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Multiple representations and mechanisms for visuomotor adaptation in young children

Pierre-Karim Tahej [a], Carole Ferrel-Chapus [a,*], Isabelle Olivier [b], Dominique Ginhac [c], Jean-Pierre Rolland [a]

[a] *Centre de Recherche sur le Sport et le Mouvement, Université Paris Ouest, Nanterre, France*
[b] *Laboratoire TIMC-IMAG, Université Joseph Fourier, Grenoble, France*
[c] *LE2I, Université de Bourgogne, Dijon, France*

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In this study, we utilized transformed spatial mappings to perturb visuomotor integration in 5-yr-old children and adults. The participants were asked to perform pointing movements under five different conditions of visuomotor rotation (from 0° to 180°), which were designed to reveal explicit vs. implicit representations as well as the mechanisms underlying the visual-motor mapping. Several tests allowed us to separately evaluate sensorimotor (i.e., the dynamic dimension of movement) and cognitive (i.e., the explicit representations of target position and the strategies used by the participants) representations of visuo-proprioceptive distortion. Our results indicate that children do not establish representations in the same manner as adults and that children exhibit multiple visuomotor representations. Sensorimotor representations were relatively precise, presumably due to the recovery of proprioceptive information and efferent copy. Furthermore, a bidirectional mechanism was used to re-map visual and motor spaces. In contrast, cognitive representations were supplied with visual information and followed a unidirectional visual-motor mapping. Therefore, it appears that sensorimotor mechanisms develop before the use of explicit strategies during development, and young children showed impaired visuomotor adaptation when confronted with large distortions.

* Corresponding author. Address: Centre de Recherche sur le Sport et le Mouvement (EA 2931), UFR STAPS, Université Paris Ouest, 92 000 Nanterre, France. Tel.: +33 1 40 97 71 77.

E-mail address: cferrelc@u-paris10.fr (C. Ferrel-Chapus).

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1. Introduction

Studies analyzing the movements of subjects in perturbed visuo-proprioceptive environments enable us to understand the mechanisms whereby the human visuomotor system adapts to new situations during life. In these studies, the mental transformation of visual information regarding hand and target position is necessary to achieve efficient levels of motor performance on the part of the participants. Paillard (2004) proposed that this transformation can occur on several different processing levels, leading to the dissociation of unconscious sensorimotor representations of movement from cognitive (or perceptual) representations.

It has been assumed that these two mechanisms of spatial-information processing (sensorimotor and cognitive) are represented by the dissociation between the dorsal and ventral streams (Milner & Goodale, 2008). The ventral stream refers to "vision for perception" (i.e., mental representations that can reach conscious awareness), whereas the dorsal stream refers to "vision for action" (i.e., processes that do not reach conscious awareness). This dissociation has also been described as the difference between knowing "where is the target" vs. knowing "how to get there", or in other words, positional cues vs. movement execution (Paillard, 1991). However, this dissociation can lead to a dual representation of movement when subjects are confronted with visuomotor rotational paradigms (Boy, Palluel-Germain, Orliaguet, & Coello, 2005). In this study, adult participants were asked to perform pointing movements based on visual information that had been rotated 45° relative to actual arm trajectory, and two tests were administered to evaluate movement dimensions. (1) The Spatial Evaluation test (SE test), which evaluated the spatial dimensions of the response (i.e., "where is the target"). During this test participants were asked to point to their initial hand location and to trace the direction of the movements that they performed. (2) The Movement Reproduction test (MR test), on the other hand, was used to evaluate the dynamic dimensions of the response (i.e., "how to get there"). Subjects were asked to reach for the target presented during the adaptation phase. The results from this study indicated the existence of a dissociation between visuomotor representations - visual information appeared important during the evaluation of the spatial dimension of the response but not during its dynamic dimension.

When confronted with repeated visuo-proprioceptive distortions, adaptation takes place, eventually leading to a resumption of normal levels of performance (i.e., without visuomotor rotation). In addition, Krakauer (2009) showed that when adult participants were informed of a 45° counter-clockwise visual rotation and given a cognitive strategy to counter it, they could not overcome the visuomotor distortion and became progressively worse at hitting the target. Therefore, Krakauer proposed that rotational learning is implicit and is not dependent on explicit strategies. Therefore, the sensorimotor level of information processing appears to be most important in this kind of adaptation.

However, the role of cognitive representations might be more important during childhood than during adulthood. As early as 7 yrs of age, children exhibit a dissociation between cognitive and sensorimotor representations of movement (Rival, Olivier, Ceyte, & Bard, 2004; Rival, Olivier, Ceyte, & Ferrel, 2003). These studies showed that children confronted with Müller-Lyer or Duncker illusions made erroneous perceptual judgments but performed pointing movements toward the illusion accurately (i.e., they had precise sensorimotor representations). When a visual rotational paradigm was used, an effect of children's cognitive level on adaptation was observed. For example, the behavior of children 4-6 yrs of age was perturbed by spatial transformations, such as a vertical display instead of an aligned display, which induced more planning variability in children than in adults (Bo, Contreras-Vidal, Kagerer, & Clark, 2006). Moreover, when confronted with a 180° rotation of a visual scene, 5-yr-old children were more highly affected than either older children or adults, and they showed difficulty integrating visual and proprioceptive information (Ferrel-Chapus, Hay, Olivier, Bard, & Fleury, 2002). This difference in adaptation may result from the fact that 5-yr-old children do not re-align map visual and motor spaces in the same way that adults do. Ferrel, Bard, and Fleury (2001) showed that 5-yr-old children increased the amplitude of errors as visual rotations were increased from 0-180°, which suggests, according to Cunningham (1989), the use of a unidirectional mechanism to realign visual and motor mapping. In contrast, when subjected to visual distortion, adults showed increasing errors from 0-90°, although this decreased from 90-180°. This finding reveals that movement direction in adults is coded via a set of bidirectional axes (i.e., a bidirectional visual-motor mapping), and these large amplitude adaptations imply that adults inverse the polarity of the axes (equal to 180° rotation) and then perform a backward shifts toward smaller angles (Abeele & Bock, 2001). Ferrel et al. (2001) proposed that 5-yr-old children re-map visual and motor spaces differently than adults because of the immaturity of their ability to perform mental rotations. Therefore, young children would be predicted to be unable to utilize efficient cognitive strategies to overcome spatial perturbations.

The present experiments were designed to determine whether the sensorimotor and cognitive levels of action representation differed between young children and adults. We tested the assumption that 5-yr-old children do not use the same sensory information when evaluating the spatial and dynamic dimensions of pointing movements. Participants were subjected to two tests that were based on the protocols reported by Boy et al. (2005) and to two new tests. The first additional test was designed to assess the influence of movement cues on spatial representations. The Spatial Evaluation test (SE test) used by Boy et al. (2005) required participants to reproduce previously performed movements, which could also rely on the "how" system. Thus, in our study, participants were asked, in a third test, to indicate the position of the target without reproducing previously performed movements, a protocol similar to that reported by Paillard (1999) and Paillard, Michel, and Stelmach (1983). A fourth test was performed to evaluate the ability of the children to use explicit strategies to encompass visuomotor perturbation. Krakauer (2009) showed that when adult participants are informed of (or have a perceived) visuo-proprioceptive distortion, they voluntarily aim away from visual targets in order to ensure that the cursor will touch the desired target. We therefore wanted to evaluate whether children have perceived visual distortions and use explicit strategies to overcome them, as adults sometimes do. We hypothesized that sensorimotor representations (assayed using the MR test, which evaluates "how" to reach a target) would be similar in adults and children because they are implicit and develop during early childhood (Rival et al., 2003, 2004). However, according to Ferrel et al. (2001), cognitive representations should differ between adults and children because of differences in the visual-motor mapping that is used, as well as the immaturity of children's ability to perform mental rotations (Estes, 1998). Moreover, children have difficulties representing explicit spatial distortions, which would be predicted to impair their ability to adapt to visual-motor distortion.

2. Materials and methods

2.1. Participants

Eighty 5-yr-old children (25 females and 55 males; mean age = 5.5 ± 0.5 y) and 66 adults (23 females and 43 males; mean age = 21.1 ± 1.1 y) participated in the experiment and were evenly represented in each experimental group. Participants and the parents of the children gave informed consent prior to the experiments. The children had no histories of difficulty in school, and no sensorimotor deficits were mentioned in their school and health reports. It was also verified that they were unable to perform mental rotations, assayed using a reproduction of Estes' (Estes, 1998) experiment. All participants were right-handed and did not have prior experience with virtual displays. These studies were conducted in accordance with the ethical guidelines of the American Psychological Association.

2.2. Experimental setup

Fig. 1 shows a schematic of the experimental setup. A virtual environment was created using the Vizard™ software program. A Cy-visor head mounted display (with a resolution of 800 × 600 pixels) was used to provide a virtual three-dimensional (3D) representation of movements, targets and starting points, which were projected onto a homogeneous blue surface. Participants sat in front of a table and placed their chins on the end of a vertical rod (40-60 cm in height, according to the height of the participant), which was used to help the children bear the weight of the virtual helmet and to avoid head drift due to discomfort. In the virtual environment, participant's hand positions were symbolized by a moveable black cursor (Ø = 8 mm). The target was a white sphere (10 mm in diameter) located 10 cm from the origin (i.e. the starting point) at an angle of 57° from the horizontal. The virtual environment represented the real scene from the point of view of the participant, and the real starting po-

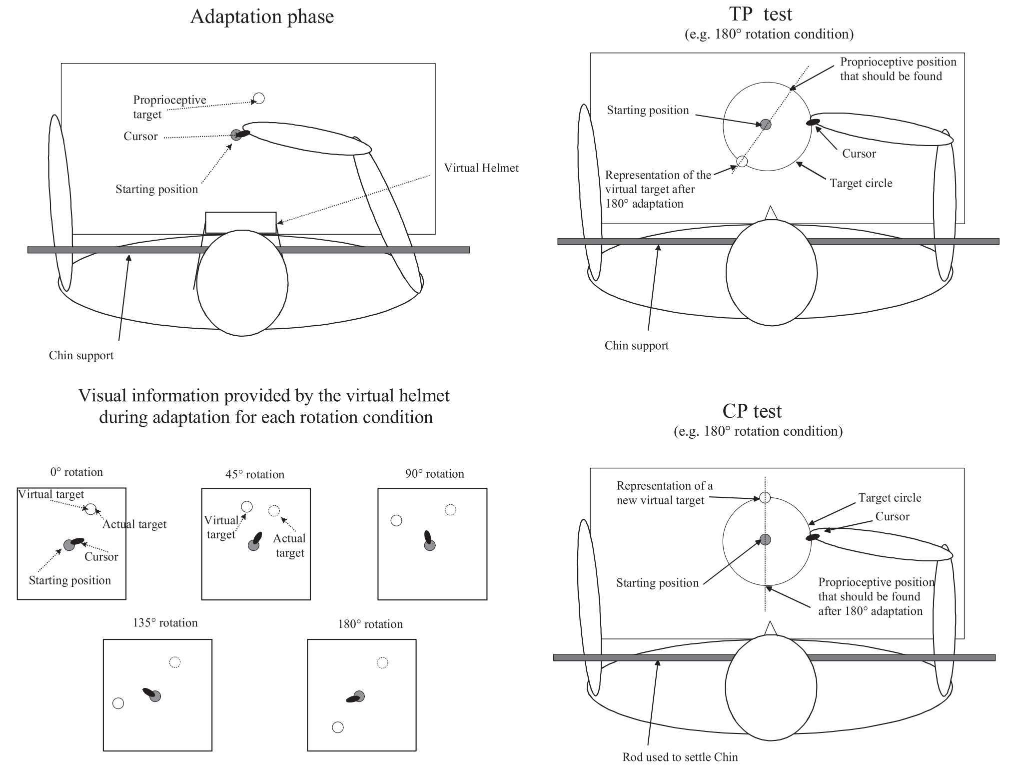

Fig. 1. Overhead schematic representation of the experimental settings. Left: Setup for the adaptation phase and visual information provided by the virtual helmet. Note: the actual target (corresponding to the proprioceptive target) was not visible in the virtual helmet. Right: setup for the Target Position (TP) and Conscious Prediction (CP) Tests after a 180° adaptation.

sition corresponded to the virtual starting position. For the Target Position (TP) and Conscious Prediction (CP) tests, a target circle (with a 10 cm diameter was drawn on the table in order to symbolize target distance. An 8 mm MiniBIRDS magnetic tracker (Ascension Technology Corp) was used to capture cursor coordinates during pointing movements.

2.3. Procedures and experimental conditions

Participants were familiarized with the device (0° rotation) and were divided into five groups corresponding to the five visual rotation conditions (Fig. 1). For all conditions tested, groups were composed of 16 children and 13-14 adults. The experiments began with an adaptation phase, during which participants were asked to perform 10 pointing movements toward the target under different conditions of visual feedback. The control condition (0° rotation) corresponded to normal visuomotor coordination; that is, movements performed in the virtual environment were similar in amplitude and direction to actual movements. Under perturbed conditions, participants were exposed to 45°, 90°, 135° or 180° counter-clockwise rotations of the visual scene. For all conditions, the center of rotation coincided with the starting position, leaving initial hand position unchanged. Trials began upon target appearance. Rotation, which corresponded to the condition of the participant, was introduced at the beginning of a trial and visual feedback (i.e., the virtual cursor) was present until the participant stopped on the target position. Then, the visual scene was frozen, and their hands were moved back by the experimenter to the starting position for the next trial.

Following the final adaptation trial, participants were asked to perform four tests. The first two were performed without visual information and were similar to the tests used by Boy et al. (2005):

1) the Spatial Evaluation test (SE test), during which participants were asked to point to their initial hand location and trace on the table the direction of the movement they performed; and 2) the Movement Reproduction test (MR test), during which participants were asked to reach for the target presented during the adaptation phase, after their fingers being moved back to the starting position by the experimenter. The order of presentation of these two tests was randomized across participants, and the delay between the two evaluation tasks was limited to less than 3 s. Immediately following those two tests, participants were allowed to remove the virtual helmet and could see the starting position and a representation of the virtual target drawn on the table. Then, all participants were asked to perform two more tests. 3) The Target Position test (TP test) was used to answer the question: "where is the target?". Participants were required to use a schematic representation of the virtual situation (Fig. 1, TP test), similar to experiments reported by Paillard (1991). A sheet of paper represented the starting position, the visual target and a target circle line. Participants had to indicate the proprioceptive target position without reproducing the movement they performed, but they did so by following the target circle line with the cursor and stopping at the proprioceptive target position. 4) Finally, the Conscious Prediction test (CP test) was used to evaluate the cognitive strategies of the participants. Krakauer (2009) showed that participants could be instructed to aim for a target rotated 45° clockwise from the desired target in order to correct for visual perturbations. Therefore, we wanted to determine whether the participants had perceived the visual rotation and were able to use deliberate strategies to reach the visual target. To test this (Fig. 1 CP test), a representation of a new virtual target was presented along the sagittal axis. Participants were instructed to trace the target circle and to stop where they thought the proprioceptive target was located.

2.4. Data analysis

x-y Positions of the hand cursor were recorded at 100 Hz (spatial accuracy was within 1.8 mm). Data were then processed using Kikosoft OASIS software and filtered using a second-order Butterworth dual-pass filter (cut-off frequency = 10 Hz). This program analyzed spatial accuracy and kinematic characteristics of the movements, according to Meyer, Abrams, Kornblum, Wright, and Smith's (1988) procedure. Movement onset was defined to be the first moment (after trial initiation) when tangential velocity exceeded 0.4 cm/s for at least 20 ms. Ballistic submovement was considered to be over when the acceleration value of the first subsequent movement crossed zero (changing from negative to positive). The angular error of movement (AE) corresponded (in the Cartesian coordinate system) to the difference in degree between the real direction of the target and the participant's evaluation of target location. During the adaptation phase and the SE or MR tests, error measurements were calculated as the difference between the target direction and the ballistic direction of the movements. Movement was considered to be over when velocity dropped to less than 0.4 cm/s and the hand cursor was immobilized on the target. Movement time (MT) was defined as the time elapsed between the beginning and ending of a movement.

3. Results

3.1. Adaptation

The adaptation data were analyzed using 3-way analyses of variance (ANOVAs) [2 (Age) × 5 (Rotation) × 10 (Trial)] with repeated measures on the last factor. LSD post-hoc corrections were used at a significance level of $p < .5$. Ballistic error results revealed a significant Age × Rotation × Trial interaction, $F(36, 1188) = 1.80$, $p < .001$, which confirmed that mechanisms of adaptation used by children differed from those used by adults. As shown in Fig. 2A, error reduction over multiple trials was similar in adults and children for 0 and 45° rotations. However, children were more perturbed by larger visuomotor rotations, and a significant Age × Trial interaction was observed for 90° rotations, $F(6, 792) = 2.41$, $p < .001$, and 135° rotations, $F(6, 792) = 13.44$, $p < .001$. Adults were able to reduce their ballistic errors over repeated trials (90° rotations: $F(6, 792) = 5.48$, $p < .001$; and 135° rotations: $F(6, 792) = 25.95$, $p < .001$), whereas the children could not. When the visual scene was rotated by 180°,

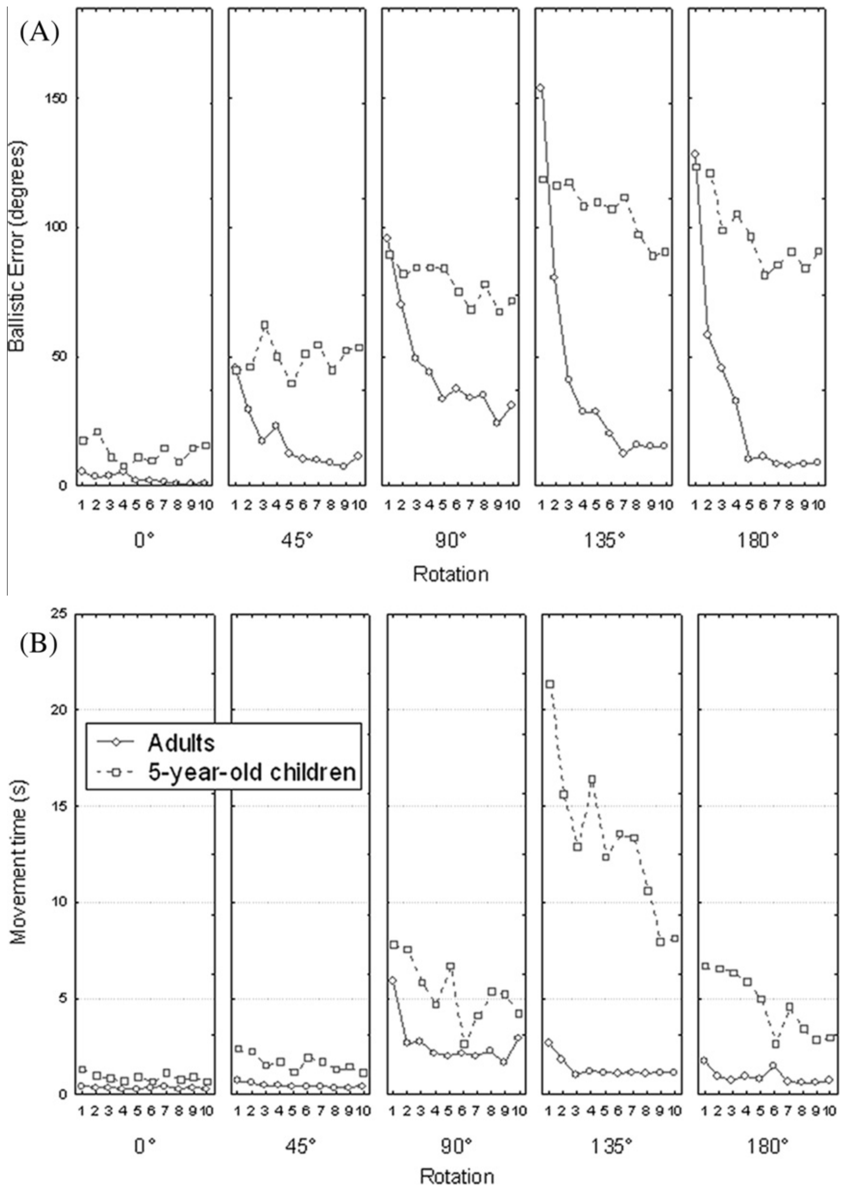

Fig. 2. (A) Angular error of ballistic movement (degrees), and (B) Movement time (seconds) as a function of Adaptation Trial (1 to 10), Age (5-year-old children and adults) and Visuomotor Condition (Rotation of 0°, 45°, 90°,135° and 180°).

both adults and children showed decreased errors over the course repeated aiming movements, $F(6, 792) = 23.94$, $p < .001$, but the adults exhibited a higher rate of adaptation than the children, $F(6, 792) = 2.92$, $p < .001$.

Movement time showed a significant Age × Rotation × Trial interaction, $F(36, 1188) = 1.83$, $p < .001$, which indicates that the children took longer than the adults to overcome visuomotor distortions. As shown in Fig. 2B, movement time reductions across trials differed in adults and 5-yr-old children only for 135° rotations, $F(6, 792) = 4.14$, $p < .001$. Children were more affected by visual rotation

($M = 21.35$, $SD = 1.22$) than adults were ($M = 2.64$, $SD = 1.31$); they quickly reduced the duration of movement execution, although these durations still remained longer than those of the adults, $F(1, 132) = 22.82$, $p < .001$. For the 0° and 45° rotations, movement time did not change across trials, whereas it decreased with repetition for all participants during 90°, $F(6, 792) = 5.39$, $p < .001$, and 180°, $F(9, 1188) = 1.99$, $p < .05$, rotations. Movement time was also longer in children than in adults for the 90°, 135° and 180° rotations.

3.2. Tests

A 3-way ANOVA [2 (Age) × 5 (Rotation) × 4 (Test)] with repeated measures on the last factor was performed on the angular error results. ANOVA analysis revealed a significant interaction between the three factors, $F(12, 357) = 3.43$, $p < .001$, suggesting that children and adults utilized distinct mechanisms of information processing during these trials. As illustrated in Fig. 3, the Rotation × Test interaction was not significant in adults ($F(4, 152) = 0.736$, $p = .72$) and failed to show that sensorimotor and cognitive processing modes used distinct mechanisms of visual-motor mapping. The strategies used by participants were less effective than other spatial or sensorimotor representations, as indicated by the higher errors observed during the CP test compared with the other tests (all contrasts were significant at $p < .05$). The three other tests (besides the CP test) did not have statistically significant differences in their error rates. Consistent with our hypotheses, the children displayed multiple representations of visuomotor integration, $F(12, 357) = 8.97$ $p < .001$). Taking into account the results from all the rotations, the errors of the children were higher during both the CP and TP tests (which had similar errors) compared to the SE and MR tests (which had similar errors). However, the errors caused by 45° rotations were similar during all the tests, and the results failed to show a difference between the SE and MR errors, as previously described by Boy et al. (2005). Moreover, the mechanisms used to re-map visual and motor spaces varied between the tests, as indicated by the Rotation × Test interaction seen in the children, $F(12, 357) = 8.98$, $p < .001$.

Further analyses were performed using 2-way ANOVAs [2 (Age) × 5 (Rotation)] separately applied to each test. To determine the mechanisms of visual-motor mapping (bidirectional vs. unidirectional)

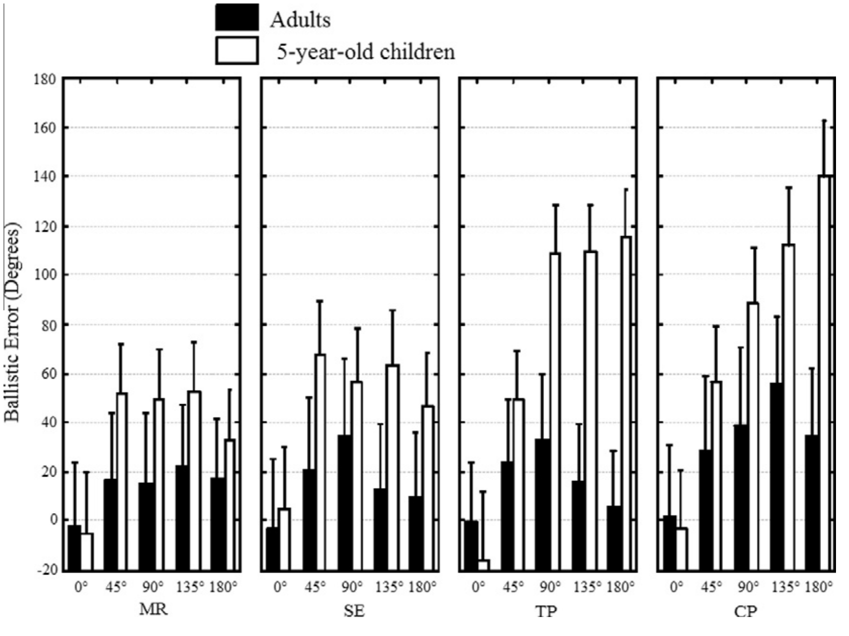

Fig. 3. Angular Error of movement (degrees) as a function of Test [Movement Reproduction (MR), Spatial Evaluation (SE), Target Position (TP) and Conscious Prediction (CP)] and Rotation condition (0°, 45°, 90°,135° and 180°).

used by participants, orthogonal polynomial contrasts were used to test the relationship between angular error and the amplitude of rotation. A significant linear function would correspond to a unidirectional visual-motor mapping, whereas a quadratic function would correspond to a bidirectional visual-motor mapping.

The MR test revealed that children made more errors than adults, $F(1, 136) = 19.15$, $p < .001$), but the Age × Rotation interaction was not significant, $F(4, 136) = 1.69$, $p = .15$. Furthermore, our results indicated that the errors followed both a linear, $F(1, 136) = 11.33$, $p < .001$, and a quadratic function, $F(1, 136) = 26.96$, $p < .001$. The linear and quadratic components represented 29.94% and 71.22% of the rotation variance, respectively, which suggests that the relationship between error and rotation is mostly quadratic. The angular errors observed after all rotations differed from those of the 0° rotation (the contrasts were all significant at $p < .05$), indicating that adults and children were both affected by the visual perturbation.

The SE test showed that children behaved like adults when confronted with visuomotor rotations, $F(4, 136) = 1.38$, $p = .24$, but made more errors, $F(1, 136) = 29.67$, $p < .001$. Orthogonal polynomial contrasts showed both quadratic and linear relationships between angular error and rotation, $F(1, 136) = 23.83$, $p < .001$; and $F(1, 136) = 6.19$, $p < .05$, respectively). The linear and quadratic components represented 19.78% and 76.33% of the rotation variance, respectively, which suggested that the relationship between angular error and rotation was mostly quadratic.

The TP test indicated that the evolution of rotational error was different between children and adults, $F(4, 135) = 14.45$, $p < .001$. For adults, the relationship between error and rotation was quadratic, $F(1, 135) = 5.23$, $p < .05$. Errors in distorted rotations were always greater than the 0° rotational errors, with the exception of 180° rotational errors. For children, the orthogonal polynomial contrasts revealed a linear relationship, $F(1, 135) = 136.68$, $p < .001$. Moreover, errors were similar for 90°, 135° and 180° rotations and significantly greater than those of adults.

The CP test indicated that the evolution of rotational error was different between children and adults, $F(4, 119) = 5.32$, $p < .01$. For adults, errors were always significantly different from the 0° rotational errors, with the exception of 180° rotational errors, and the results indicate a mainly quadratic trend, $F(1, 119) = 4.68$, $p < .005$. Children showed greater errors with increased rotation (the contrasts were all significant at $p < .05$), revealing a linear relationship between error and rotation, $F(1, 119) = 96.50$, $p < .001$. Furthermore, the errors made by children were only significantly greater than errors made by adults for 90°, 135° and 180° rotations.

4. Discussion

This study was designed to determine whether the sensorimotor and cognitive levels of action representation differ between young children and adults. Our ANOVA analyses indicate that a) children perceive visuomotor distortions differently from the way adults do, and b) large spatial perturbations induce multiple representations of movement.

4.1. Sensorimotor representations of movement

Paillard (2004) proposed that humans possess an unconscious sensorimotor representation that describes "how" movements are performed. Using the visuo-proprioceptive rotation paradigm, Boy et al. (2005) performed MR tests to examine the sensorimotor representation and suggested that it utilizes internal and unbiased information. Our results show that MR errors increased both in children and adults (compared to 0° rotations) when visual distortions were introduced. These results suggest that the dynamic dimension of motor responses does not exclusively rely on proprioception and/or an efferent copy but also depends on visual information. Nevertheless, the use of visual information in the evaluation of "how" to reach a target is consistent with the planning-control model of Glover (2004), which suggests that both visual and proprioceptive information are integrated to control movements. It is also in agreement with Milner and Goodale's (2008) suggestion that the ventral stream is used for actions.

Furthermore, despite the fact that children made more errors than adults, none of the Age × Rotation interactions was significant, and the relationship between error and rotation was mainly quadratic. If the participants had used only static proprioceptive information about final hand position to make their judgments, their errors should not vary with the amplitude of visual rotation; on the contrary, the use of visual information would be expected to cause a linear increase in errors. A quadratic function implies that errors increase and decrease with the amplitude of rotation, consistent with a bidirectional visual-motor mapping. Therefore, these data suggest that children and adults are mainly dependent on efferent copy to perceive the dynamic dimension of movement (i.e., "how" movements are performed). Bidirectional visual-motor mapping have been observed in adults (Cunningham, 1989; Ferrel et al., 2001) and are consistent with the "backward shift" hypothesis (Abeele & Bock, 2001). These authors proposed that when confronted with large visuomotor rotations, adults inverse the polarity of the axes (equal to a 180° rotation) and then perform backward shifts toward smaller angles. The appearance of this trend in children was surprising, as previous research has suggested that they use unidirectional visual-motor mapping (Ferrel et al., 2001). This suggests that even though the children exhibited higher movement variability, they possess adult-like mechanisms. Moreover, the results we observed during large rotations suggest that children also use kinesthetic information about hand position to construct their sensorimotor representations. The final adaptation trial errors vs. MR test errors were 71.56° vs. 49.58° (for 90° rotations), 90.27° vs. 52.91° (for 135° rotations) and 90.01° vs. 33.03° (for 180° rotations). Furthermore, ballistic error did not decrease with repeated trials, whereas movement duration did. It is possible that children use on-line proprioceptive corrections more efficiently upon repeated trials of large visuomotor rotations. This hypothesis is consistent with the study of Hay, Bard, Ferrel, Olivier, and Fleury (2005), which showed that 5-yr-old children used on-line proprioceptive feedback when confronted with tendon vibrations. Therefore, children and adults may similarly construct their sensorimotor representations based on efferent copy, kinesthetic information and visual feedback, but children are more likely than adults to rely on visual information for large perturbations (e.g., rotations larger than 90°).

Lastly, the results of the MR and SE tests were similar. As no statistical differences were observed, this suggests that similar processes may be at work during both tests. This assumption is reinforced by the similar quadratic relationships observed between error and rotation in the two tests. Moreover, errors were smaller in the SE test than in the CP test, which is not consistent with explicit mechanisms of visual-motor mapping. The errors that were made by the children caused us to reconsider the assumption that the SE test evaluates the "where" system and the position of target, as proposed by Boy et al. (2005). Instead, it suggested that spatial evaluation relies mainly on kinesthetic movement information and efferent copy. Therefore, our data support the assumption that the SE test does not evaluate the "where" system (i.e., the position of the target). We assume that both the MR and SE tests evaluate sensorimotor representations of movement, which might be implicit. Instructions given to the participants during the MR and SE tests could have induced egocentric- or allocentric-coding of movements, respectively. Nevertheless, the errors of these two modes of coding were similar in our studies because the initial hand position was not visually modified.

4.2. Cognitive representations of movement

The TP and CP tests were designed to determine, respectively, children's conscious representations of target location and the possible strategies they use in order to overcome spatial perturbations. According to Paillard (2004), these tests evaluate cognitive representations of movement (i.e., representations that result from the ventral stream). The results showed that, except for 45° rotations, the errors in both tests were much greater than those observed during the MR and SE tests. These errors were, on average, 111° for the TP test and 113° for the CP test. These data suggest that for visual rotations larger than 45°, 5-yr-old children are unable to explicitly retrieve static proprioceptive information concerning hand position at the end of a trial. Similar results were obtained by Hay et al. (2005), who showed that 5-yr-old children performed poorly when coding hand position. Moreover, 5-yr-old children made more errors than adults during the TP test. This difference is consistent with Kovacs's (2000) suggestion that the ventral visual pathway is not fully developed in young children. We propose that this deficit in the coding of hand position impairs children's representations of visuo-proprioceptive distortion. As a consequence, they were unable to predict the location of new targets, despite having relatively precise sensorimotor representations. Therefore, our results support the hypothesis that children differ from adults and possess multiple representations of visuomotor integration for large visual rotations.

The results from the children also showed that the errors observed during the TP and CP tests followed a linear function, which suggests the utilization of a unidirectional visual-motor mapping. This trend has also been reported in a study by Ferrel et al. (2001) using a video-display device. These tests, which evaluated the explicit representations of the situation, suggest that cognitive representations mainly rely on visual information. Similar results were obtained by Orliaguet (1986) during visuo-proprioceptive conflicts. Their research showed that cognitive difficulties (e.g., giving the answer with a hand different from the hand that was visually perturbed) induce visual capture in 5-yr-old children.

Visual capture, which was not observed in adults, may induce inefficient strategies that prevent adaptation to visuo-proprioceptive distortion. Compared to adults, 5-yr-old children exhibited larger errors and movement durations. Moreover, these differences were especially high during 90° and 135° rotations. This phenomenon has been previously reported by Ferrel et al. (2001), who stated that errors increased when rotations are higher than during 90°. It should be noted that children had difficulty modifying their internal models during 90° and 135° rotations, as revealed by the absence of errors modifications with the repetition of trials. One limitation of our study could be the small number of adaptation trials that were performed. However, the number of trials could not be increased for the large rotation tests because, under these conditions, the time between the beginning of a trial and target acquisition often reached 20 seconds. Towards the end of the experiments, children displayed difficulty maintaining their attention toward the tasks, and we judged that the number of trials could not be extending without exceeding the attentional capacities of the children. We also noted that the errors during the final adaptation trials were higher than during the MR test. This could indicate that children, when confronted by large visuomotor distortions, did not exclusively rely on sensorimotor processes and attempted to use explicit strategies. Moreover, they may use "backward shift" adaptation in the same way that adults do, as children appeared to have less difficulty with 180° rotations, indicating a weak but significant rate of adaptation. This suggests that the 180° rotation is the first type of large-magnitude rotation acquired by children during development. As the sensorimotor representations of movements performed under 180° rotations appear to be more precise than the cognitive representations, it would be interesting to investigate the effectiveness of different methods to increase the rate of visuomotor distortion adaptation. Additional practice trials, performed for several days, could reinforce sensorimotor processes, leading to modification of children's cognitive representations of movement and reduce their usage of inadequate strategies. In addition, it would be interesting to evaluate the effects of explicit strategies, similar to those reported by Krakauer (2009). These strategies were inefficient for adults, but they might be able improve children's explicit representations (taking into account the cognitive difficulties displayed by children for understanding visual distortion) and to accelerate adaptation to visuo-proprioceptive distortion.

In conclusion, our results show that 5-yr-old children possess multiple representations for visuomotor integration. Visual information is important for cognitive representations of movement and children were unable to adequately represent the visual-proprioceptive distortion. Furthermore, our data indicate that children use a unidirectional mechanism of visual-motor mapping, which leads to inefficient strategies to compensate for large visual perturbations. Conversely, their sensorimotor level of processing information was adult-like - they used bidirectional visual-motor mapping and established reasonably efficient sensorimotor representation of movement. Overall, these data suggest that implicit sensorimotor representation matures before explicit spatial representation during development. This result could open a broad field of research concerning the implications of sensorimotor adaptation with respect to improving children's impaired spatial representations. In this way, Rode, Rossetti, and Boison (2001) showed that visuo-proprioceptive distortions induced by prisms improve the representations of adult unilateral neglects, and it is possible that the same mechanisms would be effective for young children. Therefore, we hypothesize that sensorimotor distortions could facilitate the development of spatial mental imagery during childhood. As a consequence, it would be interesting to investigate the relationship between sensorimotor experiences and mental imagery in injured children presenting cerebral palsy or other developmental coordination disorders, who demonstrate impaired spatial representations leading to deficiencies in voluntary action planning (Deconinck, Spitaels, Fias, & Lenoir, 2009; Preobrazhenskaya, Shelyakin, Katysheva, & Bogdanov, 1997).

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