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Developing motor planning over ages

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ABSTRACT

Few studies have explored the development of response selection processes in children in the case of object manipulation. In the current research, we studied the *end-state comfort effect*, the tendency to ensure a comfortable position at the end rather than at the beginning of simple object manipulation tasks. We used two versions of the unimanual bar transport task. In Experiment 1, only 10-year-olds reached the same level of sensitivity to end-state comfort as adults, and 8-year-olds were less efficient than 6-year-olds. In each age group, children's sensitivity did not increase during a session: i.e., either clearly showed the sensitivity or showed no sensitivity at all. Experiment 2 replicated these results when the bar was replaced by a pencil and when the task did not require much precision. However, when the task required more precision, 8-year-olds increased their level of sensitivity to the end-state comfort effect, whereas this was not the case for younger children. These results describe the development of advanced planning processes from 4 to 10 years of age as well as the positive effect of task constraints on the end-state comfort effect for 8-year-olds.

Introduction

Most usual objects we use in the real world can be grasped, a priori, in numerous manners. For example, picking up a pair of scissors could be done by either of the two handles or even by the cutting end. However, depending on the *purpose* of the action, certain types of grasps are more efficient than others. In the case of scissors, to cut a piece of paper we would take the scissors by the two handles,

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whereas we might grab them by the end of the cutters to give them to somebody else who wants to use them to cut some piece of paper. Or, if we want to convey a spoonful of syrup to our mouth, we would grab it overhand, with the right hand and with the thumb pointing down, if the bowl of the cup is pointing to the left. By contrast, we would grab the spoon handle overhand, with the left hand, if its bowl is pointing to the right, or we might grab it underhand, with the right hand and with the thumb in an upward location and the index finger in a downward location, and then rotate the wrist counterclockwise to convey the bowl to the mouth. These examples suggest that, among the many ways an object can be carried, only a subset of them are really comfortable (and, in the examples above, are safe for our shirts or outfits) and that efficient actions require accurate movements. In the motor control literature, determining how a movement or a combination of movements is chosen from the many available possibilities is referred to as the *degrees of freedom problem* (Bernstein, 1967). When a person consistently selects a specific action pattern when many movement options are available, one may infer that this combination of movements was planned in advance with respect to the goal.

One major constraint on movement selection is the *end-state comfort effect* (Cohen & Rosenbaum, 2004; Fischman, 1998; Fischman, Stodden, & Lehman, 2003; Lam, McFee, Chua, & Weeks, 2006; Rosenbaum & Jorgensen, 1992; Rosenbaum, van Heugten, & Caldwell, 1996; Rosenbaum et al., 1990; Weigelt, Kunde, & Prinz, 2006). The effect illustrates the tendency to ensure a comfortable position at the end of manual object manipulation rather than at the beginning when picking up a tool or kitchen utensil. It has also been reported that prehension of a particular object specifically changes as a function of what participants intend to do with it (Marteniuk, MacKensie, Jeannerod, Athenes, & Dugas, 1987; Rosenbaum et al., 1990). A popular task used to investigate this phenomenon is the unimanual bar transport task, in which participants use either an overhand or underhand grip to pick up a bar lying horizontally on supports before placing its left or right end on a flat disk laid on either the left or right of the bar (Fischman, 1998; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Rosenbaum et al., 1990) or placed at different heights (Rosenbaum & Jorgensen, 1992; Short & Cauraugh, 1997). The authors observed that adults spontaneously switched strategies (overhand vs. underhand grip) depending on which end of the bar was to be brought to the target disk. Thus, it appeared that the postures that participants adopted on taking hold of the bar depended on what they planned to do with it because they anticipated their future bodily states. Researchers generally attributed a functional advantage of end-state comfort in the sense that ending in a comfortable posture would maximize control over the fine positioning movements needed during the final phase of the positioning task or would facilitate subsequent movement production. Some researchers observed that adults selected more comfortable end states and thus minimized awkwardness when the precision requirements of the task were greater (Rosenbaum et al., 1990, 1996; Short & Cauraugh, 1999). Rosenbaum and colleagues (1996) also reported that the end-state comfort effect vanished for some participants when the final positioning did not demand precision (see also Rosenbaum, Cohen, Meulenbroek, & Vaughan, 2006, for a review).

There is a large body of literature regarding grip adaptation in the neuropsychological literature (Carey, Harvey, & Milner, 1996; Dijkerman, Milner, & Carey, 1998; Goodale, Milner, Jakobson, & Carey, 1991) and in the developmental psychology literature. For example, Newman, Atkinson, and Braddick (2001) combined preferential reaching, preferential looking, and kinematic measures to study the development of infants' adaptation to the size of an object while reaching it. The results revealed that between 8.5 and 12 months of age, children developed sensitivity to the size of objects; they preferred to reach for graspable objects even though these were visually less salient than larger objects. According to the authors, these results would suggest an emerging ability to override the initial strong coupling between eye and hand movements (see Gauthier & Mussa-Ivaldi, 1988).

Recently, some authors have used the end-state comfort effect to study the planning of manual movement of infants and children (Adalbjornsson, Fischman, & Rudisill, 2008; Manoel & Moreira, 2005; McCarty, Clifton, & Collard, 1999, 2001). However, they observed inconsistent results. For example, Manoel and Moreira (2005) studied the sensitivity to end-state comfort of 2.5- to 6-year-olds in low- and high-precision tasks. Children needed to pick up a wooden bar and insert one of its distal parts into a hole in a box either cylindrical (low-precision condition) or semicylindrical (high-precision condition). They exhibited little evidence of end-state comfort or advanced planning ability in that study regardless of the precision required. Rather, the way they picked up the bar indicated strong preference for start-state comfort, suggesting that planning is restricted for grasping. Similar results were reported by Adalbjornsson and colleagues (2008) with children of similar ages to those in Manoel and Moreira's (2005) experiment. The task was to pick up an overturned glass, turn it right side up, and pour water from a pitcher into the glass. The use of an awkward thumb-down posture to grasp the glass was taken as evidence of sensitivity to end-state comfort. The authors reported that only 11 of the 40 children exhibited the end-state comfort effect, showing little evidence of advanced planning ability between 2.5 and 6 years of age. Contrasting results were reported by McCarty and colleagues (1999, 2001), who studied 9- to 24-month-olds as they used "tools" such as a spoon, a hairbrush, a toy hammer, and a magnet. For the spoon, the results revealed a strong tendency to use the preferred hand when it was on the same side as the handle (i.e., easy trials), that is, the radial ("correct") grip. When the handle was on the other side as the preferred hand, 9- and 14-month-olds chose only 30 to 35% of radial ("correct") grips. As for the hand choice, not until 19 months of age did a majority of children use the hand that was on the other side as the handle of the spoon. Thus, only 19-month-olds could inhibit their tendency to reach the spoon with their preferred hand when the other hand was preferable to complete the task in a comfortable end state. Using a different task, Achard and von Hofsten (2002) observed a similar trend during the same age period. Infants needed to retrieve food either through a slit or in the absence of the slit, at monthly intervals, from 12 to 17 months of age. Results showed that even the younger children could adapt their movement to the slit and its orientations, that is, to new task constraints. In a similar way, Örnkloo and von Hofsten (2007) examined 14- to 26-month-olds' understanding of the spatial relationships between objects with different shapes and holes in which the objects can fit. The authors showed that the greatest improvement in the number of successful insertions took place at 22 months of age, that is, when children showed significant preadjustments of object orientation. According to the authors, this required the infants to be able to mentally rotate the object. Thus, on the one hand, there is strong evidence of motor anticipation during infancy; on the other hand, 6-year-olds did not show evidence of sensitivity to end-state comfort.

With respect to sensitivity to the end-state comfort effect, to date no study has explored the age at which children exhibit sensitivity to end-state comfort similar to the one found in adults. For that purpose, children's behavioral changes over age would reveal the development of advanced planning processes to achieve a goal. Thus, the aim of the current study was to explore the end-state comfort effect in 4- to 10-year-olds and in adults as a control group (Experiment 1) in a bar transport task as well as the effect of the increasing demand for precision in subsequent actions on advance movement preparation (Experiment 2). In this latter case, children needed to pick up a pencil lying horizontally on two supports and use it to either make a dot or line on a sheet of paper (low-precision task) or draw a line between two parallel close black lines (high-precision task). We expected that (a) the sensitivity to end-state comfort would increase with age to reach the adults' sensitivity (Experiment 1) and (b) the sensitivity to end-state comfort would be higher in the high-precision task, especially among older children for whom efficient planning capacities were expected (Experiment 2).

Experiment 1 also considered behavioral variability across trials and microlearning during an experimental session. McCarty and colleagues (1999) observed within-participant variability for the nondominant response that was used on some trials. The authors (see also Siegler, 2007) stressed the importance of variability in learning and development that allows children to determine the strategy that gives the best results. In our case, each session was composed of 20 trials. The variability training view would predict more correct trials at the end of a 20-trial session than at the beginning in the most difficult case, that is, the underhand grip. From the results above and this variability hypothesis, we would expect a shift to take place between two ages, with a large majority of participants selecting the comfortable end state at one age and a majority of participants choosing the comfortable start state at the previous age. We have no a priori hypothesis about the comfortable end state stage, but previous experiments and informal observations suggest that it would appear after 6 years of age. A maturational perspective would predict such a shift between start comfort and end comfort after 6 years. On the other hand, a learning view might predict more within-participant variability, the sign of children's propensity to test new solutions. Both views are compatible with the idea that performance should increase with age. The learning view is more compatible with the presence of microlearning during the experiment view than the maturational view that predicts stable performance across trials.

Experiment 1

Method

Participants

A total of 120 right-handed children were tested, 30 for each age group (equally divided among girls and boys): 4-year-olds (*M* = 4.4 years, *SD* = 3.3 months), 6-year-olds (*M* = 6.3 years, *SD* = 3.1 months), 8-year-olds (*M* = 8.4 years, *SD* = 3.1 months), and 10 year-olds (*M* = 10.4 years, *SD* = 2.6 months). Informed consent was obtained from their parents. Children had no motor impairment. Because we wanted to avoid any interaction with children's knowledge of the terms *left hand* and *right hand* or, more generally, any interaction with laterality development, we asked for children whose dominant hand was the right hand. However, we systematically controlled for handedness by asking children to grab several objects before the experiment and by asking them whether they always used the identified dominant hand to grab objects. A control group of 20 adults (10 men and 10 women, *M* = 32.6 years, *SD* = 4.9 years) also performed the experiment but was not included in the analysis because all of the participants followed the end-state comfort effect (see Rosenbaum et al., 1990, for similar results and discussion).

Material

Fig. 1 shows the apparatus adapted from Rosenbaum and colleagues (1990). It was composed of a wooden bar that was 20 cm long, 1.5 cm in diameter, and weighed approximately 40 g. Both ends were colored for a length of approximately 4 cm, one in blue and the other one in red. The bar rested on two supports 14 cm apart so that the two ends of the bar did not stick out beyond the external edge of the supports. When it was laid on the supports, the bottom edge of the bar was 7 cm above the table

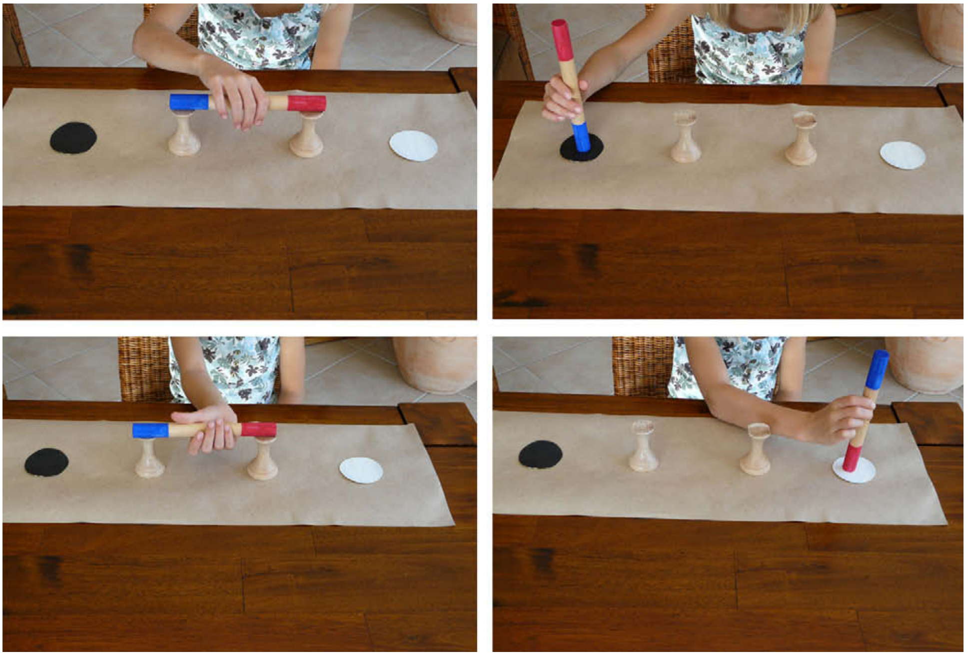

Fig. 1. Apparatus used in Experiment 1. The bar with red (on the left from the children's perspective) and blue (on the right) ends and the white and black target disks are represented. Overhand (top left photo) and underhand (bottom left photo) grips toward the experimental array are illustrated, as is the final state (photos on the right). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

so that children could pick it up easily without touching the table with their hand. The experimenter put a flat disk, 6 cm in diameter, on each side of the supports, a white disk on the left side and a black disk on the right side. The midpoint of each disk was approximately 12 cm from the nearest support.

Procedure

Once children were seated next to or on the other side of the table, in front of the experimenter, the experimenter described the device and the task. The experimenter pointed to the color of each end of the bar and the two colored disks. Children were told that they would need to grab the bar firmly and that they would need to place one end of the bar (the color of which was specified on each trial) on either the white or black disk so that the bar would stand up vertically by itself on the end of the bar that the experimenter mentioned. At the beginning of the experiment, children were asked to put their hands on their knees, the left hand on the left knee and the right hand on the right knee. All of the children were asked to use the bar with the right hand only (remember that all children were right-handed) and to leave the left hand on the knee. They were told to avoid bar manipulation after its grasp.

This instruction was repeated during the experiment when necessary. At the beginning of each trial, the blue end of the bar was always on the right and the red end was always on the left from the children's perspective. There were four types of trials: blue end of the bar on the white disk, blue end on the black disk, red end on the white disk, and red end on the black disk. A block consisted of these four types of trials that were presented randomly. There were five blocks for a total of 20 trials. It took children 10 to 15 min to complete the task with no time pressure. As reported by Rosenbaum and colleagues (1990), adults always followed the end-state comfort effect: they picked up the bar with an underhand grip when they needed to place the left red end of the bar on either the white or black disk, and they picked up the bar with an overhand grip when they needed to place the right blue end of the bar on either the white or black disk.

Results

Percentage of success

The main dependent variable was the percentage of grips that were consistent with end-state comfort: *overhand* grips when the right blue end of the bar needed to be placed on either the white or black disk and *underhand* grips when the left red end of the bar needed to be placed on either the white or black disk. A grip was scored as overhand when children grasped the bar thumb pointing down and then moved the bar using this grip. A grip was scored as underhand when children grasped the bar thumb pointing up and then moved the bar using this grip (see Fig. 1). Thus, only the position of the hand at the start of the movement mattered. There were cases where the underhand grip was consistent with end-state comfort and where children picked up the bar with an overhand grip and then changed their grip to an underhand grip during the course of their movement. These cases were scored as overhand grips. The data[1] were analyzed in a 4 (Age: 4, 6, 8, or 10 years) × 5 (Block: 1, 2, 3, 4, or 5) × 2 (Grasp: overhand or underhand) analysis of variance (ANOVA) with repeated measures on the last two variables.

The ANOVA revealed significant main effects of age (*M*s = 42, 66, 49, and 81% of consistent with end-state comfort grips for 4-, 6-, 8-, and 10-year-olds, respectively), $F(3, 116) = 6.60$, $MSE = 0.43$, $p < .001$, $\eta_p^2 = .15$, and grasp (*M*s = 93 and 60% of consistent with end-state comfort grips for the overhand and underhand grasps, respectively), $F(1, 116) = 78.78$, $MSE = 0.41$, $p < .001$, $\eta_p^2 = .40$, as well as a significant Age × Grasp interaction, $F(3, 116) = 4.69$, $MSE = 0.41$, $p < .005$, $\eta_p^2 = .11$. The breakdown of the interaction (Tukey's test [see Fig. 2]) revealed that for the 4-, 6-, and 8-year-old groups, the percentage of grips consistent with end-state comfort was lower for underhand grasps than for overhand grasps ($p < .05$). For underhand grasps, 6- and 10-year-olds had higher scores than 4- and 8-year-olds ($p < .001$), whereas 10-year-olds were better than 6-year-olds ($p < .025$). There was no effect of age on

[1] Because of the initial binomial distribution of data, percentages of success were normalized by an arcsine transformation. Results of the ANOVAs were similar for both transformed and untransformed data.

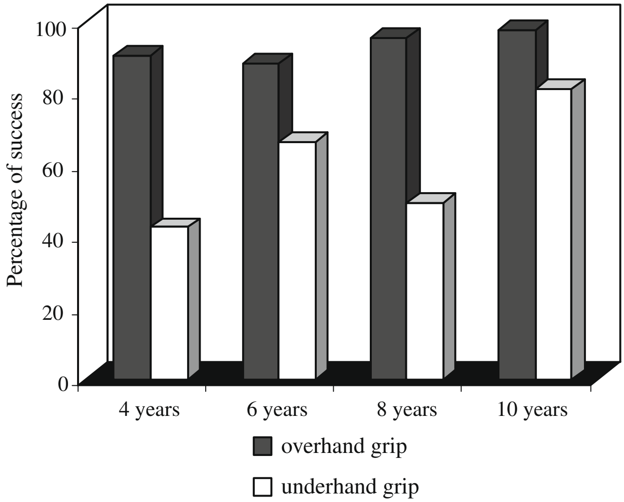

Fig. 2. Percentages of trials consistent with end-state comfort for overhand and underhand grips as a function of age in Experiment 1.

overhand grasps. A subsequent polynomial analysis revealed that the cubic trend was significant for the underhand grasps, $F(1, 116) = 8.14$, $p < .01$, which is consistent with the lower results obtained by 8-year-olds compared with 6- and 10-year-olds.

Interestingly, there was no main effect of block and no interaction involving this factor. This result means that children's performance did not develop during the experiment. Indeed, higher scores in the last block would mean that children progressively adjusted themselves to the specific constraints of the task during the experiment. Our data are not consistent with such a progressive adjustment view.

We also characterized children's stability across trials. For each child, we assessed whether he or she had a dominant pattern of grips on the trials that requested underhand grips. Each child was then classified into one of the following four categories: 0–20%, 20–50%, 50–80%, or 80–100%; for example, 0–20% meant that the child used the underhand grip in 0 to 20% of the 20 trials. The purpose of this measure was to calculate the percentages of children who fall into the extreme patterns of behavior, that is, 80–100% and 0–20%. A high percentage in one of these extreme regions would mean that children keep the same strategy across trials. Results are illustrated in Fig. 3.

The results are clear-cut and show that, in each age group, most children are either very good ($\geqslant$80% of correct underhand grips, i.e., 0, 1, or 2 errors in 10 trials) or very poor ($\leqslant$20% of correct underhand grips, i.e., 8, 9, or 10 errors in 10 trials). Thus, the percentage of children who fall in between is low in each of the age groups: 17% at 4 and 8 years, 23% at 6 years, and 20% at 10 years. This result suggests that in a particular age group, most children follow the comfortable end state or the comfortable start state but do not test the two strategies from one trial to another. More generally, the result also shows that in each age group there is a high percentage of children who follow one of the two strategies. As shown by Fig. 3, this is particularly clear for the 4- and 8-year-olds.

Discussion

Our results show that most children used the overhand grip when it was consistent with end-state comfort, that is, with the easy trials. On the other hand, only 10-year-olds displayed a large majority of underhand grips when it coincided with end-state comfort; this was not the case for younger children. Before 10 years of age, children always used the overhand grip when it was more comfortable, but they also used this grip when the underhand grip would have been more consistent with end-state

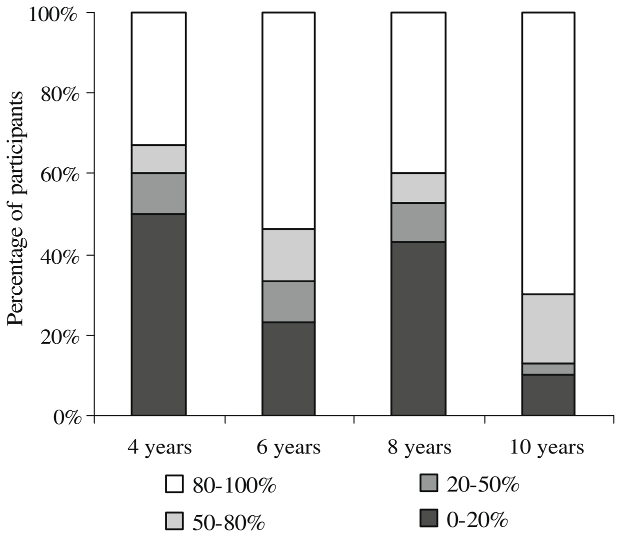

Fig. 3. Percentages of children who used correct underhand grips in 0–20%, 20–50%, 50–80%, and 80–100% of trials.

comfort. In other words, as observed previously by other authors, the default procedure for children seems to be the overhand grip. Thus, here we discuss the underhand grip case (when it coincides with end-state comfort). One surprising result, at first glance, is the developmental pattern for underhand grips, with 6-year-olds being better than 8-year-olds, which was confirmed by the polynomial contrasts. We return to this result later in Experiment 2 and in the General Discussion.

The analysis of individual patterns revealed that children's performance, in each age group, was clear-cut; either children clearly failed to choose the underhand grip or they clearly succeeded. This is consistent with the idea that children whose performance was not perfect and thus had some room for improvement (i.e., 4-, 6-, and 8-year-olds) did not test both strategies during the experiment. Indeed, testing both strategies would have resulted in a higher percentage of performance between 20 and 80%. In a related way, there was no evidence of improvement during the task; children's performance did not increase across blocks, showing that children did not adapt their behavior when they gained more expertise with the task.

These results are surprising because, for what might appear to be a simple task, the developmental range is very broad in the sense that once a significant percentage of participants used underhand grips to comply with the end-state comfort effect, there was still a significant percentage of children who failed several years later. Overall, our pattern of results is not compatible with a strict maturational or learning account of development. A simple maturational account would predict a linear developmental trend and a narrower window of development. A learning account would also predict the same result but with more evidence of testing different strategies across trials. The purpose of Experiment 2 was to replicate these results with a slightly different task and to examine the development of children's planning as a function of task constraints in the same age groups as in Experiment 1.

Experiment 2

Experiment 1 relied on a task that might have been lacking functional meaning for children. Maybe the task was not very familiar and/or not very interesting for them. This might have resulted in a lack of involvement, especially for the younger children. Note, however, that this lack of functional meaning would not explain the decrease in performance observed in 8-year-olds. In the second experiment, we designed three tasks that were expected to be more meaningful for children. We used a wooden pencil rather than the wooden stick. Our purpose was to replicate Experiment 1 in different functional contexts and to see whether we would obtain the same developmental pattern. Manoel and Moreira (2005) studied children ranging from 2.5 to 6 years of age in two precision conditions. Their task was quite similar to the one used in our first experiment except that children needed to insert one end of the bar into a hole in a box. In the high-precision version of the task, the ends of the bar and hole were semicylindrical so that the insertion was more difficult unless the children planned their initial grasp in advance. In both conditions, little evidence of end-state comfort was obtained at any age regardless of the precision required. In our pencil case, the first task was a *pointing-with-pencil* task in which children needed to grasp a pencil and make a dot on a sheet of paper. In the second task, the *tracing-with-pencil* task, children needed to trace a line on a sheet of paper. The line was not part of a larger drawing so that tracing was not constrained. In the third task, the *pencil alley* task, children needed to trace a line with a pencil in an alley without crossing the edges defining that alley. In contrast to the second task, the third task was much more spatially constrained. The general purpose of the experiment was to assess the developmental pattern in three tasks that differ in their motor requirements. Of particular interest was the 8-year-old group's performance, especially in the pencil alley task that requires dynamic organization of the motor behavior over several seconds.

There are many studies on the development of drawing abilities (see Lange-Küttner & Vinter, 2008, for an overview). For example, Vinter and Marot (2007) discussed the development of the strategies used by children in their drawings and how children are affected by various factors at different ages. The authors mentioned that 5-year-olds copied figures as a series of individual independent segments, whereas older children depicted the patterns they needed to copy as whole figures made up of a series of individual shapes (see also Vinter, Picard, & Fernandes, 2008). However, the authors did not consider lower levels of description such as the grips involved in drawings. By contrast, Braswell and Rosengren (2008) reviewed biomechanical and cognitive constraints involved in children's drawings and particularly the development of grip configurations. We did not focus on these constraints per se. Rather, we studied whether children's grips would be influenced by the end-state comfort effect; that is, we were interested in what happens before drawing starts.

Method

Participants

A total of 80 right-handed children (see Experiment 1) were tested, 20 for each age group (equally divided among girls and boys): 4-year-olds (M = 4.5 years, SD = 2.9 months), 6-year-olds (M = 6.5 years, SD = 4.0 months), 8-year-olds (M = 8.4 years, SD = 2.9 months), and 10-year-olds (M = 10.5 years,

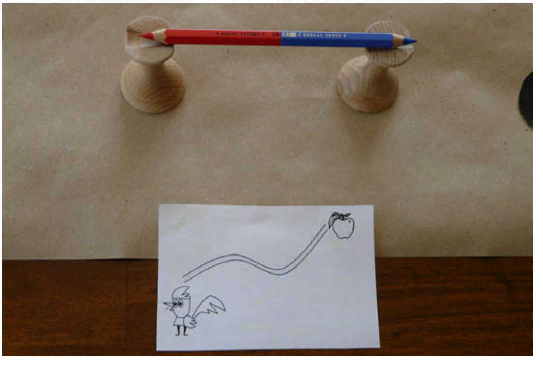

Fig. 4. Apparatus used in Experiment 2. The two-colored (red and blue) wooden pencil is represented, as is the sheet of paper (for the pencil alley task) placed ahead of the support. In the pointing-with-pencil and tracing-with-pencil tasks, we used a white sheet of paper. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

SD = 3.4 months). Informed consent was obtained from their parents. Children had no motor impairment and did not participate in Experiment 1.

Material

The apparatus, adapted from Rosenbaum and colleagues (1990), was similar to the one used in Experiment 1 except that the bar was replaced by a wooden pencil that was sharpened on both ends and was 17 cm long, 1.2 cm in diameter, and weighed 33 g. One half of the pencil was colored in blue, and the other half was colored in red. The pencil rested on the same two supports as in Experiment 1 that were put 12 cm apart. The two ends of the pencil did not stick out beyond the edges of the support. The experimenter put a sheet of paper (15 × 10 cm) 12 cm ahead of the support (Fig. 4). In the three conditions, the sheet of paper had the same size and was located in the same place, between children and the stimulus.

Procedure

Children were seated next to the experimenter, who described to them the experimental apparatus and task. The experimenter mentioned the pencil, the color of each of its ends, and the sheet of paper. Children were told that they needed to perform three tasks presented in a random order. In the pointing-with-pencil task, children needed to take the pencil and make a dot on the sheet of paper. In the tracing-with-pencil task, children needed to take the pencil and were asked to trace a line segment without any additional constraint. The instructions were to "take the pencil and draw a line with the blue [or red] end." In the pencil alley task, a rooster was depicted in the bottom left corner of the sheet, and an apple was depicted in the top right corner. The rooster and apple were connected by a sinuous alley (approximately 10 cm in length) composed of two edges 4 mm apart. Children were told that they would need to take the pencil and trace a line going from the rooster to the apple with the additional constraint that they should not cross the edges of the alley with the pencil (see Vicari et al., 2005, for a similar task).

For the three tasks, at the beginning of each trial, the blue end was always on the right and the red end was always on the left for children. There were two types of trials: tracing with the blue end and tracing with the red end. For each task, each trial was presented two times in a random order. It took children 10 to 15 min to complete the three tasks. There was no time pressure to achieve any of the tasks.

Results

Percentage of success analysis

We computed the mean percentages of overhand and underhand grips when they ended in a comfortable orientation. In this experiment, participants did use palmar grips or other types of grips. Among others, they used the mature standard tripod grasp in which the object is held between the thumb and the first two fingers. The proportion of tripod grasps increased with age (see Braswell & Rosengren, 2008; Braswell, Rosengren, & Peirroutsakos, 2007). A grip was scored as overhand when children grasped the pencil thumb down and forefinger up. A grip was scored as underhand when children grasped the pencil thumb up and forefinger down. It was the position of the fingers at the start of the movement that mattered. Note that in both experiments the side of the wrist (ventral of dorsal) that is up is a perfect cue to the type of grasp. There were also cases where the underhand grip was consistent with end-state comfort and where children first picked the pencil with an overhand grip and then changed their grip to an underhand grip during the course of their movement. This was particularly the case for the younger children, who often started with a palmar overhand grip. These cases were scored as overhand grips because children modified their grip during the movement. As mentioned above, we focused on children's grip at the very onset of the movement and did not differentiate the strategies that were followed right after the grip (see McCarty et al., 1999 for a description of planning strategies after the grip). These percentages of success[2] were submitted to a 4 (Age: 4,

[2] See Note 1.

6, 8, or 10 years) × 3 (Task: pointing-with-pencil, tracing-with-pencil, or pencil alley) × 2 (Grasp: overhand or underhand) ANOVA with repeated measures on the last two variables.

The analysis revealed significant main effects for age (*M*s = 71, 85, 79, and 95% of grips consistent with end-state comfort for 4-, 6-, 8-, and 10-year-olds, respectively), $F(3, 76) = 6.84$, $MSE = 0.17$, $p < .001$, $\eta_p^2 = .21$, for grasp (*M*s = 97 and 67% of grips that are consistent with end-state comfort for the overhand and underhand conditions, respectively), $F(3, 76) = 64.31$, $MSE = 0.16$, $p < .001$, $\eta_p^2 = .04$, and for task (*M*s = 80, 81, and 86% of grips that are consistent with end-state comfort for the pointing-with-pencil, tracing-with-pencil, and pencil alley tasks, respectively), $F(2, 152) = 3.08$, $MSE = 0.05$, $p < .05$, $\eta_p^2 = .46$. A significant Age × Grasp interaction, $F(3, 76) = 8.15$, $MSE = 0.16$, $p < .001$, $\eta_p^2 = .24$, was also observed. There was a marginally significant Age × Grasp × Task interaction, $F(6, 152) = 1.89$, $MSE = 0.05$, $p = .08$, $\eta_p^2 = .07$ (see Fig. 5).

Because we were interested in the developmental profile of each task, we performed separate Age × Grasp ANOVAs on each task. Significant Age × Grasp interactions appeared in the pointing-with-pencil task, $F(3, 76) = 3.74$, $MSE = 0.10$, $p < .025$, $\eta_p^2 = .20$, in the tracing-with-pencil task, $F(3, 76) = 4.39$, $MSE = 0.10$, $p < .01$, $\eta_p^2 = .14$, and in the pencil alley task, $F(3, 76) = 6.84$, $MSE = 0.08$, $p < .001$, $\eta_p^2 = .21$. A posteriori tests on these interactions (Tukey's test) in the pointing-with-pencil and tracing-with-pencil tasks revealed results that were similar to the ones reported in the first experiment. The percentage of underhand grasps was lower for 8-year-olds than for 6-year-olds ($p < .01$) (Fig. 5, top panels). By contrast, this decrease in performance observed for 8-year-olds disappeared in the pencil alley task (Fig. 5, bottom panel), where their performance fell in between the 6- and the 10-year-olds' performance. Subsequent polynomial analyses on the three tasks revealed that the cubic trend was significant for the underhand grasps in the pointing-with-pencil task, $F(1, 76) = 10.29$, $p < .005$, and in the tracing task, $F(1, 76) = 5.37$, $p < .05$, whereas this trend was not sig-

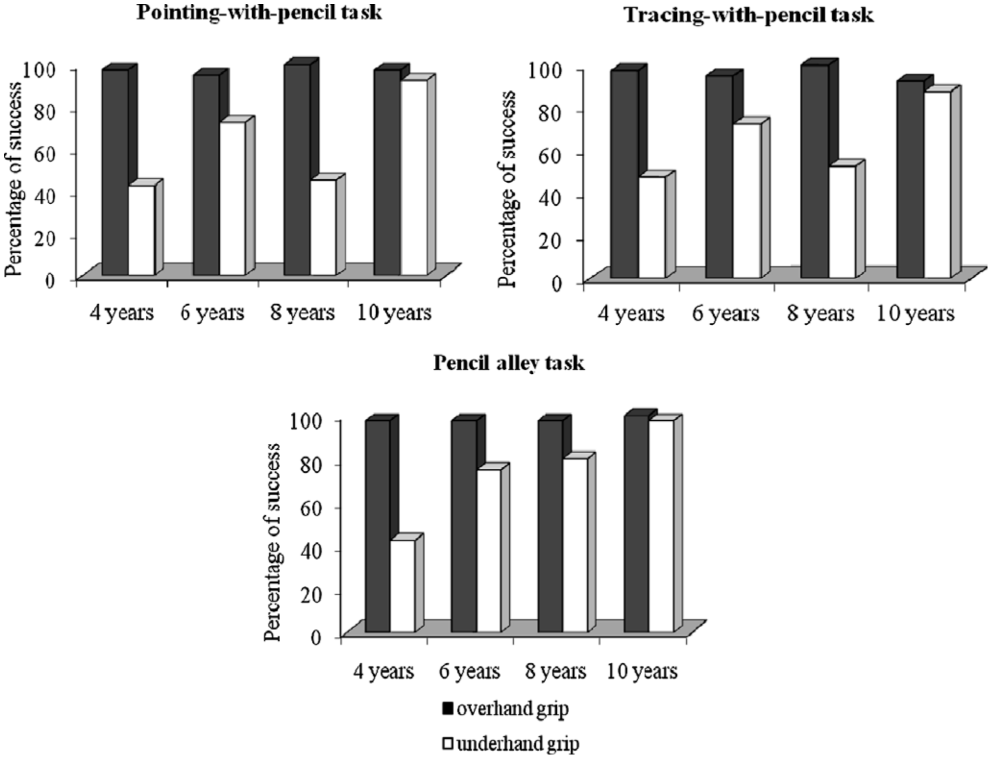

Fig. 5. Percentages of success for both overhand and underhand grips as a function of age for each task.

nificant in the pencil alley task, $F(1, 76) = 1.18$, $p > .05$. Finally, note again that children's performance for the overhand grips was virtually perfect for all age groups.

We also calculated a consistency measure for these data. Because there were only two underhand trials in each task, we could not use the same measure as in Experiment 1. For each task, we computed the number of participants who succeeded on both underhand trials or failed on both underhand trials. A majority of children in each age group and in each task were highly consistent on each of the three tasks, with the percentages of consistency varying between 85 and 95%; for example, 85% meant that the corresponding age group would have failed or succeeded on the two trials defining a task 85% of the time, whereas children chose an overhand grip for one trial and an underhand grip for the other trial in the remaining 15% of trials.

Discussion

The pointing-with-pencil and tracing-with-pencil tasks replicated the results obtained in Experiment 1, with the same developmental pattern. The vast majority of 10-year-olds used underhand grips when it was compatible with end-state comfort, but this was not the case for younger children. In these two tasks, 8-year-olds' performance was lower than 6-year-olds' performance. By contrast, the pencil alley task did not reveal this decrease in performance for 8-year-olds.

As in Experiment 1, children's performance was highly consistent in the three age groups; that is, children either failed on both underhand trials defining a task or succeeded on both trials.

Finally, in the pencil alley task, in contrast to the other two tasks, the 8-year-old group obtained better results that the 6-year-old group. This suggests that a more constraining task could elicit better anticipation in this group. We discuss this discrepancy between the pencil alley task and the two other tasks for 8-year-olds next in the General Discussion.

General discussion

In two experiments, right-handed 4-, 6-, 8-, and 10-year-olds were asked to grip either a wooden bar or a wooden pencil with their dominant hand to perform a goal-directed behavior. The central issue was whether their grasp would be driven by start-state comfort or end-state comfort in two different tasks. Both tasks provided a similar pattern of results.

The first important result is that it was not until 10 years of age that a vast majority of children displayed the end-state comfort effect that has been described for adults (Rosenbaum et al., 2006). To the best of our knowledge, these are the first experiments depicting the developmental course of the end-state comfort effect. Before 10 years of age, a large proportion of children chose the overhand grip (thumb down) when the underhand grip (thumb up) made the end state more comfortable. However, younger children's planning was not random given that they also never chose the underhand grip when the overhand grip was more comfortable.

A second important finding concerns children's grip consistency. Experiment 1 showed that when the underhand grip was more comfortable, children younger than 10 years of age chose either the overhand grip or the underhand grip on the majority of trials (albeit less often than older children) but did not mix the two grips across trials. Experiment 2 confirmed this result with a different measure across the three tasks.

The third important result was the contrast in 8-year-olds between the pencil alley task in Experiment 2 and the performance obtained in Experiment 1 and the pointing-with-pencil and tracing-with-pencil tasks in Experiment 2. In the latter cases, 8-year-olds' performance was lower than 6-year-olds' performance, whereas in the pencil alley task their performance was better than 6-year-olds' performance. We discuss these three results in turn.

Developmental span

We compared more age groups than have been compared in previous studies. This allowed us to reveal a more complete developmental pattern for the end-state comfort effect. The vast majority of 10-year-olds, more than 80% in Experiment 1 and 90% in Experiment 2, exhibited the end-state comfort effect. On the other hand, for the younger age groups, our data are consistent with previous studies. Manoel and Moreira (2005) showed that 2.5- to 6-year-olds exhibited little evidence of end-state comfort or advanced planning ability regardless of the precision required. Adalbjornsson and colleagues (2008) reported the same results with children of similar ages. Interestingly, the authors reported that only 11 of the 40 children exhibited the end-state comfort effect, suggesting that at these ages only a minority of children planned their behavior in terms of the end state. Our data confirm this point, showing that fewer than 42% of the youngest children displayed the end-state comfort effect. Both experiments show that the overhand grip is the default procedure used by most children before 10 years of age regardless of the nature of the end-state comfort requirements. However, the developmental pattern revealed by our data does not mean that younger children fail to produce motor anticipations in *any* situation requesting it. As mentioned in the Introduction, studies by von Hofsten and colleagues (Achard & von Hofsten, 2002; Örnkloo & von Hofsten, 2007) and McCarty and colleagues (1999, 2001) revealed children's anticipation capacities.

Grip consistency

Children's grasps were consistent within each task in both experiments in the sense that children either succeeded or failed in the great majority of trials. We believe that this absence of within-participant variability is not consistent with McCarty and colleagues' (1999) proposal that nondominant responses would reflect children's testing of the strategy that gives the best results. By contrast, our data show that most children are stuck on the same solution for a particular task. However, it might be argued that variability increases only when children are shifting from one dominant strategy to a new one. In our case, there may be a point where variability increases somewhere between 9 and 10 years of age. One difficulty with this view is that there was a large proportion of 4-, 6-, and 8-year-olds who consistently followed the end-state comfort effect. Another possibility would be that variability increases before children shift to the end-state comfort strategy and that this can take place at different ages. Our experiments were not devised to test this hypothesis. However, because a majority of children used only one strategy in our experiments, the only thing we can say is that there is no strong evidence of increased variability at any age for our particular tasks.

Motor reorganization in 8-year-olds

A third important result was 8-year-olds' difficulties with most of the tasks (but not the most constrained one, i.e., the pencil alley task) in comparison with 6-year-olds' better performance. Our data are compatible with other observations of a reorganization of planning strategies taking place at this age in other areas of goal-directed movements. For example, Bard, Hay, and Fleury (1990) showed that 8-year-olds moved a lever more slowly and with less accuracy than 6-year-olds. According to the authors, this demonstrates that 8-year-olds need more feedback control than the other age groups. Meulenbroek and Van Galen (1988) described reorganization processes in writing. The authors observed, between 8 and 9 years of age, a decrease in the speed of writing together with an increase of writing dysfluency (i.e., gestures are less fluid than in younger and older ages). The interpretation is in terms of the explicit control of writing quality. In trying to improve their writing quality, children of this age rely more on visual cues that they probably fail to integrate with all of the motor aspects. By contrast, younger children do not try to integrate visual cues, and older children have integrated the aspects of motor complexity of cursive graphemes that lead to an improved writing quality (see also Ferrel, Bard, & Fleury, 2001; Pellizzer & Hauert, 1996; Lange-Küttner, 2009, who described the emergence of sensitivity to spatial constraints in 9-year-olds). Other reorganization processes also take place around the same age in drawing. For example, Lange-Küttner (2009) showed that 9-year-olds also appear to show sensitivity to spatial constraints in the sense that, considering area and spatial boundaries in a pictorial space, this group of children seems to use a unidimensional learning system, whereas 7-year-olds use a multidimensional learning system.

In our case, by definition, children needed to plan the end state so as to adapt the onset of the movement (see Rosenbaum et al., 2006). Compared with 6-year-olds, 8-year-olds were less influenced by the end state in the less constraining tasks (i.e., the pointing-with-pencil and tracing-with-pencil tasks), whereas they outperformed younger children in the more constraining task (i.e., the pencil alley task).

By analogy with previous contributions showing a pattern of reorganization at 8 years of age, it might be that 8-year-olds did also try to integrate more cues than 6-year-olds. Because this integration is not straightforward, it leads to many errors, whereas younger children who use fewer cues have less difficulty. For the pencil alley task, in which 8-year-olds were much more successful than in the other two tasks, it might be that the constraints that must be fulfilled to perform the task are clearer; the affordance of the task might make clear that a high(er) level of precision is required. This greater precision might have led children to analyze the task more effectively and/or to take more time to analyze it, resulting in a better integration of cues. If 8-year-olds need more cues to accomplish the task, a clear perception of its constraints might afford some sort of anticipated feedback that can be projected on movement planning. By contrast, tracing a line or pointing does not afford the same level of required precision. When the task affords no real constraints, or when the end state requires less precision or does not afford a set of clearly perceivable constraints, this would mean that feedback is less available. In fact, it might be that in most tasks where some precision is requested, 8-year-olds would show more end-state comfort effects than younger participants. Otherwise, they do not engage in a complete analysis of the task and could not integrate all of the information available. In a recent study (Thibaut, Vinter, & Toussaint, 2009), children needed to manipulate tools that required a high level of precision to be used correctly. In all of these cases, 8-year-olds outperformed 6-year-olds. The 8-year-olds' results in the less constrained tasks mirror adults' results in tasks where the end state did not require precision (see Rosenbaum et al., 1996).

To summarize, we believe that a significant number of younger children (4- and 6-year-olds) succeeded in the task they needed to perform because they reduced each task to a number of properties that were sufficient to perform the task, whereas others tended to map cues that were not correctly related to the end-state comfort effect. The 8-year-olds did consider more cues than the older children but failed to integrate them into advanced planning processes. The 10-year-olds could use and integrate all of the cues used by the adults to comply with the end-state comfort effect. Hence, the course of development would be that young children more efficiently use subsets of cues that allow a significant number of them to perform the task. There is a reorganization at 8 years of age, leading to the integration of more cues beyond 8 years.

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