

## Sequential Pointing in Children and Adults

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The development of visuomotor control in sequential pointing was investigated in 6- to 10-year-old children and in adults. In 3 experiments we manipulated task difficulty by changing the number, the size, and the spacing of the targets in the sequences. In Experiment 4, only 1 movement was required; we varied independently the distance between targets and the distance of the starting point from the participant's body. Children's temporal and spatial parameters of the motor sequences showed large age-dependent trends, but did not reach the adult values. Comparison of performance across levels of difficulty and ages suggests that motor development is not a uniform fine-tuning of stable strategies. Instead, we argue that each stage of development is best characterized by the set of strategic components potentially available at that stage, and by the (age-dependent) rules for the selection of components in a given context. © 2000 Academic Press

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Reaching manually for a perceived object is a basic sensorimotor skill that emerges very early in infancy (Hofsten, 1980, 1982; Hofsten & Rönnqvist, 1993; Konczak, Borutta, Topka, & Dichgans, 1995; Meer, Weel, & Lee, 1995). The transport phase toward the target is usually followed by a final approach phase under visual guidance; in many real-life situations, it is also followed by the

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action of grasping and retrieving the object. These components may overlap and interact (Jeannerod, 1984; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1990). However, the transport phase is sufficiently autonomous to merit independent investigation. Indeed, the reason for many of the existing studies of visuomanual pointing is the belief that the mechanisms for planning and executing the transport phase in such a simple task also come into play in behaviorally more meaningful situations.

Recent evidence (e.g., Flanders, Tillery, & Soechting, 1992) suggests that vision specifies the position of spatial targets within an extrinsic system of coordinates centered either on the trunk or on the head. In contrast, hand position is determined by arm posture, that is, by the set of joint angles at the wrist, elbow, and shoulder which, collectively, represent an intrinsic frame of reference. Therefore, pointing to a visual target involves at least two strategic processes: establishing a mapping between two heterogeneous representations of a spatial location and choosing one among the infinite postures compatible with the desired final hand position (Feldman, 1995).

In principle, to reach several targets in sequence, one may simply iterate the strategy used for a single movement, and this is what is likely to happen when the sequence is executed slowly. At fast rates of execution, the step-by-step approach is progressively abandoned in favor of a more holistic strategy, in which more than one step is prepared in advance and executed without correction for the intervening errors (Bock & Arnold, 1993; Hauert, Deiber, & Sevino, 1996). The amount of look-ahead, which depends on the spatiotemporal constraints of the task, affects both the initial latency (Bock & Arnold, 1992) and the movement times (Burton, 1987).

It has been argued that useful insights into the programming of visually guided movements can be obtained by investigation of their development in the course of childhood, at a time when the underlying control strategies are being developed and are therefore more identifiable. Experiments involving simple aiming tasks, as well as more complex tasks, such as alternate pointing or visuomanual tracking, have shown that several aspects of the motor performance evolve in a nonmonotonic fashion during childhood (Burton, 1987; Fayet, Minet, & Schepens, 1993; Hay, 1978, 1979; Hofsten & Rösblad, 1988; Mounoud, Viviani, Hauert, & Guyon, 1985; Rösblad, 1997). Such nonmonotonic trends support the notion that development entails the progressive integration of diverse mechanisms and strategies.

The focus here is on aiming hand movements. Hay (1978, 1979) reported that when the task is performed in open-loop conditions (i.e., when visual information is available only prior to movement onset), spatial accuracy levels off (or even decreases) around age 7. According to Hay, this remarkable developmental discontinuity reflects a transition between differing modes of motor control. The kinematics of the movements suggest that, before age 7, children predominantly adopt a ballistic mode of control (Brooks, 1974), in which movements are

triggered visually and completed without further monitoring. At age 7, they begin to integrate proprioceptive information for online control of the movement. Hay argues that performance drops at this stage of development because children have not yet mastered this more complex strategy and that later improvements toward adult proficiency reflect the increasing ability to make online monitoring automatic.

Other authors have challenged this specific interpretation because they were unable to reproduce the alleged predominance of the ballistic mode in 5-year-olds in comparison with older children (Schellekens, Kalverboer, & Scholten, 1984; Pellizzer & Hauert, 1996). Pellizzer and Hauert (1996) argued that the drop in accuracy between 7 and 8 years reflects a reorganization of the sensorimotor mapping associated to cortical maturation and that it occurs only in open-loop conditions. This view is in keeping with the results of a study of sequential pointing in which the targets remained visible throughout the movement (Burton, 1987). Indeed, comparison between 7-year-olds and adults revealed a monotonic decrease in movement times. Also, the movement time for a given step of the sequence did not increase with the total number of steps, suggesting that the amount of online programming and feedback processing does not change from age 7 onward.

The conditions under which the development of visuomanual coordination departs from a steady trend, and the factors implicated in these departures, are still controversial. The purpose of our study is to show that developmental discontinuities emerge even for sequences of aimed movements toward visible targets. With a case series of 6- to 10-year-old children and of adults, we conducted four types of experiments (three main, one control). Differences in experiment type consisted in variations of a basic paradigm in which participants are required to point sequentially to a set of visual targets. Experiment 1 investigated the complexity of the *motor planning* required by the task by varying the number of steps in the sequence. Experiment 2 controlled the degree of difficulty in the *execution* of a sequence of pointings by varying the relative size of the targets with respect to their distance (Fitts, 1954; Fitts & Peterson, 1964). Experiment 3 examined the movement-planning phase, and the extent to which such planning depends on the regularity of the movement steps in the sequence; accordingly, the experiment varied said regularity. Experiment 4, the control, was a simple pointing task.

## EXPERIMENT 1

The aim of this experiment was to evaluate the effect of the number of targets included in the sequence. To assess the contribution of biomechanical factors to the temporal organization of the movement, the experiment required participants to perform the pointing task along both a sagittal and a transversal axis.

### Method

*Participants.* Fifty boys divided into five equal age groups (6, 7, 8, 9, and 10 years) and 10 male adults (mean age = 32 years) volunteered for the experiment. Only male individuals were tested because sex factor matching would have required too large a population sample. The children's birthdays fell within a 6-month interval centered on the day of the testing. All participants were right-handed (Bryden's, 1977, score > .6), and had normal, or corrected-to-normal, vision. The children were attending various schools in the Canton of Geneva, and had unremarkable school curricula. Permission to enroll the participants for the experiment was obtained from the Department of Public Instruction of the Canton of Geneva.

*Material and stimuli.* The recording device was a  $60 \times 30$ -cm metal table connected to a 12-bit analog-to-digital converter. Touching the table surface with a bare finger transmitted to the converter the 50-Hz electromagnetic background of the laboratory (from the power line) picked up by the participant's body. Sampling (50 Hz) this signal provided a 20-ms-accuracy measure of contact times. Six plastic rings (radius: 2 cm) were aligned on the long axis of the table, the distance between the centers of the rings being 10 cm. The first ring defined the starting point; the other five defined the targets. A 0.3-cm yellow light-emitting diode (LED) was mounted 0.5 cm to the left of each target. Targets were identified by paper labels of different colors glued close to the LEDs. On each trial, the participant identified both the starting position and all the targets to be reached by turning on the appropriate LEDs. The starting-point LED was controlled by computer, and remained on until the participant had positioned the finger. The target LEDs were turned on by the experimenter (see later), and remained on until the end of the movement. Participants sat in front of the experimental apparatus on an adjustable seat, with the right elbow flexed at approximately  $90^\circ$ . In the *sagittal condition*, the long side of the recording table was aligned with the midsagittal axis of the participant. In the *transversal condition*, the table was turned  $90^\circ$  toward the right hemisphere of the participant. In both cases, the starting point was positioned 10 cm from the participant's chest, along his midsagittal axis. The experiment was run in a quiet room, in dim light.

*Procedure.* For each participant, the sagittal and transversal conditions were tested in two sessions separated by 1 week at the most. After allowing the participant to adapt to the experimental setting, the experimenter gave oral instructions and two practice trials for each sequence. In all experiments, trials were paced by the experimenter. Trials began with the participant's right forefinger on the initial position. The experimenter lit the targets to be reached, and the participant identified them by sequential naming of the color of the corresponding labels. After a high-pitched warning signal, and a 200-ms "Go" signal with a random delay (200–500 ms), the participant had to point to and touch successively, as fast as possible, all the indicated targets in the indicated spatial

TABLE 1

Experiment 1: Statistical Effects of Age (6–10 Years), Sequence (S1–S5), and Orientation (Sagittal–Transversal) on the Temporal Parameters (TR, TM1–TM5, and TP1–TP4)

Variable	Factor	<i>df</i>	<i>F</i>	<i>p</i>
RT (S1–S5)	Age (A)	4,45	7.81	<.001
	Sequence (S)	4,42	24.00	<.001
MT1 (S1–S5)	Age	4,45	8.47	<.001
	Orientation	1,45	5.40	<.026
PT1 (S2–S5)	Age	4,45	3.91	<.009
	Orientation	1,45	7.94	<.008
MT2 (S2–S5)	Age	4,45	18.95	<.001
	Sequence	3,43	3.88	<.016
PT2 (S3–S5)	Age	4,45	5.46	<.002
	Orientation	1,45	8.52	<.006
	A × S	8,90	2.84	<.008
	O × S	2,90	4.66	<.013
	A × O × S	8,90	2.59	<.015
MT3 (S3–S5)	Age	4,45	19.87	<.001
	Sequence	2,90	14.59	<.001
PT3 (S4–S5)	Age	4,45	7.50	<.001
	Sequence	1,45	6.24	<.017
MT4 (S4–S5)	Age	4,45	16.45	<.001
PT4 (S5)	Age	4,45	7.89	<.001
MT5 (S5)	Age	4,45	22.48	<.001
	Orientation	1,45	10.12	<.004
	A × O	4,45	7.55	<.001

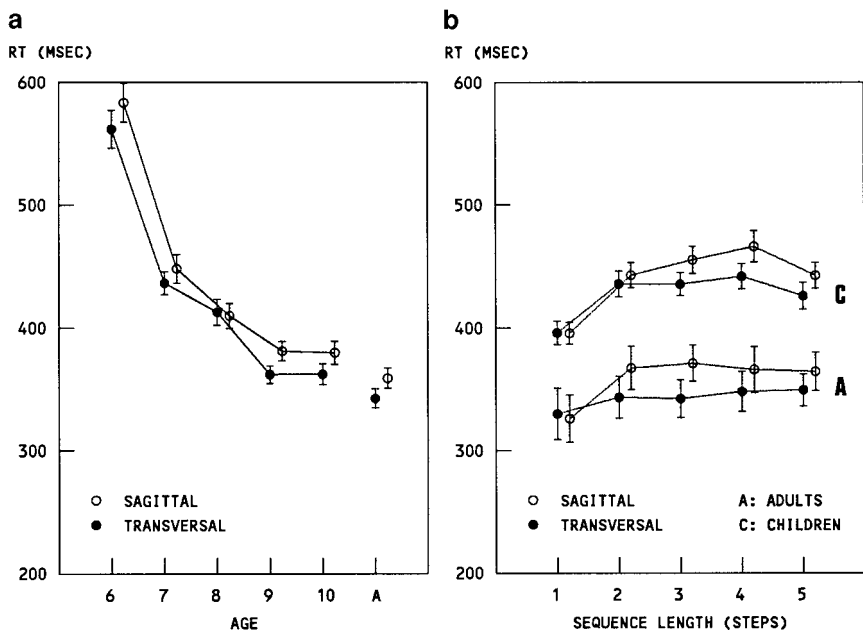
*Note.* The number of levels for the factor sequence varied for each temporal parameter (e.g., for MT3, the factor sequence included only three levels; for MT1, the same factor included five levels). For brevity, only the highest number of levels is indicated.

sequence. The number of targets varied from one to five (S1 to S5). Successive targets were contiguous, so that each movement step had the same size. Ten repetitions of each sequence were administered in a random order. The order in which conditions were assigned to sessions was counterbalanced across participants.

The following measures were taken: (1) the interval between the onset of the “Go” signal and the beginning of the movement sequence (reaction time: RT), (2) the interval between the moment the finger left a target (or the starting point) and the moment it reached the next target (movement time: MT (MT1 to MT5)), and (3) the time spent on each target (pause time: PT (PT1 to PT4)).

*Results and Discussion*

For all experiments, statistical analyses were carried out on individual means computed over all repetitions for each combination of factors. Children and adult data were analyzed separately. Table 1 reports the statistical analysis for children



**FIG. 1.** Reaction times in Experiment 1. (a) RT averaged across sequence length as a function of age (A: adults). (b) RT averaged across ages for children (C) and RT for adults (A) as a function of sequence length. Bars encompass two standard deviations of the mean.

of the temporal parameters of the performance (RT, MT, and PT; three-way ANOVA with repeated measures, 5 (ages)  $\times$  5 (sequence lengths)  $\times$  2 (orientations)). The analysis of adult data (two-way ANOVA with repeated measures, 5 (sequence lengths)  $\times$  2 (orientations)) revealed significant effects only for RT and MT1.

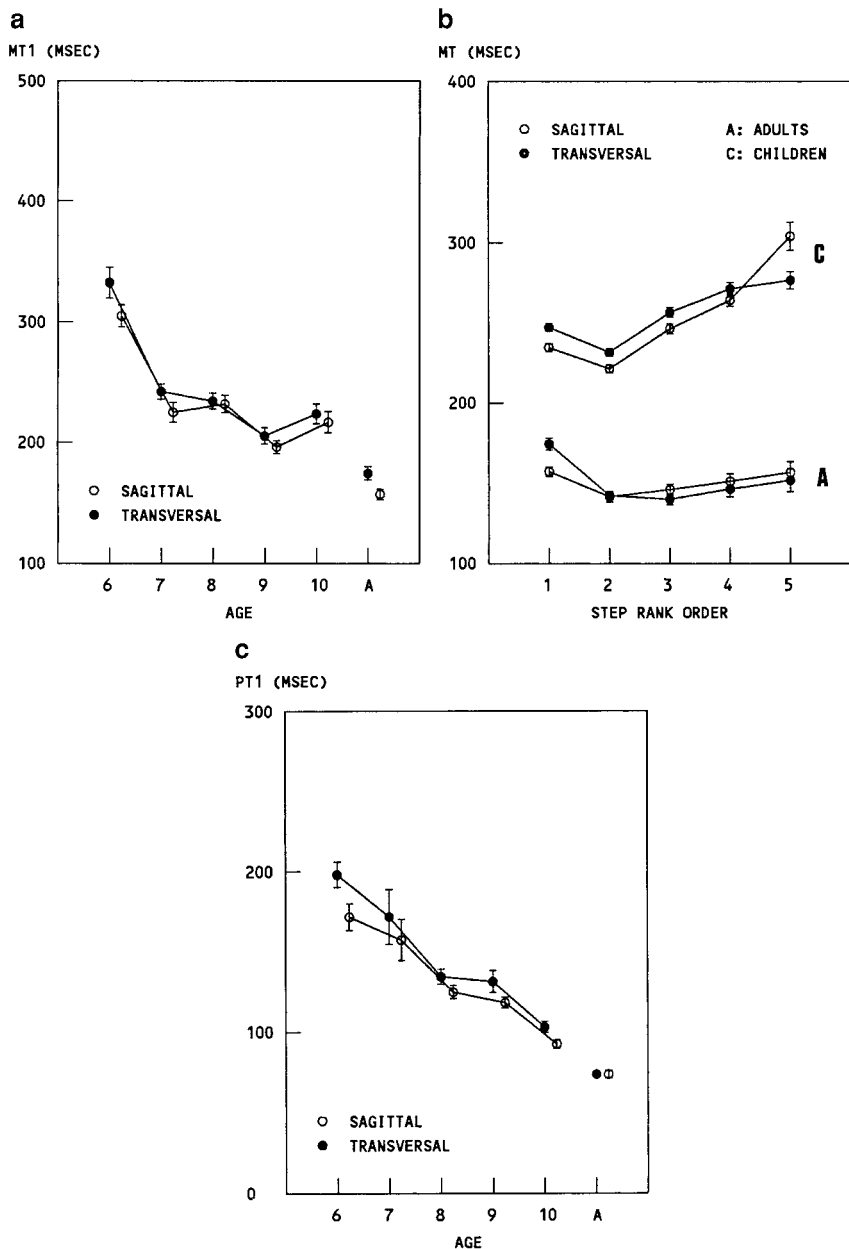
*Reaction time.* RT decreased with age and increased as a function of sequence length; orientation had no effect. Statistical significance of the differences between successive ages was tested by comparison of the corresponding means ( $t$  tests on population means, pooling over sequence length). For the transversal orientation, the largest difference was between 6 and 7 years,  $t(98) = 4.78$ ,  $p < .001$ , followed by the one between 8 and 9 years,  $t(98) = 2.76$ ,  $p = .007$ . All other differences failed to reach significance. For the sagittal orientation, the only significant difference was between 6 and 7 years,  $t(98) = 4.73$ ,  $p < .001$ . Figure 1 summarizes the effects on RT by pooling individual results and collapsing the data over (a) age and over (b) sequence length. Although the largest drop in RT occurred between ages 6 and 7, the improvement continued throughout the range of ages investigated. As for the sequence length, the most consistent difference in RT was between S1 and S2. Indeed, this initial increase in RT was uniformly present at all ages. For the three longest sequences, RT

leveled off, and was somewhat shorter in the transversal than in the sagittal condition.

*Movement time.* All MTs decreased with age too. Figure 2a shows the results for MT1. For both orientations, the largest drop was between ages 6 and 7,  $t(98) = 6.32, p < .001$  and  $t(98) = 6.51, p < .001$  (for sagittal and transversal movements, respectively), followed by the one between age 10 and adults,  $t(98) = 4.95, p = .001$  and  $t(98) = 5.97, p < .001$ . The 8- to 9-years break was also significant,  $t(98) = 3.04, p = .003$  and  $t(98) = 3.92, p < .001$ . The effects of orientation and sequence length were more complex. Averaged across ages, MT1 was independent of sequence length. However, for all sequences, the first pointing was faster in the sagittal direction than in the transversal direction. Figure 2b shows the change in MT (collapsed over age and over sequence length) as a function of the rank order of the step in the sequence. In all cases, the second step was significantly shorter than the first one (in the transversal orientation,  $t(448) = 2.21, p = .027$  for children and  $t(88) = 4.41, p < .001$  for adults; in the sagittal orientation,  $t(448) = 2.05, p = .041$  for children and  $t(88) = 2.35, p = .021$  for adults). In children, the trend was clearly reversed for subsequent steps, whereas the increase in adults was only marginal. The high value for MT5 in the sagittal orientation reflected the results for 6- and 7-year-olds, who might have had difficulty stretching the arm as much as required to reach the furthest target in S5. On the basis of these data, it was not possible to evaluate whether variations in MT along the sequences depended on the rank order per se or on the distance from the participant's body. This point was further dealt with in Experiment 4. However, the analysis of individual sequences revealed an effect that is related only to the sequential structure of the action, namely that MT for the last step (e.g., MT3 in S3) was generally shorter than MT with the same rank order in a longer sequence (e.g., MT3 in S5). The effect was tested for the two orientations and for each age separately by evaluation of the average difference between each MT for the last step and the corresponding MTs in longer sequences. Averages were based on 10 differences (4 for MT1, 3 for MT2, 2 for MT3, and 1 for MT4). Differences became significant only after age 7. Thus, from age 8 onward, the temporal sequences began to exhibit a temporal structure, thus suggesting coordinated planning.

*Pause time.* PT too decreased with age, but, unlike for RT and MT, the only significant trend was the linear one (Fig. 2c). Generally, sequence length did not affect PT1 much. Only at age 6 did pauses tend to increase in the course of the sequence. In children, PT was significantly shorter in the sagittal than in the transversal orientation.

Besides the massive effect of age on all temporal parameters, the most salient result of this experiment was the demonstration, both in children and in adults, that the latent period before movement inception increases in the transition from single-step to multistep sequences. This effect is reminiscent of the increase in mean latency observed when adults produce increasingly long sequences of



**FIG. 2.** Movement and pause time in Experiment 1. (a) MT1 averaged across sequence length as a function of age (A: adults). (b) MT averaged across ages for children (C) and MT for adults (A) as a function of the rank order of the step along the sequence. (c) PT1 averaged across sequence length as a function of age. Bars encompass two standard deviations of the mean.



finger or arm movements (Canic & Franks, 1989; Fischman, 1984; Henry & Rogers, 1960), of utterances (Monsell & Sternberg, 1981), and of keystrokes (Sternberg, Knoll, Monsell, & Wright, 1983). In all cases, it has been suggested that increasing RTs reflect a latency component that is used for advance planning of the entire sequence: the more elements in the sequence, the longer the time to plan them all. By analogy, the results of Fig. 1b suggest that the ability to prepare a multistep sequence in advance is already present at age 6. However, the lengthening of RT was not a linear function of the number of steps, as in the studies quoted above; this finding suggests either a saturation of the capability of planning or a qualitative difference between single- and multistep motor sequences. Orientation did not influence motor preparation. By contrast, both movement parameters (MT and PT) were significantly shorter in the sagittal direction. This difference, which is likely to be due to biomechanical factors, must be taken into account in comparison of motor sequences across directions.

By choosing a recording device that did not require the use of a handheld implement, we wanted to assess performance in the most natural condition. The rather low sampling rate of the instrument set an upper limit to the resolution of the results. However, both the decrease in RT and MT1 between ages 6 and 7 and the increasing trend of MT as a function of the step rank order far exceeded this limit, and were certainly not artifactual.

## EXPERIMENT 2

The first experiment suggested that children have the spontaneous tendency to plan sequences of movements as a coordinated whole that characterizes adult behavior. If so, the spatiotemporal coordination of the sequence should respond adaptively to changes in the difficulty of the task, as it does in adults. The aim of the second experiment was to test this prediction by reducing target size relative to target distance, that is, by increasing Fitts's index of difficulty (Fitts, 1954). The assignment and the general experimental conditions were as in Experiment 1. To evaluate the interaction between spatial and temporal parameters, we also measured the spatial accuracy of the pointings. A different measuring device was required for the recording of spatial data. Thus, we also ran a control experiment in which the new device was used to test the same conditions and the same adult population as those described for Experiment 1.

### *Method*

*Participants.* Main experiment: Fifty boys evenly divided in five age groups (6, 7, 8, 9, and 10 years) and 10 male adults (mean age = 33 years) participated in the experiment. Participants were selected with the same criteria as in Experiment 1. Control experiment: The same adult individuals were tested as in Experiment 1.

*Material and stimuli.* Main experiment: The  $x$ - $y$  coordinates of the pointings were recorded by a digitizing table (Summagraphics Microgrid II 1724H; spatial

TABLE 2  
 Experiment 2: Statistical Effects of Age (6–10 Years) and Sequence (S1–S4)  
 on the Temporal Parameters RT, MT1–MT4, and PT1–PT3

Variable	Factor	<i>df</i>	<i>F</i>	<i>p</i>
RT (S1–S4)	Age (A)	4,45	5.64	<.001
MT1 (S1–S4)	Age	4,45	5.65	<.002
	Sequence (S)	3,135	38.81	<.001
	A × S	12,135	3.14	<.002
PT1 (S2–S4)	Age	4,45	5.65	<.002
MT2 (S2–S4)	Age	4,45	10.27	<.001
PT2 (S3–S4)	Age	4,45	6.38	<.001
MT3 (S3–S4)	Age	4,45	12.68	<.001
PT3 (S4)	Age	4,45	5.39	<.002
MT4 (S4)	Age	4,45	15.60	<.001

accuracy = 0.127 mm; sampling frequency = 168 samples/s). A custom-made modification of the instrument permitted us to record with a 1-ms accuracy the time when the stylus was lifted from the table and the time when contact was made again at the end of the pointing. Six circular holes (radius = 1 cm) cut in a paperboard and aligned along the midsagittal axis of the participant marked the targets. The distance between the centers of the targets and the distance between the participant and the closest target were 10 cm. As in Experiment 1, the required sequence of pointings in a trial was identified by a color code and an array of light-emitting diodes. In the control experiment, targets had a radius of 2 cm, as in Experiment 1.

*Procedure.* The experiment replicated the sagittal condition of the first experiment. Participants older than age 8, and both the new and the previous group of adults, were administered 10 trials for each sequence length, for a total of 50 trials. Because of their limited armlength, 6- and 7-year-olds tended to alter their posture in order to reach the furthest target. Thus, these two groups of participants did not perform the trials corresponding to S5 (5 pointings sequence).

*Measures.* We measured the same temporal parameters as in Experiment 1 (RT, MT, and PT) to a higher resolution. The endpoint spatial distribution was characterized by the amplitude and direction of the vector joining the center of the target to the endpoint. Directions were measured with 1° accuracy. Amplitudes of less than 0.5 cm were considered to be zero. We also measured the number of trials when one or more targets in the sequence were not reached correctly (vector amplitude > 1 cm).

### Results and Discussion

Table 2 reports the statistical analysis of experimental effects on RT, MT, and PT for the children group (two-way ANOVA with repeated measures, 5 (ages) × 4 (sequence lengths); the results for the five-step sequence executed by the older

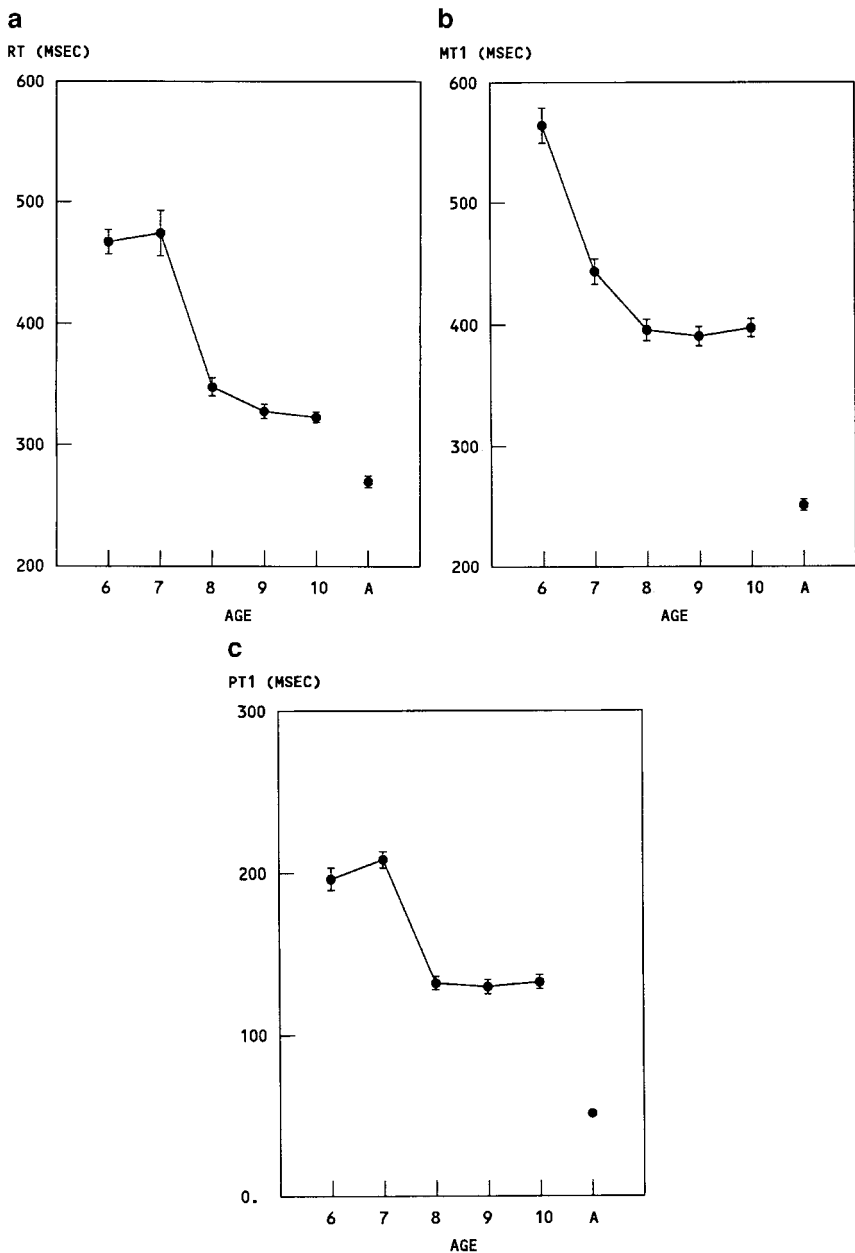
children alone were not included in this analysis). Figures 3 and 4 illustrate the result of collapsing RT, MT, and PT across the experimental factors.

All temporal parameters decreased with age. The statistical significance of the differences between adjacent ages was tested by comparison of the corresponding means ( $t$  tests on population means, pooling over sequence length). For RT (Fig. 3a), the only two significant pairwise differences were between ages 7 and 8,  $t(98) = 4.17$ ,  $p < .001$ , and between age 10 and adults,  $t(98) = 5.47$ ,  $p < .001$ . For MT1 (Fig. 3b), significant discontinuities occurred between ages 6 and 7,  $t(98) = 4.04$ ,  $p < .001$ , and between ages 10 and adults,  $t(98) = 11.00$ ,  $p < .001$ . For PT1 (Fig. 3c), significant discontinuities occurred between ages 6 and 7,  $t(98) = 7.39$ ,  $p < .001$ ; between ages 7 and 8,  $t(98) = 4.16$ ,  $p < .001$ ; and between age 10 and adults,  $t(98) = 19.81$ ,  $p < .001$ . In children, sequence length did not have a consistent effect on all steps. In contrast, adult data revealed an effect of the length on the temporal parameters describing the onset of the movement (one-way ANOVA, 5 (sequence length); for RT,  $F(4, 16) = 6.16$ ,  $p = .027$ ; for MT1,  $F(4, 6) = 40.49$ ,  $p < .001$ ; for PT1,  $F(3, 27) = 4.20$ ,  $p = .016$ ; for MT2,  $F(3, 27) = 6.61$ ,  $p < .003$ ). However, the only consistent tendency was the increase in RT between S1 and S3.

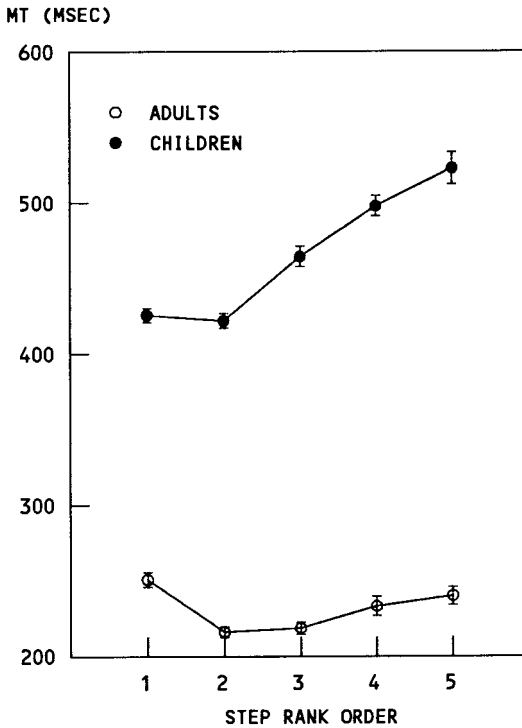
Children's performance was further analyzed by separate consideration of age and sequence length. First, a one-way ANOVA ( $5 \times$  (sequence length)) for each age group showed that in 10-year-olds RT increased significantly with sequence length,  $F(4, 46) = 7.19$ ,  $p < .001$ , as it did in adults. In contrast, there was no trend in younger participants. Second, a systematic multiple comparison based on age (Student, Newman, and Keuls method) showed that 6- and 7-year-olds had longer RT and longer PT (for all sequence lengths) than did older children. Differences within either group were not significant. Moreover, 6-year-olds had longer MT (for all sequence lengths) than did all the others. Again, this temporal parameter did not discriminate within the group of older children.

As mentioned above, comparison of the temporal parameters in this experiment with those of Experiment 1 requires some caution because the two cases used different instruments. However, the control experiment demonstrated that, at least in adults, changes in the method of recording had only a modest quantitative effect on some temporal parameters and that it had no effect on qualitative features.

On the basis of these differences, the average effects of increasing the difficulty of the task can be summarized as follows. With the exception of the 7-year-olds, the difference in RT (compare Figs. 1a and 3a) was in the same direction as in the control experiment. Therefore, the difference may be entirely due to the recording devices. However, the behavior of the 7-year-olds calls for comment. Arguably, the beneficial effect on RT of using the stylus extended uniformly to all age groups. If so, the fact that the latencies for 7-year-olds were not significantly shorter than those for 6-year-olds suggests that the reaction of children of this age to the reduction in target size differed from that of all other



**FIG. 3.** Reaction, movement, and pause time in Experiment 2. Data averaged across sequence length as a function of age (A: adults). (a) RT1. (b) MT1. (c) PT1. Bars encompass two standard deviations of the mean.



**FIG. 4.** Movement time as a function of the rank order of the step along the sequence in Experiment 2. Bars encompass two standard deviations of the mean.

participants. Specifically, one can speculate that most children before and after this critical age adopt planning strategies that are sufficiently differentiated and stable not to be altered by changes in target size. In contrast, the change is possibly sufficient to force most 7-year-old children—who could deal with the easier task as older children did—to fall back on the strategy adopted by the youngest group.

Average PT1 did not discriminate between conditions (compare Figs. 2c and 3c). In contrast, reduction in target size brought about a dramatic increase in MT1 (Fig. 3b), one that far exceeded that revealed by the control experiment. Thus, across ages, all participants reacted to the reduction of target size as predicted by Fitts's Law. However, as shown in Fig. 4, the relative changes in MT along the sequences were almost identical to those in Experiment 1 (Fig. 2b).

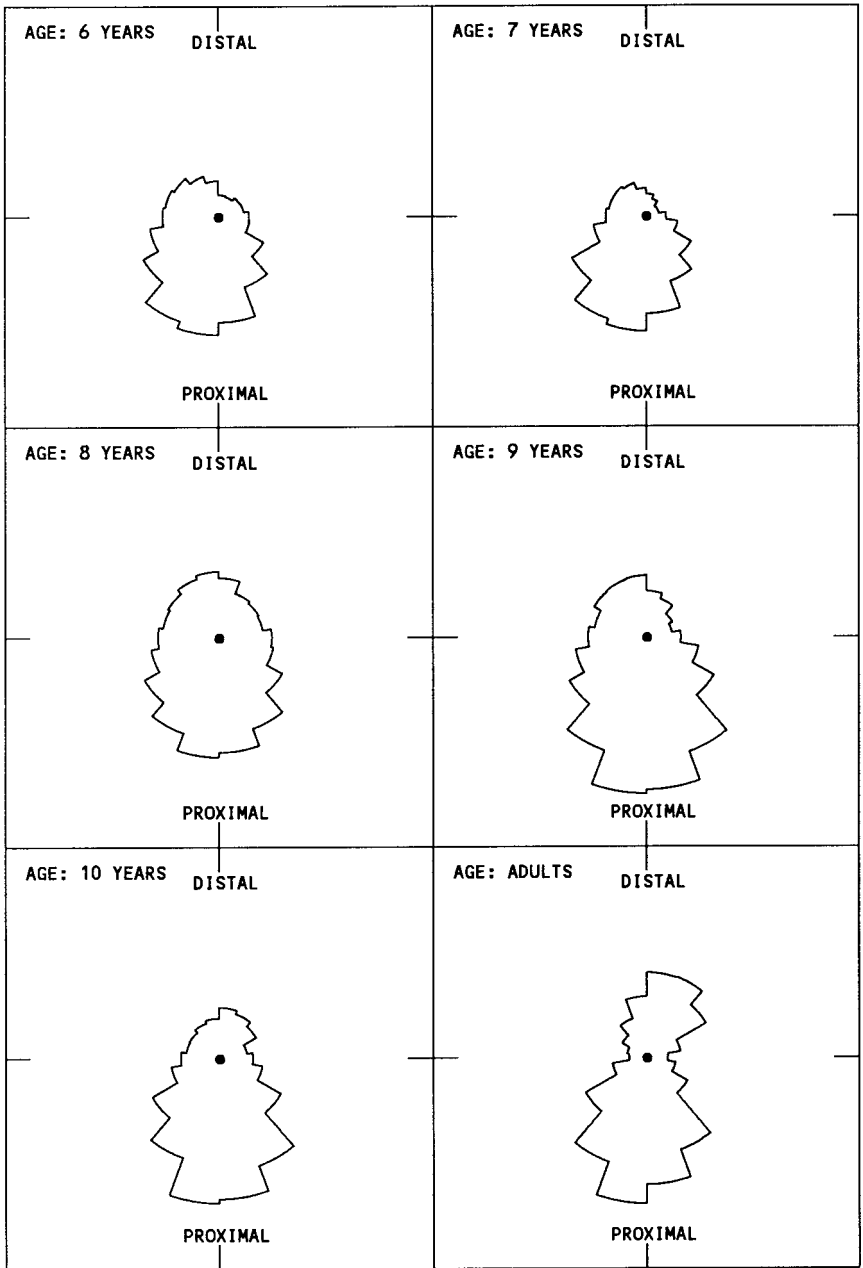
The number of missed targets (distance from the center  $> 1$  cm) was small, on average less than 10% of the total. The failure rate tended to drop with increasing age, but the trend did not reach significance. Absolute eccentricity (average over repetitions of the distance from the center) was also fairly small. Across ages and conditions, about 60% of the endpoints were at less than 0.5 cm from the center

of the target, indicating that even the youngest children spontaneously aimed at the center of the targets. Average eccentricity was weakly dependent on the target rank order within the sequence. Separate analyses within the children group (two-way ANOVA, 5 (age)  $\times$  4 (sequence length)) revealed an effect of age only for the first target,  $F(4, 44) = 3.65$ ,  $p = .013$ . Multiple comparisons (Student, Newman, and Keuls method) differentiated 6- and 7-year-old children from 10-year-old children. The spatial distribution of the pointings falling between 0.5 and 1 cm from the target center was not uniform. For all participants, including adults, the distribution of the direction of the pointings was also not uniform (chi-square test,  $p < .001$  in all cases). As shown in the polar plots of Fig. 5, all distributions peaked strongly around  $180^\circ$ , indicating a common tendency to undershoot the center of the target along the midsagittal axis. As revealed by a secondary peak around  $0^\circ$ , adults partially compensated for this tendency by a sizable number of overshoots.

Increases in the difficulty of the task revealed age-dependent differences in performance. In adults, RT correlated positively with sequence length up to S3, suggesting that at least three steps were planned beforehand. A similar correlation was present only in the eldest children group. Thus, the ability to plan more than one step in advance increases progressively and is fully achieved quite late. This conclusion was supported by the analysis of the spatial distribution of the endpoints; after age 7, the average distance from the target center increased during the sequence. Note that, in the less demanding conditions of Experiment 1, RT increased between S1 and S2 at all ages (see Fig. 1b), suggesting that the amount of advance planning depended on how much the accuracy required for each pointing taxed the available computational resources.

The analysis of MT and PT revealed a further distinction between age groups. Both parameters decreased as a function of age. However, PT (like RT) did not differentiate between 6- and 7-year-olds. Instead, with MT as a criterion, the youngest group stood out as being clearly slower than all other children. Apparently, not all ingredients of the motor skill evolve *pari passu*. Age 7 appears to be a critical transition; whereas movement speed has already reached values comparable to those observed later in childhood, the planning of the second step still takes longer than it does at age 8 or later.

Finally, the distribution of the direction of the endpoints with respect to the target revealed a fairly continuous evolution in children, and a more abrupt change in adults. It has been argued (Gordon, Ghilardi, & Ghez, 1994; Vindras & Viviani, 1998) that the elongation of the distribution of endpoints is evidence that pointing movements are planned as vectors in an extrinsic frame of reference centered on the initial hand position. If so, this mode of programming seems already to be active at the youngest age, because some endpoint elongation is present in all plots of Fig. 5. However, this elongation clearly increases with age. Moreover, undershoots are far more frequent than overshoots (only in adults are the two almost balanced). This may result from the interplay between two



**FIG. 5.** Polar distributions of the orientation of the eccentricity vectors in Experiment 2. For each trial, the eccentricity vector joins the center of the target to the point that was actually reached at the end of the pointing movement. Directions were computed only for endpoints farther than 0.5 cm from the center of the target.

mechanisms: (1) a gain control within the vectorial mode of planning and (2) a position control within a more primitive planning mode, in which the initial ballistic phase is followed by corrections made under visual guidance. Indeed, the very large difference between MT1 for 6-year-olds and MT1 for 7-year-olds (Fig. 3b) hints that visual feedback plays a significant role. The further, dramatic drop in MT1 in adults implies that vision continues to play a role as late as age 10.

### EXPERIMENT 3

In the first two experiments, all steps in the sequences had equal size so that motor planning did not have to deal with changes in movement amplitude. In this experiment we investigated how the step size factor affects the preparation and execution of the motor sequences. We adopted a paradigm similar to that introduced by Burton (1987), in which one contrasts the performance across sequences that comprise steps of two different sizes. All other aspects of the task were as in Experiment 2.

#### *Method*

*Participants.* The same individuals as those tested in Experiment 2.

*Material and stimuli.* The material was identical to that of Experiment 2, except that the target radius was 2 cm, as in the first experiment.

*Procedure.* The general conditions were the same as in Experiment 2. Let T0 be the starting position, and let T1 to T5 be the five targets defined in Experiment 2. Five types of sequence (S1 to S5) were designed: S1 = [T0, T2, T4] (two 20-cm steps); S2 = [T0, T1, T2, T4] (two 10-cm and one 20-cm step); S3 = [T0, T1, T3, T4] (one 10-cm, one 20-cm, and one 10-cm step); S4 = [T0, T2, T3, T4] (one 20-cm and two 10-cm steps); S5 = [T0, T1, T2, T3, T4, T5] (five 10-cm steps). Ten repetitions of each sequence were performed by 8- to 10-year-old children and by adults. For the reason already mentioned above, 6- and 7-year olds did not perform the trials corresponding to S5.

*Measures.* The same as in the previous experiment.

#### *Results and Discussion*

We can summarize the main aspects of the performance in the time domain by exclusively considering the reaction time RT, the duration MT1 of the first movement, and the duration PT1 of the pause on the first target (T1 for S2, S3, and S5, short steps; T2 for S1 and S4, long steps). A first statistical analysis (two-way ANOVA, 5 (ages)  $\times$  4 (sequences)) was restricted to the sequences (S1 to S4) that were administered to all age groups (Table 3). RT did not discriminate reliably among sequence types. The significant effect of this factor revealed by the ANOVA was mostly the consequence of the (inexplicably high) values for sequence S4 in 9-year-olds. By contrast, collapsing the data across sequences (including S5) shows that RT decreased with age (Fig. 6a). The general trend



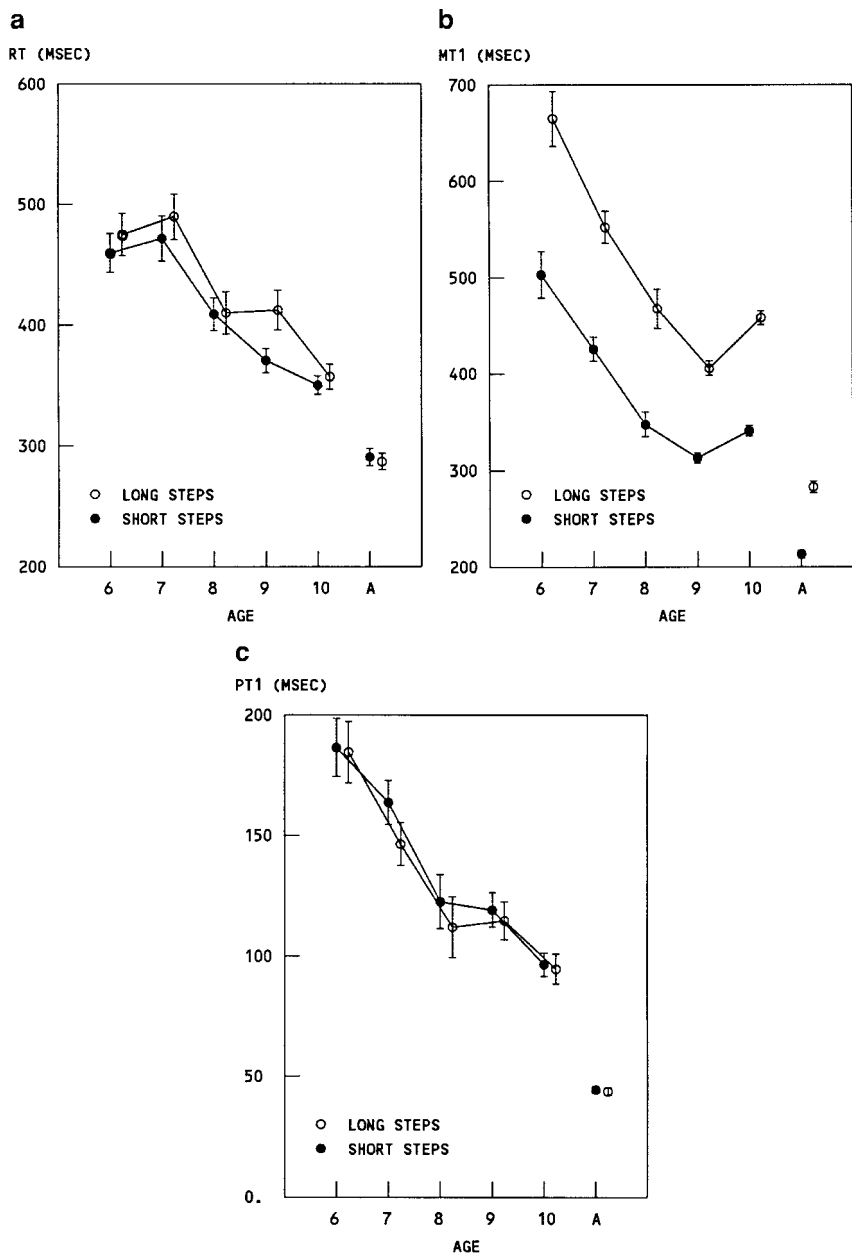
TABLE 3  
 Experiment 3: Statistical Effects of Age (6–10 Years) and Sequence (S1–S4)  
 on the Temporal Parameters RT, MT1, and PT1

Variable	Factor	<i>df</i>	<i>F</i>	<i>p</i>
RT (S1–S4)	—	—	—	<i>ns</i>
MT1 (S1, S4)	Age	4,45	7.46	<.001
	Sequence	1,45	7.80	<.009
MT1 (S2, S3)	Age	4,45	7.13	<.001
	Sequence	1,45	39.18	<.001
PT1 (S1, S4)	Age	4,45	2.92	<.032
PT1 (S2, S3)	Sequence	1,45	4.56	<.039

toward faster movements with increasing age was confirmed by collapsing also MT1 (Fig. 6b) and PT1 (Fig. 6c) across sequences. As in Experiments 1 and 2, differences in RT, MT1, and PT1 between adjacent ages were tested by comparing the corresponding means (*t* tests on population means, pooling over sequence length). For RT, the only two significant differences were between 7 and 8 years,  $t(98) = 2.78$ ,  $p = .006$ , and between 10 years and adults,  $t(98) = 5.24$ ,  $p < .001$ . For MT1, significant discontinuities occurred at the same ages,  $t(98) = 3.46$ ,  $p < .001$  and  $t(98) = 11.57$ ,  $p < .001$ , respectively. Finally, for PT1 all pairwise comparisons were significant ( $p < .001$ ).

MT1 correlated with movement size, being significantly longer for S1 and S4 (distance of first target = 20 cm) than for S2, S3, and S5 (distance of first target = 10 cm). However, whatever the age, the relative time increase was smaller than the relative increase in size. Thus, the well-known spontaneous tendency to increase velocity as a function of the distance to be traveled (Isochrony Principle, Viviani & McCollum, 1983) was present even in the youngest group. Let  $t_1$  and  $t_2$  be the times to cover the distances  $d_1$  and  $d_2$ , respectively. Then, the degree of isochrony can be estimated by the ratio  $\alpha = [\log(d_1 t_2) - \log(d_2 t_1)] / [\log(d_1) - \log(d_2)]$  (see Appendix). By inserting the values  $d_1 = 10$  cm and  $d_2 = 20$  cm and the corresponding averages of MT1 in  $t_1$  and  $t_2$ , we found  $\alpha = 0.597, 0.624, 0.573, 0.626, 0.576$ , and  $0.592$  for the five classes of age and for the adults, respectively. Therefore, unlike in the case of continuous tracing (Vinter & Mounoud, 1991; Viviani & Schneider, 1991), isochrony in our stepping movements did not evolve with age.

The fact that MT increased less than proportionally as a function of target distance is consistent with Fitts's law (Fitts, 1954). Thus, following Burton's (1987) suggestion, we also estimated the evolution of the information-processing capacity of the motor system. Let  $ID = \log_2(2A/W)$  be the index of difficulty of the pointing task, where  $A$  and  $W$  are respectively the distance between the targets and the target size. Fitts's law approximates the relation between MT and ID by the linear equation  $MT = a + b ID$ , where the inverse  $1/b$  of the slope is a measure (in bits/s) of the rate at which visual information is translated into



**FIG. 6.** Reaction, movement, and pause time in Experiment 3. Averages computed over all sequences with the same step size. (a) RT1. (b) MT1. (c) PT1. Bars encompass two standard deviations of the mean.

motor output. In this experiment, the IDs for the short (10-cm) and long (20-cm) steps were 2.32 and 3.32, respectively. We computed the corresponding MT1 by averaging individual means over the sequences S2, S3, and S5 for the short steps, and over the sequences S1 and S4 for the long steps. The information-processing capacity increased as a function of age: for 6 years,  $1/b = 6.18$ ; for 7 years,  $1/b = 7.9$ ; for 8 years,  $1/b = 8.4$ ; for 9 years,  $1/b = 10.8$ ; for 10 years,  $1/b = 8.6$ ; for adults,  $1/b = 14.5$  bits/s. At the same time, contrary to what is expected in a classical Fitts paradigm, the additive constant ( $a$ ) invariably differed from zero (for 6 years,  $a = 127.3$ ; for 7 years,  $a = 131.8$ ; for 8 years,  $a = 70.2$ ; for 9 years,  $a = 98.73$ ; for 10 years,  $a = 70.8$ ; for adults,  $a = 51.7$  s). According to Burton (1987), this fraction of MT, which is independent of the information load, reflects differences in the processing requirements for a given task. Alternatively, it may reflect the fact that the efficiency of one component of the planning and/or execution process increases with age.

Comparison of MT1 in S2 and S3 revealed an interesting effect of the sequence structure. Although the first step in these two sequences was identical, analysis (Table 3) showed that MT1 was significantly shorter for S3 than for S2; in other words, the putative anticipatory effect of the second step was almost twice as long in S3 as in S2. A similar effect was also present in adults, for whom sequence type was a discriminating factor.

Overall, sequence length did not affect PT1. However, by restricting analysis to the sequences with a 10-cm initial step (S2, S3, and S5), and to the three age groups who performed all sequences (8, 9, and 10 years), we again found evidence of an anticipatory effect, which manifested itself as a shorter PT1 in the regular sequence S5,  $F(2, 54) = 21.32$ ,  $p < .001$ .

Pointing accuracy improved with age. A two-way ANOVA of absolute eccentricity in children (4 (sequence)  $\times$  5 (age)) revealed a significant linear trend,  $F(4, 45) = 3.65$ ,  $p = .013$ , as well as a significant difference,  $F(3, 185) = 3.61$ ,  $p < .016$ , between sequences with a large first step (S1 and S4) and sequences with a small first step (S2 and S3). The direction of the endpoint was analyzed as in Experiment 2, with consideration limited to endpoints with an absolute eccentricity greater than 0.5 cm. Young children (6 and 7 years) tended to undershoot the target, most endpoints clustering near the sagittal line. An elongated distribution of endpoints was also present in older children and in adults. The tendency with increasing age toward a more balanced distribution of undershoots and overshoots was more pronounced than in Experiment 2.

The greater complexity of the sequences in this experiment was reflected in several aspects of performance. Generally, RT was longer than in Experiment 2, in which all steps had equal size. However, the difference was not uniform across ages. Six- and 7-year-olds had the same RTs in the two conditions, and the increase in adults was modest. In contrast, all intermediate age groups (8, 9, and 10) were negatively affected by the requirement to change step size during the sequence, indicating that the ability to deal with increasingly complex tasks

varies with age. Specifically, the results are consistent with the hypothesis that latencies increase at the transition between a stage of development in which no aspect of the movement other than the first step is planned and a more advanced stage in which children attempt to plan some of the subsequent steps. With regular sequences, the transition occurred between ages 6 and 7. In this experiment, the transition occurred later, possibly because the need to deal with irregular sequences more than offset the advantage of having larger (2-cm) targets.

After age 7, MT for all 10-cm steps was lower than in the previous experiment (for 8 years,  $t(78) = 2.129$ ,  $p = .036$ ; for 9 years,  $t(78) = 4.559$ ,  $p < .001$ ; for 10 years,  $t(78) = 3.544$ ,  $p = .001$ ; for adults,  $t(78) = 3.559$ ,  $p < .001$ ). Moreover, the average PT before comparable steps was lower in this experiment than in Experiment 2,  $t(378) = 2.09$ ,  $p = .036$ , suggesting that structural complexity too affected the planning of the intermediate steps in the course of execution.

## EXPERIMENT 4

In discussing the results of Experiments 1 and 2, we evoked the possibility that the increase in MT as a function of the step rank order (Figs. 2b and 4) was, at least in part, an effect of the distance from the participant at which movements were made. The question could not be resolved by those experiments, because distance was strictly determined by the rank order of the steps in the sequence. To dissociate these two factors, the last experiment adopted the classical one-step pointing task, in which the amplitude of the step and the distance of the starting point are independently varied. This also enabled us to investigate whether the distance of the starting point affects the latent period during which the pointing movement is planned.

### *Method*

*Participants.* The same individuals as those tested in Experiments 2 and 3.

*Material, stimuli, and procedure.* The apparatus was that of Experiment 3. Eight pointing tasks were designed. Using the same notations as those introduced above, the first seven stimuli (S1 to S7) were the following pairs of targets: S1 = [T0, T1], S2 = [T0, T2], S3 = [T1, T2], S4 = [T1, T3], S5 = [T2, T3], S6 = [T2, T4], S7 = [T3, T4]. The required response was a simple pointing movement with a step size of 10 (S1, S3, S5, S7) or 20 cm (S2, S4, S6). The last stimulus, introduced as a control, was the sequence S8 = [T0, T1, T2, T3, T4]. As in Experiments 2 and 3, participants had to respond to S8 by a sequence of pointings, performed as fast as possible. Each stimulus was presented 10 times in a pseudorandom order, for a total of 80 trials. Testing conditions and measurements were as in Experiment 3.

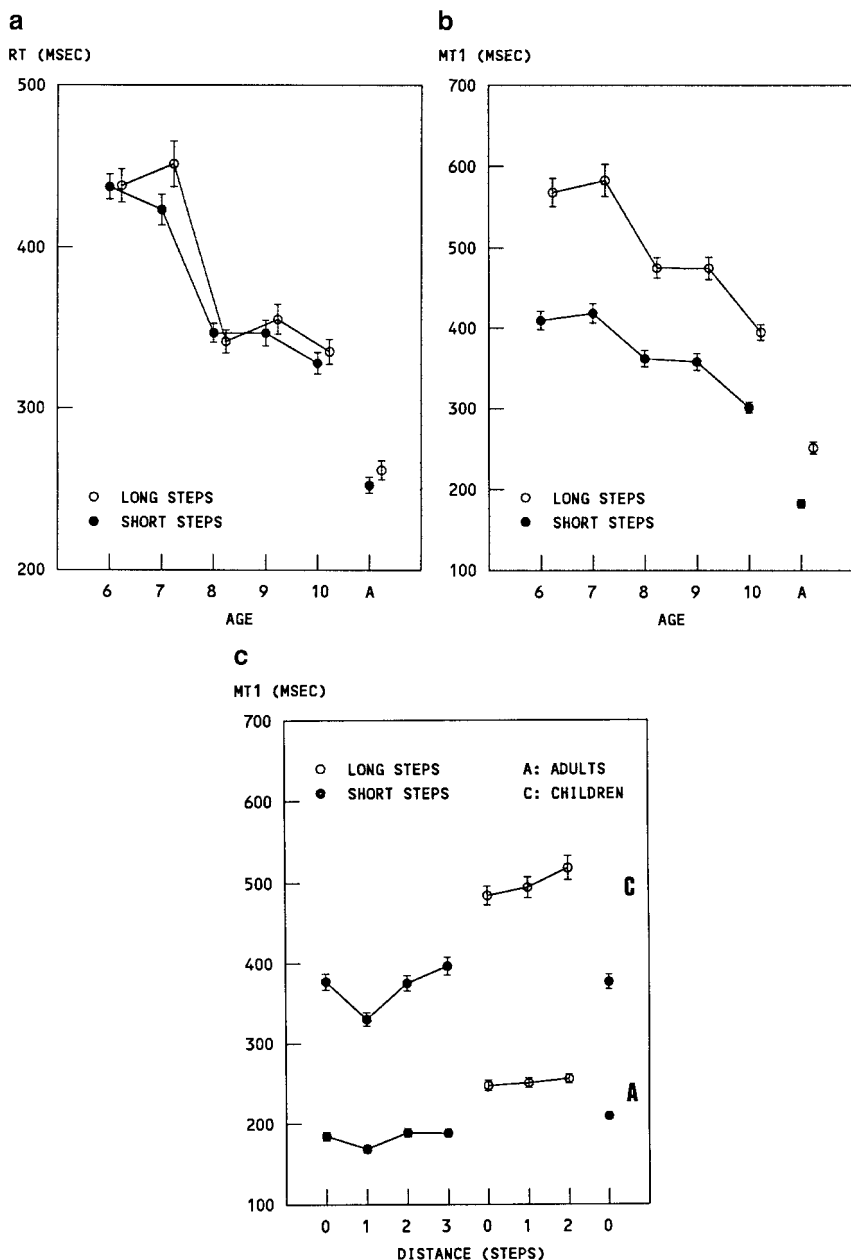
TABLE 4  
 Experiment 4: Statistical Effects of Age (6–10 Years) and Sequence (S1–S8)  
 on the Temporal Parameters RT and MT1

Variable	Factor	<i>df</i>	<i>F</i>	<i>p</i>
RT (S1–S8)	Age (A)	4,45	6.34	<.001
	Sequence (S)	7,39	3.04	<.013
	A × S	28,168	1.59	<.039
RT (S1, S3, S5, S7)	Age	4,45	6.41	<.001
	A × S	12,135	2.35	<.010
RT (S2, S4, S6)	Age	4,45	5.42	<.002
MT1 (S1, S3, S5, S7)	Age	4,45	2.65	<.046
	Sequence	3,135	47.81	<.001
	A × S	12,135	2.98	<.001
MT1 (S2, S4, S6)	Age	4,45	4.16	<.007
	Sequence	2,90	12.95	<.001
	A × S	8,90	3.22	<.004
MT1 (S8)	Age	4,45	2.73	<.042
PT1 (S8)	—	—	—	<i>ns</i>
MT2 (S8)	Age	4,45	3.08	<.026
PT2 (S8)	—	—	—	<i>ns</i>
MT3 (S8)	Age	4,45	1.26	<.014
PT3 (S8)	—	—	—	<i>ns</i>
MT4 (S8)	Age	4,45	3.35	<.018

*Results and Discussion*

RT1 and MT1 for children and adults were analyzed separately. Table 4 summarizes the results in children of several two-way ANOVAs, in which the between factor (age) was crossed with various combinations of the within factor (sequence). When all sequences are considered, the analysis revealed significant main effects of both factors, as well as significant interactions, on RT and TM1. However, the sequence effect disappeared when short-step (S1, S3, S5, S7) and long-step (S2, S4, S6) sequences were analyzed separately. Thus, step size but not distance influenced the planning of the pointing movement. In adults, the sequence effect on RT followed the same pattern as that found in children. In contrast, the effect on MT1 was significant for short-step sequences alone. Figure 7a summarizes the evolution of RT across ages. The results are strikingly similar to those of Experiment 3 (see Fig. 6a). In both cases, the decrease in RT is marked by a rather abrupt transition that separates 6- and 7-year-olds from older children (an even sharper transition was demonstrated in Experiment 2 (see Fig. 3a)). Moreover, as in the previous experiment, RT to long steps tended to be longer than RT to short steps. In conclusion, the comparison between conditions indicates that the distance of the starting point per se does not determine how complex it is to plan the initial pointing movement.

For both step sizes, MT1 decreased with age, the trends for the two sizes being



**FIG. 7.** Reaction and movement time in Experiment 4. (a, b) RT and MT1 averaged over all sequences with the same step size as a function of age (A: adults). Data for sequence S8 were included in the average for short steps. (c) MT1 averaged across ages for children (C) and MT1 for adults (A) as a function of the distance of the first movement from the participant's body (distance measured in number of steps from the starting point). Data for the sequential task (sequence S8) are plotted separately. Bars encompass two standard deviations of the means.

almost parallel (Fig. 7b). The fact that movement times for 20-cm steps were less than twice as long as those for 10-cm steps confirmed the spontaneous tendency, already documented above (see Fig. 6b), to compensate for the increased distance by increasing average velocity. The tendency toward isochrony was quantified by the previously mentioned index  $\alpha$ . The results for the five age classes and for the adults ( $\alpha = 0.527, 0.522, 0.607, 0.593, 0.610$ , and  $0.539$ , respectively) confirmed that the velocity compensation mechanism does not evolve consistently. Moreover, because  $\alpha$  values in this and in the previous experiments were almost identical, this automatic component of motor planning is affected neither by the complexity of the task nor by the distance of the starting point from the body. Both for short and for long steps, MT1 was shorter than in Experiment 3, where short and long steps alternated within the same sequence; the reduction found in Experiment 4 was particularly large at age 6.

Figure 7c shows how MT1 varied with the distance from the body. The results for 10-cm steps (filled symbols) are strongly reminiscent of the evolution of MT as a function of the step rank order when movements are embedded within a sequence (see Figs. 2b and 4; with the adopted notation, the data at distance 0 correspond to MT1 in those figures, those at distance 1 to MT2, and so on). In particular, across experiments and age groups, movements from the second to the third target were shorter than all other movements; from that point on, MT1 tended to increase in a similar manner. We conclude that the dependency of MT1 on the step rank order found in Experiments 2 and 3 should be credited to the effect of the distance rather than to constraints related to the sequentiality of the task. We also take the presence of a minimum in all MT curves as evidence that, as far as movement planning is concerned, the proximal workspace is not isotropic. Perhaps motor proficiency is particularly high within the region of the workspace (between the second and the third targets) where most of the skilled hand movements, including writing, are normally performed.

Finally, both in children and in adults the MT1 values for stimulus S8 (which required a sequence of steps) were comparable to those found for the one-step trials starting at the location closest to the participant. They were also quite similar to those measured in Experiment 3 for sequence S5, which had the same structure as S8 and just one extra step at the end. Presumably, none of the groups of participants who served in both experiments fundamentally altered their motor strategies as a result of switching from a sequential task to a one-step task. Therefore, it was meaningful to compare the results of this experiment with those of Experiment 2.

## GENERAL DISCUSSION

We studied the development of a sequential motor skill that requires advance planning for several units of motor action. We have discussed many specific points in our presentation of the results. Here we concentrate on the more general issue that motivated the study, namely the nature of the changes intervening

within the critical period of perceptuomotor development, between 6 and 10 years. The notion of maturation provides an attractively simple framework for understanding these changes. Within this framework, and on the basis that the neurophysiological mechanisms mediating perceptual and motor functions are well developed by age 6, improvements in performance with age would be attributable to a continuing process of fine-tuning of the many processes involved in the execution of the task. At a coarse-grained level of description, the results are consistent with such a view. Across conditions and stimuli, the values of all temporal parameters of the performance decreased drastically between 6 and 10 years, and, in many cases (e.g., MT1 in Experiment 2), between the eldest children and the adults too. At the same time, spatial accuracy improved, as demonstrated by the tendency to a more balanced distribution between undershoots and overshoots (Fig. 5). Besides the reversal in the MT1 trend in Experiment 3 (Fig. 6b), the developmental process that we investigated does not undergo the regression phases documented in other studies (cf. Bever, 1982; Mounoud, 1986; Strauss, 1982). Yet, we would like to argue that, at a finer level of analysis, the results point to a more articulated view of the developmental changes than the one associated with the maturational hypothesis.

If sensorimotor development in the prepuberal period consisted of a smooth, uniform refinement of otherwise well-identified sensorimotor mechanisms already in place before that period, changing the task difficulty should affect behavior in a similarly uniform fashion across ages. However, we documented several violations of this expectation, the clearest evidence coming from the analysis of the RTs (Figs. 1a, 3a, 6a, and 7a). In particular, the behavior of 7-year-old children suggests that, around that age, the motor planning strategy characteristic of older children is already emerging, but that it has not yet superseded a less effective planning mode adopted in earlier stages of development. At the time of its emergence, the new strategy is more costly than the old one. Thus, the selection of a given solution in a given context depends on how taxing the situation is for the child. In other words, we are here suggesting that the variable behavior of 7-year-olds reflects an alternation between available strategies.

Of course, it is overly simplistic to construe the transitions taking place between ages 6 and 10 as a competition between holistic, stable strategies. It seems more sensible to characterize each stage of development by the set of strategic components that are potentially available at that stage, and by the (age-dependent) rules dictating the choice of the components that are actually activated in a given context. Our data are clearly insufficient to be specific about these strategic components. Nevertheless, at least one element can be inferred by comparison of the changes in RT as a function of sequence length. By analogy with similar data for verbal and keystroke sequences, we assumed that the ability to plan more than one step of the sequence is revealed by an increase in RT with the required number of steps (Sternberg, Monsell, Knoll, & Wright, 1978). By



this criterion, we inferred that, when the pointing is relatively easy, at least the second step is taken into account while planning for the initial movement (Fig. 1b). In all but the eldest children, the increase of RT disappeared with smaller targets, indicating that, before age 10, chaining two steps in a superordinate unit of motor action is a strategic component that may or may not be present, depending on the overall difficulty of the task. Apparently, in Experiment 2 younger children fell back on a step-by-step strategy in which each movement was planned and executed independently.

Further support for this view came from the analysis of pause times. The analysis confirmed the peculiar status of 7-year-old children, who behaved almost as 8-year-olds when targets were large (Fig. 2c), just like 6-year-olds when the reduced target size made the task more demanding (Fig. 3c), and somewhere in between when the advantage of a large target size was partly offset by the difficulty of dealing with unequal step sizes (Fig. 6c). The close resemblance of the age-dependent changes in RT and PT1 in Experiments 1 and 2 is consistent with the hypothesis that, within the step-by-step strategy, part of the pause time is spent on planning the next pointing. Note also that in Experiment 2, no further reduction in PT followed the large drop between ages 7 and 8. Thus, the almost 100-ms difference between adults and 10-year-olds (Fig. 3c) suggests that yet another strategic change takes place after that age.

To conclude, we would like to argue that the analysis of movement execution is also in keeping with the notion that the motor control mode implemented at different stages of development results from the interaction of identifiable components. Indeed, the stability of the isochrony coefficient across ages is evidence of a compensatory component of kinematic planning which, unlike other components (e.g., the control of amplitude gain; see Fig. 5), does not evolve significantly between age 6 and adulthood.

## APPENDIX

The phenomenon of isochrony is the spontaneous tendency of the motor system to increase the average velocity of execution of voluntary movements ( $V$ ) as a function of the estimated distance to be covered ( $d$ ). Empirically, this increase has been found to follow a power law,

$$V = Kd^\alpha,$$

where  $K$  is a gain factor and  $\alpha > 0$ . Assuming that the gain factor remains constant across a sequence of pointing movements, the strength of the isochronic tendency is measured by the exponent  $\alpha$  ranging from  $\alpha = 0$  ( $V = K$ ; movement time  $t = d/V = d/K$  is proportional to distance, i.e., no isochrony) to  $\alpha = 1$  ( $V = Kd$ ; movement time  $t = d/V = 1/K$  is independent of distance, i.e., perfect isochrony). Measuring movement time for at least two distances  $d_1$  and  $d_2$  affords an estimate of  $\alpha$ . Applying the isochrony equation and dividing left and right terms,

$$\frac{V_1}{V_2} = \frac{d_1^\alpha}{d_2^\alpha};$$

expressing velocities in terms of time and distance ( $V_1 = d_1/t_1$ ;  $V_2 = d_2/t_2$ ) and solving for the unknown exponent  $\alpha$ , one gets

$$\alpha = \frac{\log(d_1 t_2) - \log(d_2 t_1)}{\log(d_1) - \log(d_2)}.$$

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