-action, suggesting that this psychological factor, by mediating the motivation to cooperate, can lead on a better cooperation (Valdesolo et al. 2010). Conversely, it is also possible that the coordination with an out-group member paradoxically fosters the synchronicity and, consequently, the joint outcome, via differences in the allocation of visual attention to an out-group interactive partner, as it has been shown with adults (Miles et al. 2011).

Another intriguing question is whether matching children with different ages could improve the performance of younger children, and how. A first possibility is that the older children would try to explain their younger partners how to play together. It is likely, however, that the joint performance obtained by a hypothetical different-age couple would be similar to the typical performance in the older couple-mate age range, since the older subject of this couple would adapt his own movement to that of the partner, thus reducing to (close to) zero the immaturity in performance due to the young age of his partner.

Another line of research on joint-action development could be directed to autistic children. It has been hypothesized that autistic individuals are impaired in monitoring both their actions and the actions of other people (Cattaneo et al. 2007). Several studies have reported that autistic individuals present deficiencies in mirror neuron system operations (Oberman et al. 2005; Dapretto et al. 2005). Although the exact neural mechanisms that support internal model for action are under investigation, it has been proposed that the mirror neuron system has an important role on both inverse and forward models during action execution and the observation of action (Iacoboni et al. 2005). Thus, the lack of acquisition of an internal model of (other) actions can seriously impair autistic individuals in joint-action execution. This is effectively what it has been found in an fMRI study involving autistic and same-age typically developing control subjects aged from 8 to 18 years in a virtual joint-action task (Stoit et al. 2011).

Monitoring the eyes movements would be ideal in order to check the strategies that are employed by subjects in an *online* fashion during the joint-action. It is plausible that, when a subject will have pre-programmed his cursor's trajectories, the eyes will be positioned mostly on his own cursor during cursor's movement, while, on the contrary, if a subject is using a feedback-based control, his eyes will be positioned both on his own cursor and the partner's cursor, in order to update and adjust his movement with respect to that of the partner.

Finally, it would be very interesting to test, within each age, how dominant with respect to non-dominant children (as determined by the frequency of their peers' gazes) do perform the joint-action task, since it is possible that this psychological factor could mediate the degree in which the action of the partner is taken into account (Fry, 1965).

This study is a first attempt to investigate the development of motor cooperation in a life period characterized by dramatic changes. The intriguing questions about the exact timing of appearance of the different strategies employed for an efficient cooperation, the exact neural mechanisms involved in joint-action execution, and the role of cognition and personality factors in joint-action performance during childhood are still open questions.

TABLE AND FIGURES

Table 1

MEAN AGE	AGE IN MONTHS		NUMBER OF SUBJECTS	MALES	FEMALES
	MEAN	DEV ST			
5 years	67.2	3.8	10	4	6
6 years	79.2	11.9	14	8	6
7 years	90.2	3.4	24	12	12
8 years	102.8	3.9	16	10	6
9 years	113.6	2.7	10	2	8
27 years ± 4.4	322.5	52.9	24	12	12

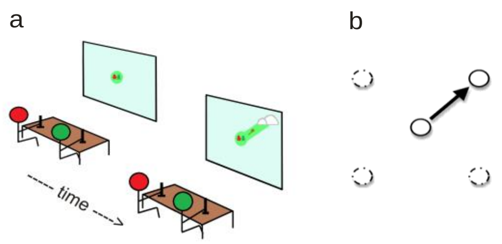

Fig. 1. a) Schema of the experimental set-up with the presentation of the task. b) Schema of the alternative positions of the peripheral target (igloo).

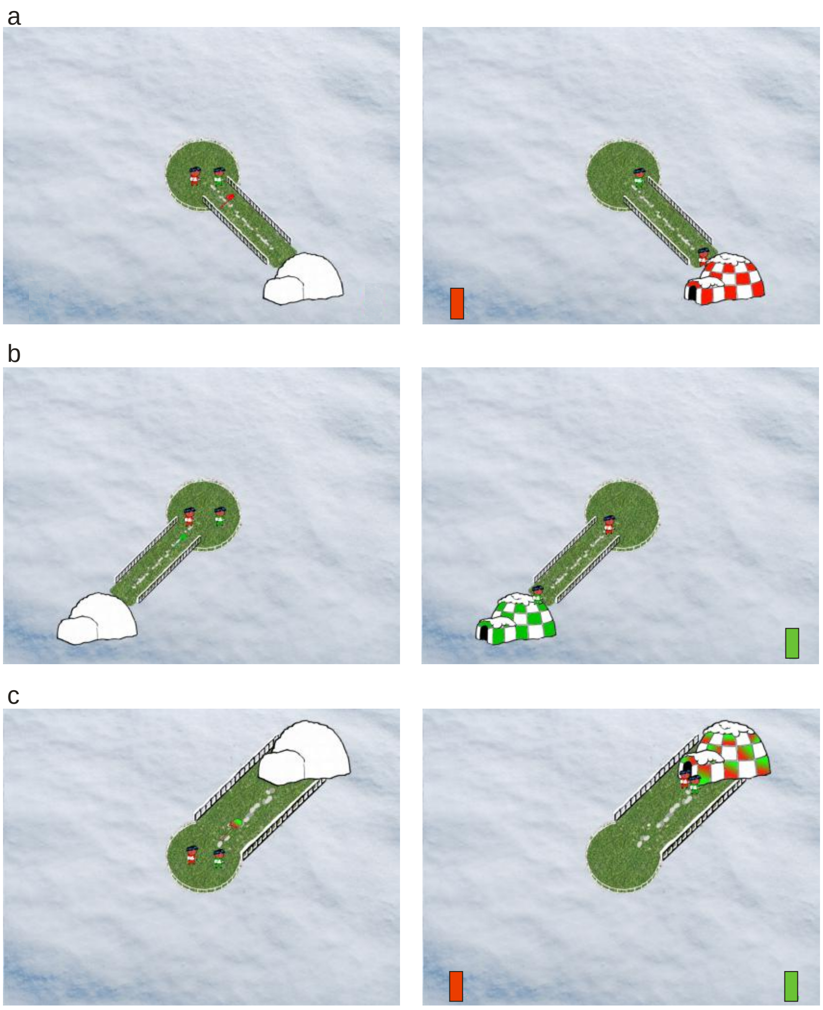

Fig. 2. Appearance of the go-signal (left images) and reaching of success (right images) for the red cursor (a), the green cursor (b) and both the cursors (c).

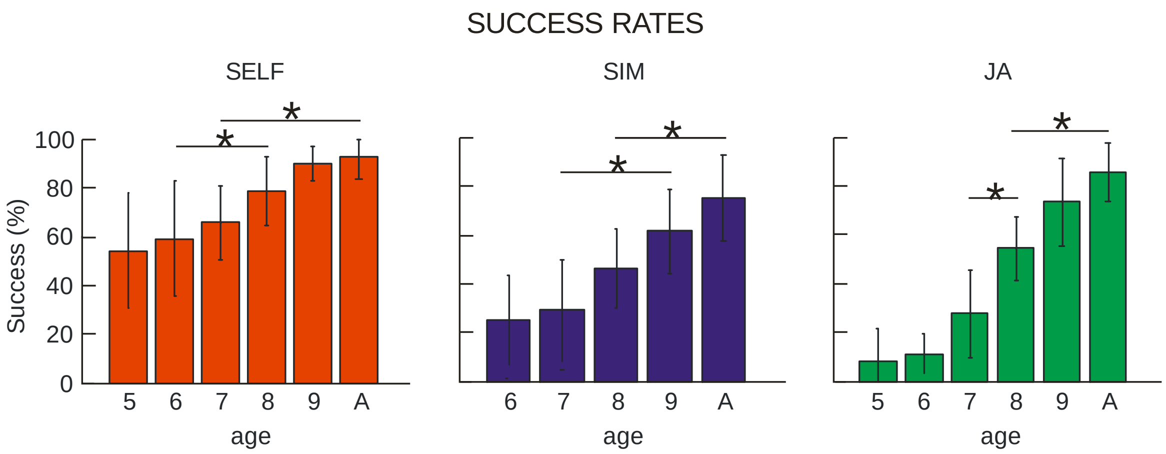

Fig. 3. Mean success rate in all task conditions across ages (A = adults). Vertical bars indicate standard deviations. One-way ANOVA shows significant main effect of age between nonadjacent age groups in both the conditions involving single actions (SELF, SIM). Small horizontal bars with asterisks indicate statistically significant comparisons.

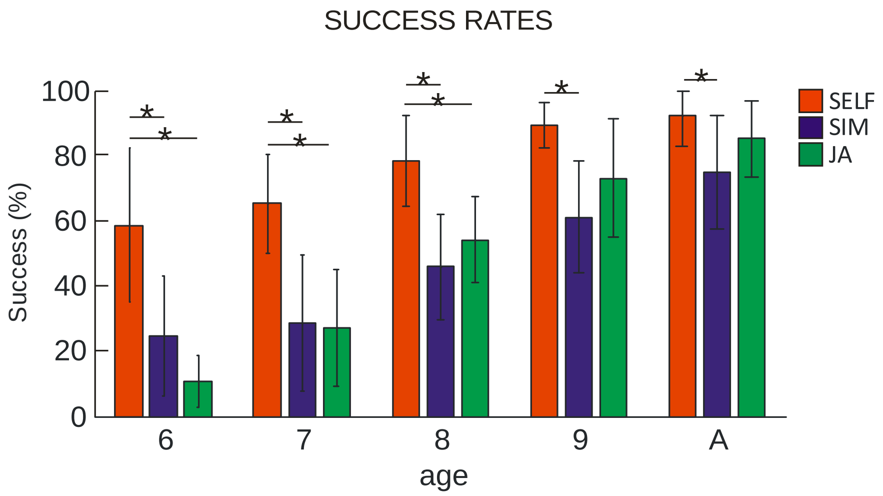

Fig. 4. Within age mean success rates and standard deviations across task conditions. Two-ways ANOVA shows significant main effect of condition across ages. Small horizontal bars with asterisks indicate statistically significant comparisons.

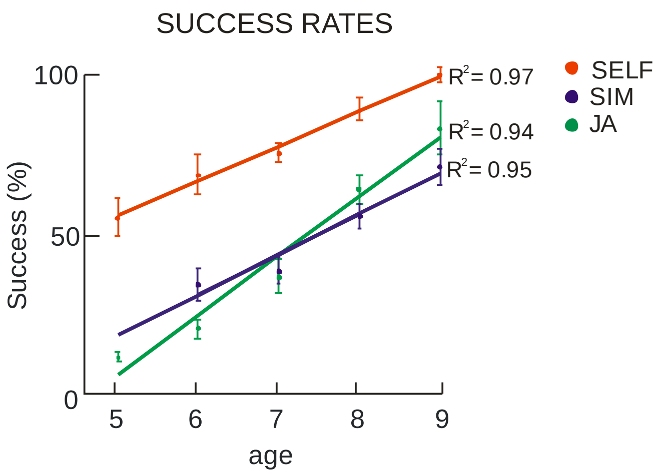

Fig. 5. Development of success rate (SR). Regression lines are shown for different task conditions. Vertical bars indicate standard error.

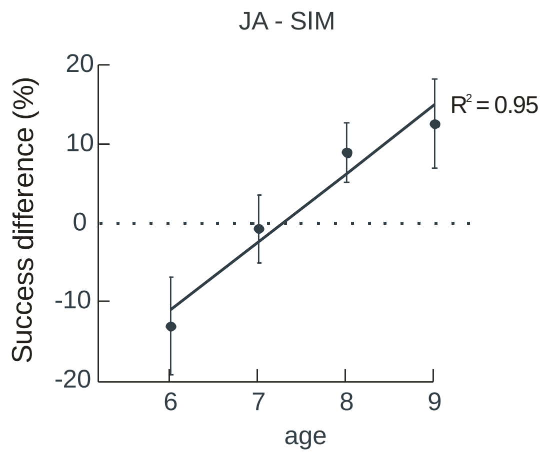

Fig. 6. "Cooperation benefit". Regression line is shown for the within age difference between the JA and the SIM SRs. Vertical bars indicate standard error.

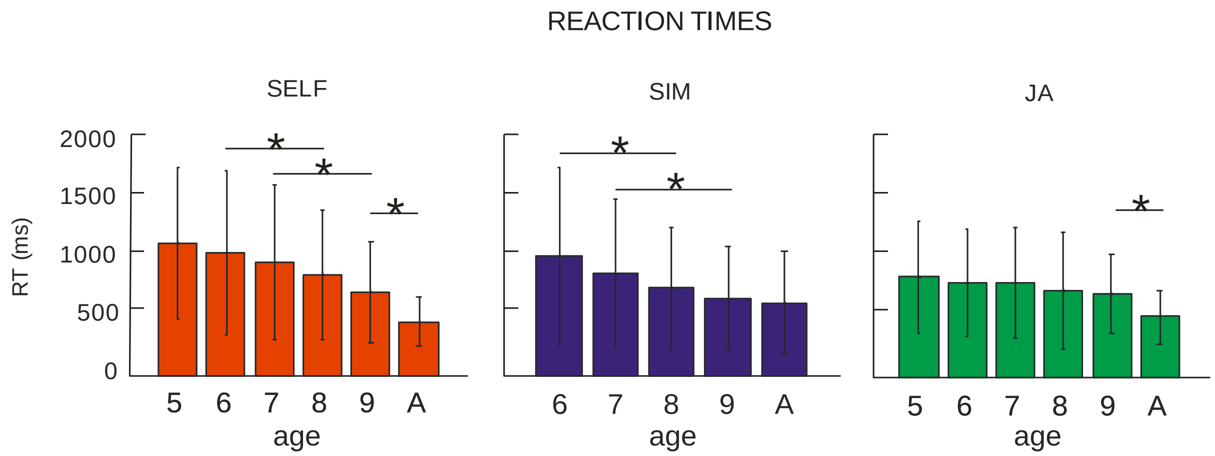

Fig. 7. Mean reaction times (RTs) and standard deviations across ages in each task condition. Small horizontal bars with asterisks indicate statistically significant comparisons.

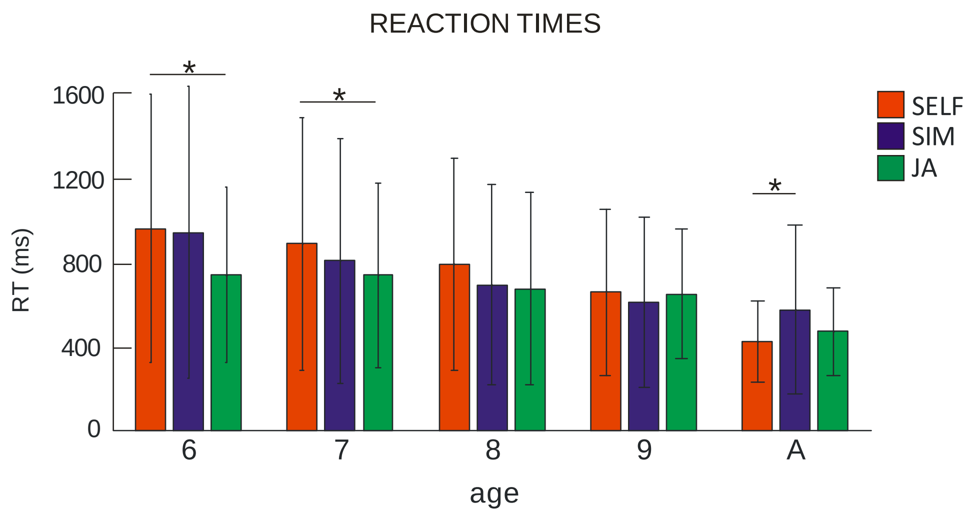

Fig. 8. Two-ways ANOVA for within age comparison of reaction time (RT) across task conditions. At each age the mean RT with standard deviations is shown for each task condition. Small horizontal bars with asterisks indicate statistically significant comparisons.

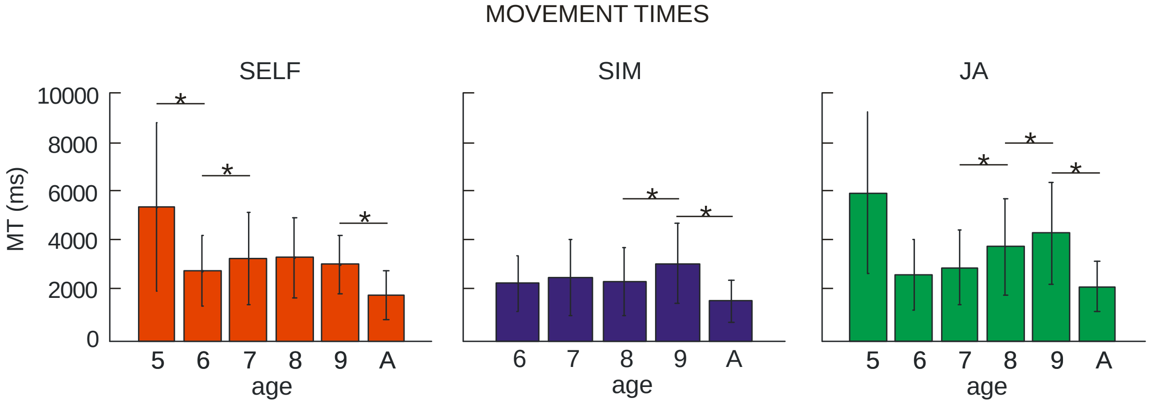

Fig. 9. Mean movement times (MTs) with standard deviations across ages in each task condition. Small horizontal bars with asterisks indicate statistically significant comparisons.

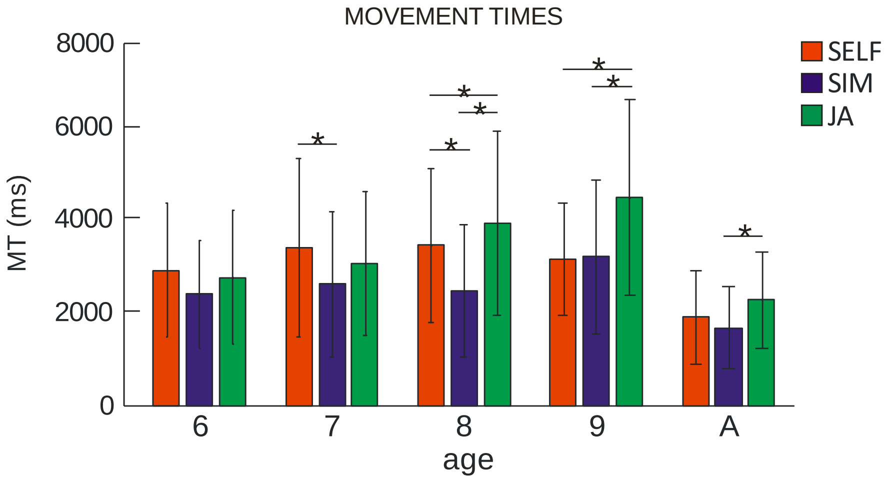

Fig. 10. Two-ways ANOVA for within age comparison of movement time (MT) across task conditions. At each age the mean MT with standard deviations is shown for each task condition. Small horizontal bars with asterisks indicate statistically significant comparisons.

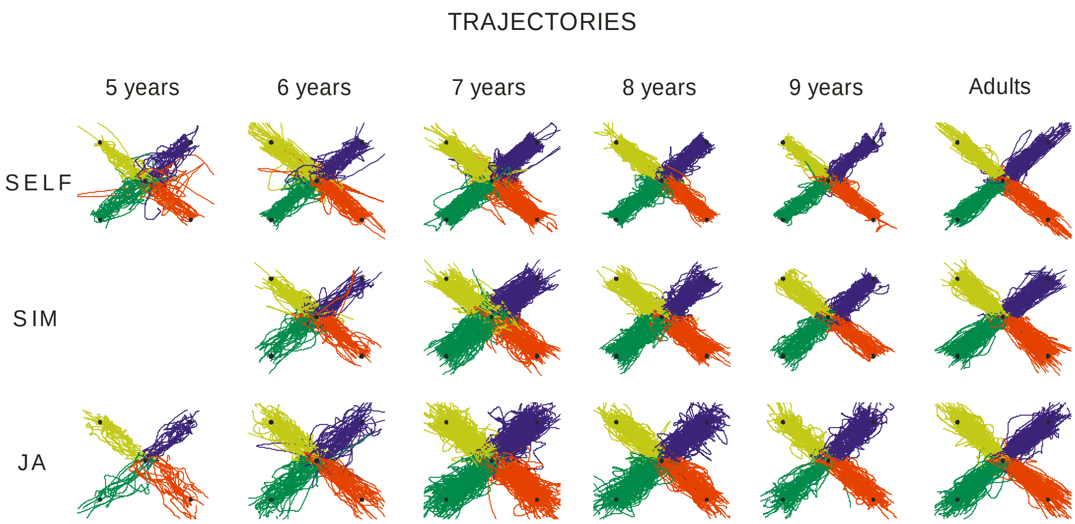

Fig. 11. Row trajectories across ages and tasks.

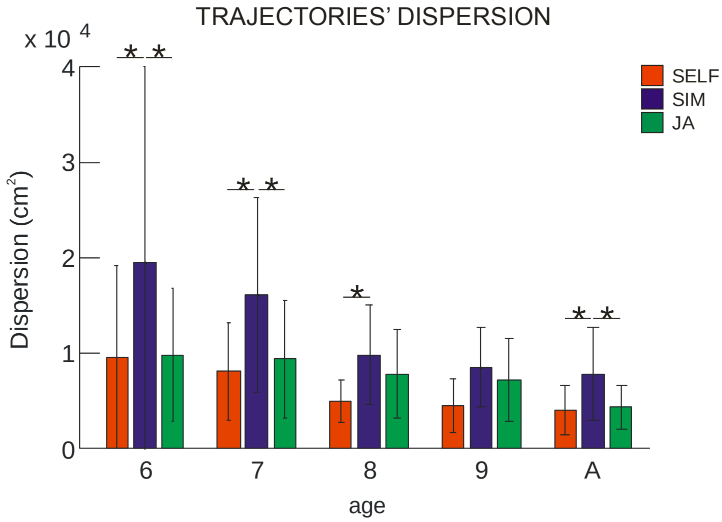

Fig. 12. Mean trajectory dispersion with standard deviations across ages and task conditions. Small horizontal bars with asterisks indicate statistically significant comparisons.

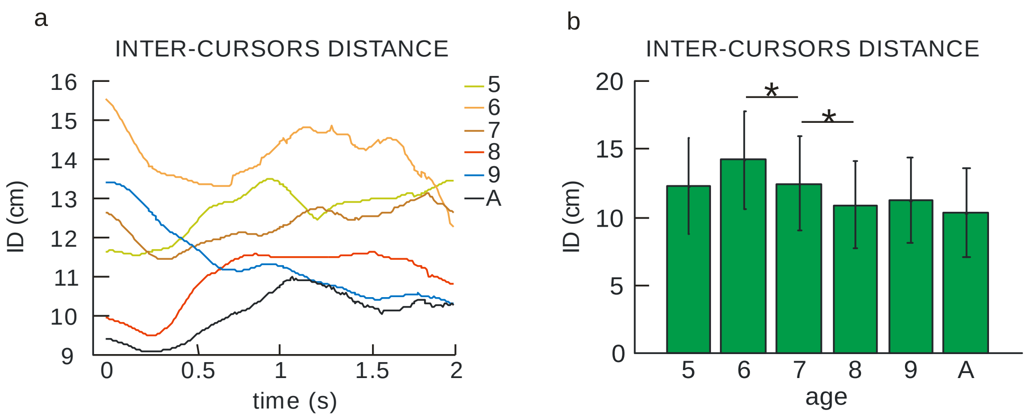

Fig. 13. a) Mean ID with time for the all JA trials across ages. b) Mean ID with standard deviations during the JA condition. Small horizontal bars with asterisks indicate statistically significant comparisons.

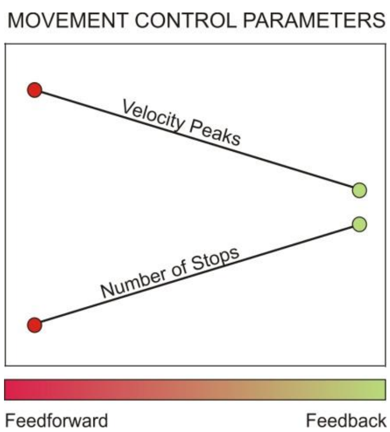

Fig. 14. Schema of a model which explains the relation between the degree of prediction in the control of movement (shifting from feedforward to feedback) and two parameters of the velocity performance: velocity peaks and number of velocity stops.

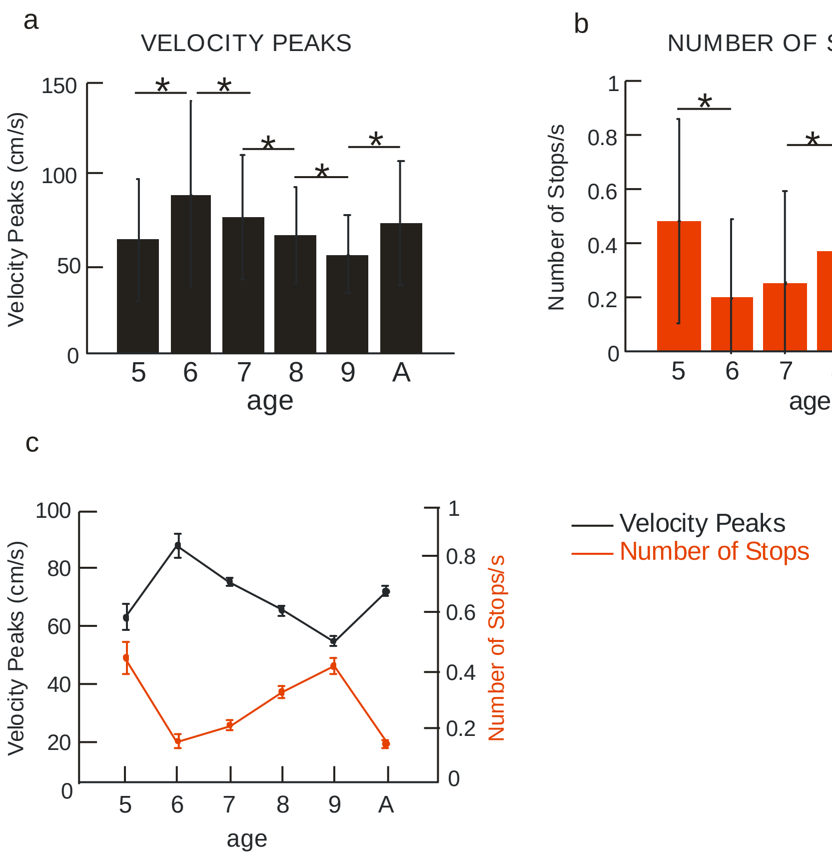

Fig. 15. a) Mean velocity peaks with standard deviations across ages in the JA condition. b) Mean number of velocity stops with standard deviations across ages in the JA condition. Small horizontal bars with asterisks indicate statistically significant comparisons. c) Mean velocity peaks and number of velocity stops with standard errors across ages.

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Acknowledgements

I would like to thank my parents, who sustained and sustain me at any time.

A special thanks goes to Gianluca Carfì, whose careful advices have guided me in the moments of major need.

Thanks to Professor Roberto Caminiti and Professor Alexandra Battaglia-Mayer, for having believed in me, and without whom I would have not had the opportunity to carry on this project.

Thanks also to Simone Ferrari-Toniolo for his ready help in every steps of this project.

Great thanks are to Professor Rosa Isabella Vocaturo, the Headmaster of the school in which this study was conducted, for her willingness and kindness.

Finally, but not less importantly, thanks to the teachers (especially Luisa Furia and Marilena Cantù) who patiently helped me to organize the spaces and times of this work, and to all the children that participated at this experiment with enthusiasm, making it all more joyful.