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Visuo-manual Aiming Movements in 6- to 10-Year-Old Children: Evidence for an Asymmetric and Asynchronous Development of Information Processes

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Sixty children from 6 to 10 years old participated in an open-loop visuo-manual aiming task (Experiment 1). They were asked to point as fast and accurately as possible toward lateralized visual targets. Responses were wrist flexion–extension movements. Results showed non-monotonic changes with age of constant error, reaction time, and movement time. Constant error for targets presented in the right visual field increased between 6 and 8 years and decreased afterward. Reaction time and movement time decreased with age except at 8 years where they tended to increase. The same subjects participated in two control tasks. One task was designed to test the spatial localization of the lateralized visual targets (Experiment 2). Results showed that subjects localized very accurately the targets at all ages. The second control task was designed to test simple reaction time to the same visual stimuli used in the previous tasks (Experiment 3). Results indicate that reaction time decreased linearly with age when no spatial processing is required for the production of the response. The results of the three experiments showed different developmental functions according to the processes involved in each task. Moreover, they suggest

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that the conversion from visual to motor coordinates undergo a qualitative change at 8 years of age, and that the prevailing process of this conversion is located in the left cerebral hemisphere.

INTRODUCTION

Several studies using visuo-manual aiming tasks with children have described non-monotonic changes of performance (e.g., spatial accuracy, kinematics) with age (Bard, Hay, & Fleury, 1990; Fayt, Minet, & Schepens, 1993; Hay, 1978, 1979; Hay, Bard, Fleury, & Teasdale, 1991; von Hofsten & Rösblad, 1988; Mounoud, Viviani, Hauert, & Guyon, 1985). These results suggest that a qualitative change of the information processes used to perform these tasks occurs during childhood. In this context it is important to distinguish between open-loop and closed-loop conditions. When visuo-manual aiming tasks are performed *with* vision of the hand, results show a simple progressive improvement of performance (viz, movement time and spatial accuracy) with age (Bard et al., 1990; Brown, Sepehr, Ettlinger, & Skreczek, 1986; Connolly, Brown, & Basset, 1968; Hay, 1981; Kerr, 1975; Salmoni, 1983; Schellekens, Kalverboer, & Scholten, 1984; Sugden, 1980). In contrast, when visuo-manual aiming tasks are performed *without* vision of the hand, results show a more complex change of performance with age. If only the control of movement *direction* is required, there is little or no improvement of accuracy with age (Bard et al., 1990; Brown et al., 1986). However, when the task requires the control of movement *amplitude,* there is a temporary decrease of movement accuracy at 7–8 years of age (Bard et al., 1990; Hay, 1978, 1979). This dissociation between the control of direction and amplitude of movement is also observed when the visuo-manual aiming task requires simultaneous control of both dimensions; the fluctuation of accuracy with age results primarily from amplitude error (Fayt et al., 1993; von Hofsten & Rösblad, 1988). In summary, these results suggest that the control of the direction of movement and the control of the amplitude of movement are distinct processes that develop at different times and rates (i.e., asynchronously) during childhood.

Using the distinction between an initial programmed phase and a terminal guided phase in aiming movements, Hay (1978, 1979) proposed the hypothesis that a guiding system responsible for amplitude accuracy is added to a preexisting programming system at 7–8 years of age. Thus, the accuracy in open-loop tasks would temporarily decrease for this age group because the guiding system needs to be calibrated before it becomes effective. In agreement with her hypothesis, Hay (1979) found more discontinuous movements from 7 years onward than at 5 years. Discontinuities in the arm kinematics have indeed been interpreted as produced by feedback-based corrections (Brooks, 1974). However, non-monotonic changes of movement discontinuities with age have been documented only when subjects executed relatively slow movements (Hay, 1979; Mounoud et al., 1985), but not when fast movements were required (Mounoud et al., 1985; Schellekens et al., 1984). On the other hand, the temporary decrease of amplitude accuracy has been observed with slow movements (Hay, 1978, 1979), and also with fast movements (Bard et al., 1990). Therefore, the use of feedback-based corrections, which may be favored in slow movements, does not seem to be the cause of the temporary decrease of amplitude accuracy but more probably a consequence of it.

The neural changes associated to the functional changes described above are not known. However, these results are compatible with neuroanatomical and electrophysiological studies of neural development during childhood. These studies showed that various structures of the human central nervous system develop until the adolescence and even adulthood (Conel, 1939–1967; Holland, Haas, Norman, Brant-Zawadski, & Newton, 1986; Yakovlev & Lecours, 1967). It was also described that homologous regions of the left and right cerebral hemispheres develop at different times and rates (Rabinowicz, Leuba, & Heumann, 1977; Thatcher, Walker, & Giudice, 1987). Therefore, assuming that different neural components are responsible for different functional processes, we can expect to observe asynchronous changes of performance (e.g., amplitude and directional errors) with age. Moreover, it is generally considered that differences of performance according to the hand and visual field factors result from the involvement of different neural components that have different processing performance (Allen, 1983; Moscovitch, 1986). Therefore, if the neural components activated in performing a task develop asynchronously, we can expect a dissociation of performance with age according to the hand and visual field factors. The different developmental profiles of performance would then reflect the componential nature of the information processing and would give a behavioral evidence for an asymmetric and asynchronous development of the neural processes involved. Previous studies of visuo-manual aiming in children did not examine whether hand and visual field factors had an effect on performance; therefore, to test the hypothesis mentioned above, we investigated these factors in a series of three experiments.

The aim of the three experiments reported here was twofold: (1) To identify which part of the processing of information involved in visuo-manual aiming movements is responsible for the nonmonotonic development of amplitude accuracy between 6 and 10 years of age; (2) To assess whether this change of performance with age is dissociated according to the hand and visual field factors, which would give a behavioral evidence for an asymmetric development of the neural processes involved in visuo-manual aiming movements. The main experiment (Experiment 1) investigated fast open-loop aiming movements with the left or the right hand to lateralized visual targets. The responses were restricted to flexion–extension of the wrist in order to involve primarily the motor command output of the contralateral cerebral hemisphere (Brinkman & Kuypers, 1973; Gazzaniga, 1970). We report also two control experiments that were designed to test components involved in the main task. The first control experiment (Experiment 2) was a perceptual localization task. It was designed to test whether the complex development of amplitude accuracy can be ascribed to the spatial perceptual processing or whether it deals with other aspects of the information processing. The targets were the same as in the visuo-manual aiming task but the motor response did not need a conversion from visual to motor spatial coordinates. The second control experiment (Experiment 3) was a simple reaction time task that tested the visuo-manual loop when no spatial processing of the target or of the response is required. Thus, we could test the effect of the spatial processing on the reaction time.

METHODS

Subjects

Sixty male children selected from public primary schools of Geneva participated in the experiments. They were divided into five age groups from 6 to 10 year-old ($N = 12$ in each group). Experiments were conducted within an interval of $\pm$ 3 months from subject's birthday. The mean and standard deviation of age (years: months) in each group were respectively 6:0 (0:1), 7:1 (0:2), 7:11 (0:3), 9:0 (0:3), and 10:0 (0:3). All subjects were right-handed according to Bryden's (1977) questionnaire and had normal or corrected-to-normal vision.

General Procedure

Subjects participated in the three experiments during two sessions. Each session lasted approximately 45 min. The main experiment, namely the open-loop aiming movement task (Experiment 1), was done during the first session. The two control experiments, that is, the perceptual localization task (Experiment 2), and the simple reaction time task (Experiment 3), were done during the second session after an interval of 5 to 10 days. The order of the two control experiments was counterbalanced across the subjects.

Experiment 1: Open-Loop Aiming Movement Task

Apparatus

Subjects were seated in front of a translucent vertical screen placed in a box (Fig. 1). The subject's forehead rested against the front of the box. The distance between the screen and subject's eyes was 46 cm. A fixation point indicated by a red square (0.6 degrees of visual angle) was permanently visible in the center of the screen. A light source projected a red circular beam onto a galvanometric mirror which reflected it on the screen (spot diameter = 0.8 degrees of visual angle). The galvanometer controlled the horizontal position of the red target spot on the screen. A buzzer was placed behind the screen to produce a warning signal.

A vertical handle was placed in the midsagittal plane at the height of the subject's shoulders. The subject's hand was comfortably strapped to the handle. The rotation axis of the handle coincided with the wrist flexion–extension axis and was at 16 cm in front of the screen. The horizontal position of the wrist was recorded using an angular potentiometer mounted on the axis of the handle. A pointer was placed on the handle at a slightly lower height than the level of projection of the targets. In this way, we could place a horizontal opaque screen to prevent the vision of the handle and of the subject's forearm. However, the pointer could be seen through a small aperture in the horizontal screen only when it was in the central position.

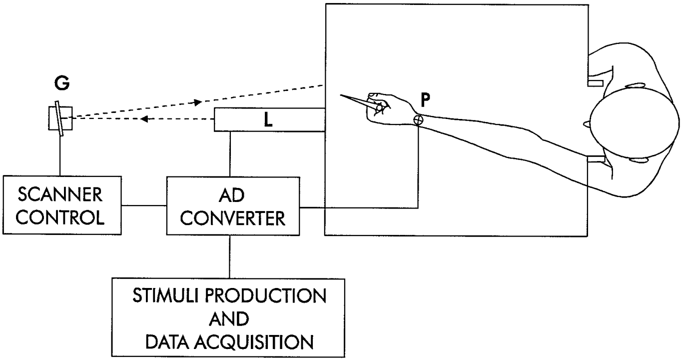

FIG. 1. Experimental setup. The light source L projected a red target spot on the galvanometric mirror G which reflected it on a vertical translucent screen in front of the subject. The subject grasped the handle placed on a potentiometer P. The axis of the potentiometer coincided with the subject's wrist axis. A horizontal opaque screen prevented the vision of the handle and subject's hand and forearm. However, the pointer could be seen when it was in the central position through a small aperture in the opaque screen. Stimuli production and data acquisition were controlled with a personal computer through an AD converter.

The recordings of the potentiometer output and the production of the warning signal and of the visual targets were controlled with a personal computer through a 12-bit AD converter. The angle of the potentiometer was measured with a spatial error of less than 0.1 degree and recorded at a sampling rate of 200 Hz.

Stimuli

The stimulus was a brief visual target of 100 msec duration. Its width was 0.8 degrees of visual angle. The target appeared to the left or right of the fixation point, and at eccentricities of 2, 3, 5, or 8 degrees of visual angle. The handle had to be rotated by an angle of respectively 5.7, 8.5, 14.1, and 22.0 degrees from the central position. The order of presentation of the targets was randomized between visual fields and eccentricities.

Procedure

A warning signal of 1000 msec duration preceded the target with a time interval varying randomly from 200 to 1000 msec. The warning signal was produced with a red light spot on the fixation point and with the buzzer. At the time of the warning signal the subject had to look at the fixation point and to keep the handle in the central position. The subjects were instructed to position the pointer in correspondence with the target position as quickly and accurately as possible when the target appeared. Several familiarization trials were performed, first with and then without vision of the hand. The first half of the experimental trials were performed with one responding hand, and the second half with the other. The order of the responding hand was counterbalanced across the subjects. In order to maintain a high level of attention, the number of repetitions for each condition varied according to the age group. The total number of trials per subject was 48 in the 6-year-old group, 64 in the 7-year-old group, and 80 in the 8-, 9-, and 10-year-old groups.

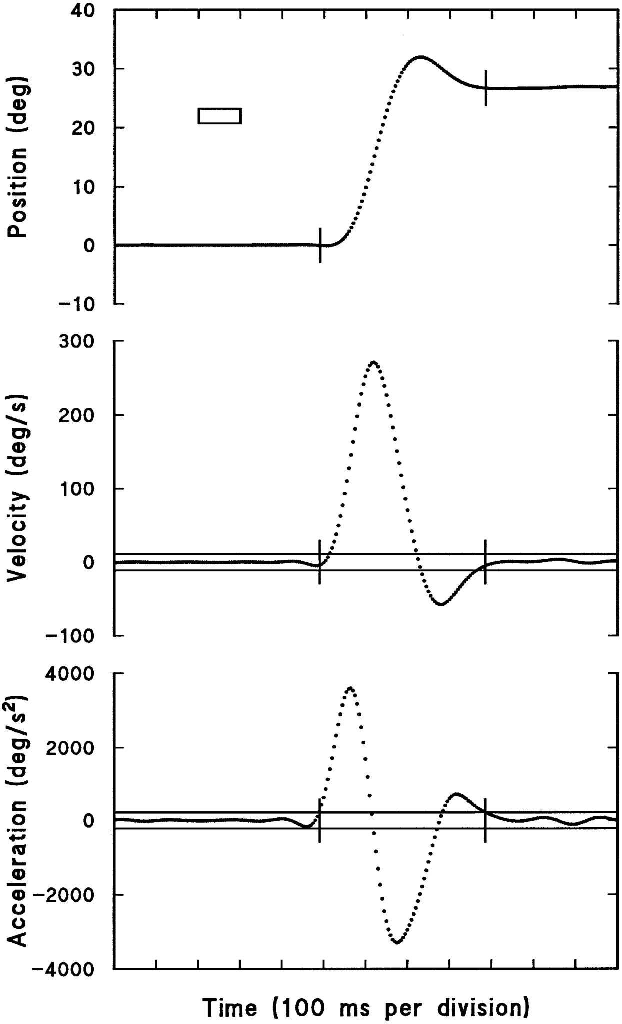

FIG. 2. Example of displacement, velocity and acceleration data. The onset and end of the movement are indicated by the vertical lines in the graphs. The thresholds for the velocity and acceleration are indicated on the respective graph. The target position, its time of occurrence and its duration are indicated by the rectangle in the displacement graph.

Data Processing

The position data were numerically filtered with no phase lag, 0 to 5 Hz pass-band, and 5 to 12.5 Hz transition-band. The filtered displacement was subsequently differentiated to obtain the velocity and acceleration data. Filtering and derivations were performed with Finite Impulse Response filters of 80 points width (Rabiner & Gold, 1975). The onset of the movement was determined by the time when the acceleration exceeded an empirically determined threshold (Fig. 2). The end of the movement was the time after which the displacement varied less than $\pm$ 1.25 degrees, and velocity and acceleration had values lower than their respective thresholds.

For each trial, several parameters were computed which included the reaction time (RT) and the movement time (MT). Trials with RT lower than 100 msec or greater than 1000 msec and/or with MT greater than 1500 msec were excluded from the analyses (0.6% of all trials). Movement kinematics was analyzed using the magnitude (spatio-temporal parameter) and time of occurrence (temporal parameter) of the first peak of velocity (V1 and TV1, respectively). The number of acceleration zero crossings between the onset and the end of the movement was recorded. This number reflects the degree of discontinuity of the movement. The first two peaks of acceleration were also analyzed, but as the results were giving similar information than the one obtained with the peak of velocity they are not presented here. Measures of accuracy were computed as constant error (CE: mean difference between handle position at the end of the movement and the position corresponding to the target) and variable error (VE: within-subject standard deviation of CE).

Results

Statistical analyses of the data were performed with $5 \times 2 \times 2 \times 4$ (Age by Hand (H) by Visual Field (VF) by Eccentricity (E)) analyses of variance. The age factor was a between-subject factor, the others were within-subject factors. Only effects with $p < .05$ were considered as significant. Effects of age and eccentricity factors were also evaluated using polynomial orthogonal contrasts. Post-hoc analyses (Student–Newman–Keusl tests with $p = .05$) were used to examine the origin of significant effects.

Movement discontinuity. The median number of acceleration zero crossings varied between 3 and 4 across the age groups, with no significant changes with age. Seventy-five percent of the movements included 1 to 4 zero crossings of the acceleration.

Spatial accuracy. In Fig. 3, the final position is presented by hand, visual field, and eccentricity for the 6-, 8-, and 10-year-old groups. It can be noticed that the movements generally overshot the targets. Analyses indicated that CE increased with target eccentricity ($F(3, 165) = 9.37$, $p < .001$). Moreover, CE was greater in the right than in the left visual field ($F(1, 55) = 36.82$, $p < .001$), and this difference increased with target eccentricity (VF by E: $F(3, 165) = 12.37$, $p < .001$). However, it must be emphasized that the difference of CE between visual fields changed with age, (Age by VF: $F(4, 55) = 38.95$, $p = .013$). In Fig. 4, CE is plotted by hand, visual field and age group. It can be noticed that CE for right visual field targets increased between 6 and 8 years and decreased afterward. In contrast, CE for left visual field targets did not show a significant age-related trend. Indeed, post-hoc analyses indicate that CE was significantly different from zero only for right visual field targets for the 7-, 8-, and 9-year-old groups.

As far as spatial variability is concerned, VE increased with target eccentricity ($F(3, 165) = 66.58$, $p < .001$). This increase was steeper for left hand than for right hand movements (H by E: $F(3, 165) = 5.87$, $p = .001$) and for contralateral than for ipsilateral movements (H by VF by E: $F(3, 165) = 2.69$, $p = .048$).

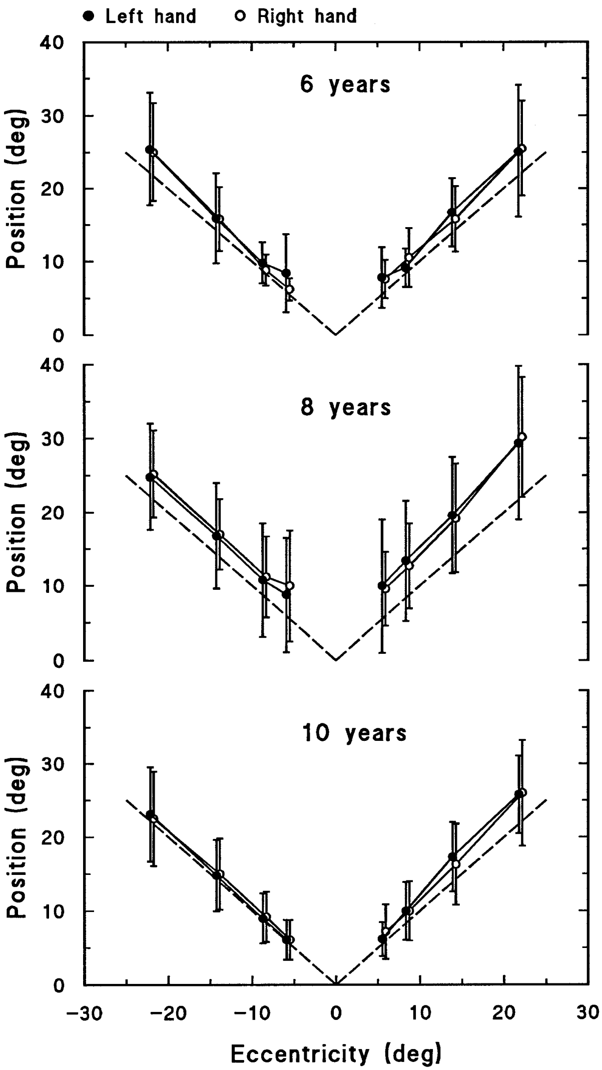

FIG. 3. Mean final position for the 6-, 8-, and 10-year-old groups as a function of hand, visual field and target eccentricity. Error bars indicate the intersubject standard deviations. Negative eccentricities correspond to the left visual field. The vertical distance between the mean position and the dashed line is equal to the constant error.

Reaction time. RT is plotted by hand, visual field, and age group in Fig. 5. The mean RT ranged from 230 to 360 msec. Only one effect was significant. It can be observed in Fig. 5 that RT changed in a complex way with age ($F(4, 55) = 7.67$, $p < .001$). The orthogonal polynomial contrasts indicate significant linear and quartic components ($F(1, 55) = 24.29$, $p < .001$, and

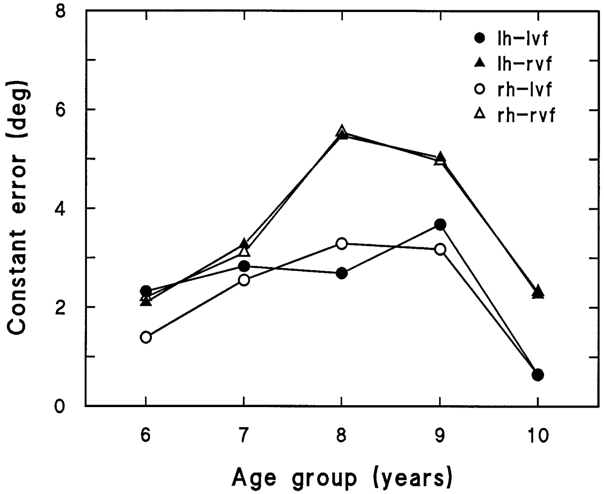

FIG. 4. Mean constant error as a function of hand (lh, left hand; rh, right hand), visual field (lvf, left visual field; rvf, right visual field), and age group.

$F(1, 55) = 5.76$, $p = .020$, respectively). This means that there was a general decrease of RT with age, but with three significant changes of slope. Post-hoc analyses revealed that RT decreased between 6 and 7 years, it did not change significantly between 7 and 8 years, it decreased again between 8 and 9 years, and finally was not significantly different between 9 and 10 years.

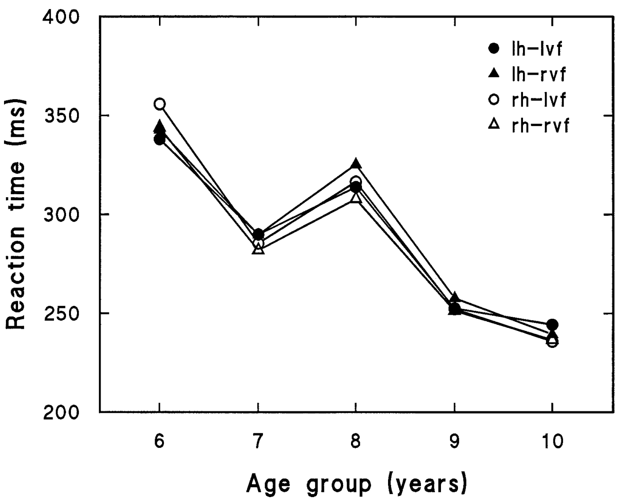

FIG. 5. Mean reaction time as a function of hand, visual field and age group. Conventions are the same as in Fig. 4.

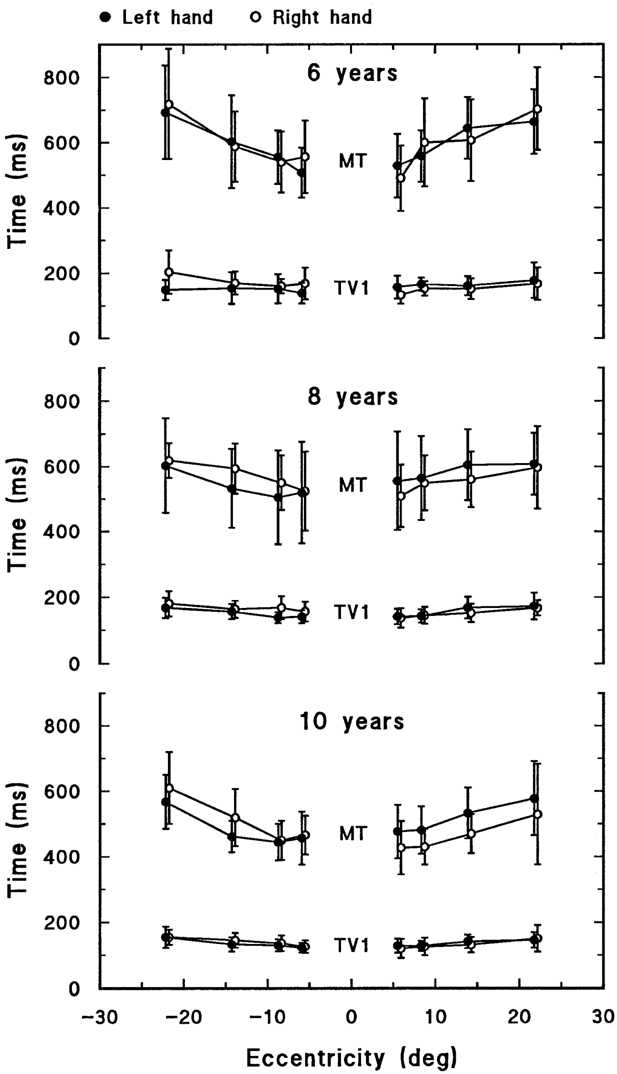

FIG. 6. Mean time of peak velocity (TV1) and mean movement time (MT) for the 6-, 8-, and 10-year-old groups as a function of hand, visual field and target eccentricity. Error bars indicate the intersubject standard deviations. Negative eccentricities correspond to the left visual field.

Temporal parameters. Temporal parameters—TV1 and MT—are plotted in Fig. 6 by hand, visual field, and eccentricity for the 6-, 8-, and 10-year-old groups. TV1 and MT increased slightly but significantly with target eccentricity ($F(3, 165) = 43.78$, $p < .001$ for TV1; $F(3, 165) = 58.54$, $p < .001$ for MT). Both had smaller values for ipsilateral than for contralateral

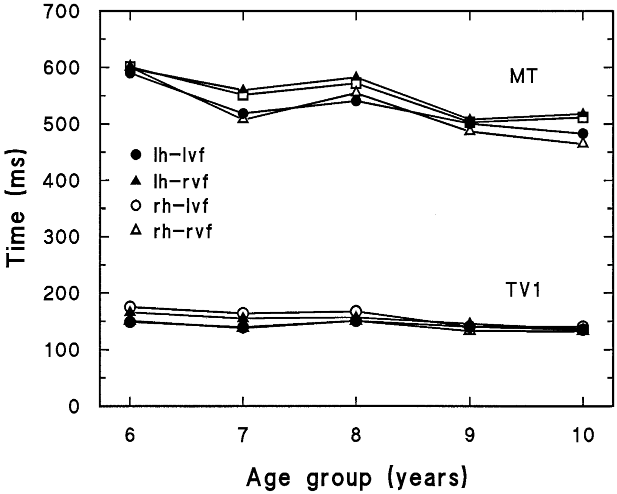

FIG. 7. Mean time of peak velocity (TV1), and mean movement time (MT) as a function of hand, visual field and age group. Conventions are the same as in Fig. 4.

movements (H by VF: $F(1, 55) = 37.65$, $p < .001$ for TV1; $F(1, 55) = 18.71$, $p < .001$ for MT). The difference in MT between ipsilateral and contralateral conditions decreased with age (Age by H by VF: $F(4, 55) = 5.26$, $p = .001$).

However, temporal parameters were affected by age as can be seen in Fig. 7 ($F(4, 55) = 4.54$, $p = .003$ for TV1; $F(4, 55) = 8.69$, $p < .001$ for MT). Orthogonal polynomial contrasts showed that the linear component was significant with both temporal parameters ($F(1, 55) = 13.95$, $p < .001$ for TV1; $F(1, 55) = 26.77$, $p < .001$ for MT). Moreover, the quartic component was also significant with MT ($F(1, 55) = 7.23$, $p = .009$). Thus, MT showed a similar profile with age than the one obtained with RT.

Spatio-temporal parameter. V1 increased with target eccentricity ($F(3, 165) = 139.72$, $p < .001$). Moreover, V1 was larger for right visual field targets than for left visual field targets ($F(1, 55) = 5.83$, $p = .019$). The difference between visual fields increased with target eccentricity (VF by E: $F(3, 165) = 6.53$, $p < .001$). Furthermore, the difference of V1 between both visual fields changed with age (Age by VF: $F(4, 55) = 2.80$, $p = .035$). In fact, post-hoc analyses showed that this difference is significant only from 8 to 10 years.

Discussion

The main results were that CE for right visual field targets increased from 6 to 8 years and decreased afterward from 9 to 10 years. The difference of CE between visual fields occurred at 8 years, and coincided with a temporary slowing down in the rate of decrease of RT and MT. The aim of the following experiments was to specify the processes that are putatively responsible for these effects.

A difference of V1 between visual fields had also been observed for the 8- to 10-year-old groups; V1 was greater when targets were presented in the right visual field. It can be shown that this effect was obtained because the subjects were making movement of larger amplitude when targets were presented in the right visual field, and that the larger the amplitude of the movement the greater the velocity. For this purpose, we tested a power law relating V1 to the actual movement amplitude (A):

$$V1 = KA^{\beta},$$

where K and β were estimated using the linear regression between Log(V1) and Log(A). The correlation coefficient did not change significantly with age, nor with hand or visual field factors. The average correlation coefficient (averaged after Fisher's *z* transform) was $r = 0.94$. Thus, the power law was a good description of the relation between these two variables in all conditions and all age groups. The intercept (i.e., Log(K)) increased linearly with age ($F(1, 55) = 7.11$, $p = .010$) from 0.970 ($SD = 0.071$) at 6 years to 1.058 ($SD = 0.074$) at 10 years. This indicates that movements of given amplitude were executed faster with increasing age. More important, there was no significant effect on the value of the slope β. That is, the shape of the relation between the amplitude of the movement and the velocity was constant across age and conditions. The average slope was $\beta = 0.88$ ($SD = 0.08$) which indicates that the magnitude of the velocity increased slightly less than the movement amplitude. This value is close to what was obtained with adult subjects (Milner, 1986). These results suggest that the way the movement is controlled and executed remains the same from 6 to 10 years of age and is also similar to adult performance.

The covariation between the magnitude of the velocity and the amplitude of the movement marks a tendency to isochrony. That is, the increase of movement amplitude is compensated by an increase of movement velocity that maintains the movement time almost constant. Despite this tendency to isochrony, the analyses of variance had shown that the values of the temporal parameters increased significantly with the target eccentricity. However, the analyses of the effect size showed that the target eccentricity explains more variance of V1 than of TV1 (72 and 44%, respectively). That is, the variation of V1 with target eccentricity is a more important effect, than the variation of TV1. Thus, the results suggest that the tendency to isochrony was present in all age groups from 6 to 10 years. It should be noted, that the tendency to the movement isochrony during childhood has been documented for movements as different as forearm's swings (Viviani & Zanone, 1988) and drawings (Vinter & Mounoud, 1991; Viviani & Schneider, 1991). Overall, these results suggest that the control and execution of the movement do not change significantly between 6 and 10 years of age and thus cannot account for the non-monotonic changes observed on RT, MT and CE.

Experiment 2: Perceptual Localization Task

The change of spatial accuracy with age in Experiment 1 shows a complex profile. Processing stages like the spatial localization of the target, and the conversion from visual to motor coordinates could all be involved in this effect. The aim of this experiment was to test the spatial accuracy of the perceptual localization independently of the movement accuracy.

Apparatus

The apparatus was partly the same as in the previous experiment. Stimuli were produced in the same way, but a computer mouse with two switches was used for the response. A press on the left or the right switch produced a horizontal displacement of a red light spot on the screen respectively to the left or the right. Each press produced a displacement of 0.5 degrees of visual angle.

Procedure

Targets were presented exactly in the same way as in Experiment 1. Immediately after the target presentation a red light spot of unlimited duration appeared at the center of the screen. The subjects were asked to displace the red light spot toward the position where they had perceived the target. They responded by doing successive presses on the appropriate mouse switch. There was no time constraint to give the response. Note that there was no hand factor in this experiment. The subject used usually one finger of one hand on a switch and one finger of the other hand on the other switch. Several familiarization trials were performed before the experimental trials. The number of experimental trials per subject was 24 in the 6-year-old group, 32 in the 7-year-old group, and 40 in the 8-, 9-, and 10-year-old groups.

Results

For all age groups and both visual fields, CE had a smaller value than the target width (0.8 degrees). Indeed, CE never exceeded 0.6 degrees of visual angle, which means that it was practically negligible. On the other hand, VE increased with target eccentricity ($F(3, 165) = 50.27$, $p < .001$). However, values of VE were small compared to the target width; mean VE from the smallest to the largest target eccentricity was 0.5 degrees ($SD = 0.2$), 0.6 degrees ($SD = 0.3$), 0.8 degrees ($SD = 0.3$), and 1.1 degrees ($SD = 0.5$) respectively.

Discussion

We tested the accuracy of perceptual localization of lateralized visual target, in order to compare it with the accuracy of visuo-manual aiming movements obtained in Experiment 1. In contrast to what was observed in Experiment 1, we found that the spatial error of the perceptual localization was practically negligible for all age groups and conditions.

First, the question may be raised whether perceptual report and visuo-manual aiming use the same visual information. Indeed, Goodale, Pélisson, and Prablanc (1986) for example showed that normal subjects could reach a visual target in open-loop conditions, although they were not aware that the target was shifted during the saccade of the eye. This indicates that the information used for visuomanual aiming may be dissociated from perceptual awareness. However, this does not mean that the perceptual localization of the target is not modified. Indeed, when the perceptual localization of targets shifted during the saccade is measured, it is highly correlated with the motor localization (Honda, 1990). This suggests that the information about the localization of the target is the same for perceptual and motor localizations.

The results obtained in Experiment 2 suggest that the complex development of CE in Experiment 1 cannot be attributed to the process of perceptual localization of the target. Indeed, the perceptual localization of the target was accurate for each age group, visual field, and even target eccentricity. Thus, we must assume that other processes accounted for the complex development of CE in the open-loop aiming movement task. One process that is present in the visuo-manual aiming task, and is absent in the perceptual localization task, is the conversion from visual to motor coordinates. Therefore, this process is likely to be responsible for the change of CE with age observed in Experiment 1.

Experiment 3: Simple Reaction Time Task

The change of RT with age observed in Experiment 1 cannot be described as a simple linear function. The aim of this experiment was to test the change of RT with age in a task that did not require the spatial processing of the target, nor the conversion from visual to motor coordinates that were involved in Experiment 1.

Apparatus

The apparatus was the same in Experiment 2. A press on one of the switches recorded the value of the clock of the AD converter with a precision of 1 msec. The clock was initialized at the onset of the target.

Procedure

Targets were presented exactly as in the two previous experiments. The subjects were instructed to press a switch as quickly as possible when the target appeared. Several familiarization trials were performed before the experimental trials. One half of the experimental trials was performed with one hand and the other with the other hand. The order of responding hands was counterbalanced across the subjects. The number of experimental trials per subject was 48 in the 6-year-old group, 64 in the 7-year-old group, and 80 in the 8-, 9-, and 10-year-old groups.

Results

The only significant effect observed on RT was due to the age factor ($F(4, 55) = 9.47$, $p < .001$). The orthogonal polynomial contrasts showed that only the linear component was significant ($F(1, 55) = 34.77$, $p < .001$). This indicates that RT decreased in a simple progressive way with age. Mean RT for each age group was, respectively, 458.5 msec ($SD = 90.3$), 386.9 msec ($SD = 50.1$), 370.1 msec ($SD = 48.8$), 332.4 msec ($SD = 59.9$), and 320.3 msec ($SD = 47.7$).

Discussion

In Experiment 1, RT changed in a complex way with age; it decreased from 6 to 10 years of age, with a distinctive plateau between 7 and 8 years of age. In contrast, simple RT to lateralized visual targets decreased linearly with age. This is particularly remarkable for the same subjects were tested in both experiments. These results indicate that some of the processes involved in the two tasks develop in a different way with age. In the simple reaction time task, the spatial localization of the target and the conversion from visual to motor coordinates were not relevant processes, whereas they were critical in the visuo-manual aiming task. Thus, it can be hypothesized that the different developmental profiles of RT in Experiments 1 and 3 were produced by one or both of these processing stages. This will be further discussed under General Discussion.

It can also be noticed that RT was of longer duration in Experiment 3 than in Experiment 1. Now, if we consider RT in the aiming task a choice RT, we would expect the reverse, since it is known that simple RT are shorter than choice RT. This effect was most probably due to technical changes in recording RT. Indeed, in the open-loop aiming movement task, RT was measured at the very beginning of the movement (i.e., increase of acceleration, Fig. 2), whereas in this third experiment, the response was detected when the switch was pushed down and therefore slightly after the movement was initiated.

GENERAL DISCUSSION

The aim of the three experiments presented was to gain information about the origin of the temporary decrease of visuo-manual performance occurring at about 8 years of age that was documented in the literature. We assumed that the changes observed at the behavioral level are consequences of changes occurring to the neural components involved while performing the task. The different developmental profiles of performance in the experiments agree with the idea that the neural components related to the different information processes develop a different times. Moreover, the asymmetry observed in some of the data are compatible with studies indicating that homologous regions of both cerebral hemispheres develop asynchronously (Rabinowicz et al., 1977; Thatcher et al., 1987).

The following general conclusions can be drawn when the three experiments are considered together. A first result was the non-monotonic age-related change of RT in the main experiment; particularly noteworthy was the plateau between 7 and 8 years of age. Let us recall that in Experiment 3, the simple RT to the same stimuli decreased linearly with age. RT is traditionally considered to reflect the processing time of the operations involved in the generation of the response (Sternberg, 1969). In this context, the relative increase of RT from the age of 8 years in Experiment 1 suggests that a qualitative change occurred in the operations that the children use to perform the task. The complex development of RT in Experiment 1 may result from age-related transformations in at least one of the following processes involved in performing the task, that is, the spatial localization of the target and the conversion from visual to motor coordinates. The second of these components is the best candidate, for no age-related change in the spatial localization of the target was observed in Experiment 2. Some aspects of the performance dramatically suffered from this change (even until the age of 10).

Indeed, as a second result to discuss is the non-monotonic age-related change of CE observed in Experiment 1. This result is similar to what was observed in other developmental studies that required the control of amplitude in open-loop aiming movements (Bard et al., 1990; Hay, 1978, 1979; Fayt et al. 1993; von Hofsten & Rösblad, 1988). However, previous studies did not use lateralized visual targets and consequently CE could not be analyzed according to the visual field. In contrast, in the present study CE was evaluated separately for both visual fields. It was found in Experiment 1 that CE increased temporarily at 8 years only in the condition where the targets were presented in the right visual field, that is, to the left cerebral hemisphere. It is remarkable that this age-related change of CE was observed for both hands, one of them responding through extension movements and the other through flexion movements. This suggests that its very origin is likely related to a process preceding the motor command.

In contrast, results of Experiments 2 and 3 showed simple changes of performance with age. Accuracy of visual processing of stimuli was independent of age (Experiment 2), and the speed of visuo-motor connection increased linearly across the age groups (Experiment 3). Therefore, these processes cannot explain the non-monotonic change of performance observed in Experiment 1. Moreover, the hypothesis that a feedback-based guiding system adds to a previously operational programming system at approximately 8 years of age (Hay, 1978, 1979) was not supported by the results. Indeed, for each hand of response and visual field, we failed to observe change in the degree of movement discontinuities across the age groups. This is in agreement with other studies in which fast movements were tested

(Mounoud et al., 1985; Schellekens et al., 1984). Furthermore, the analysis of kinematics of Experiment 1 indicated that the execution and control of the pointing movements had the same characteristics across the age groups, and therefore cannot account for the change of CE with age.

Consequently, the origin of the non-monotonic development observed in the spatial aspects of the aiming task may be attributed to modifications, in the left cerebral hemisphere, of a process located downstream with respect to the perceptual visual processes and upstream with respect to the motor processes. In other words, the functional link, in the left cerebral hemisphere, between the visual and motor processes is here concerned. This linking process is assumed to translate the coordinates of the target from the visual space to the motor space. Note that these results suggest the existence of relatively independent visuo-manual linking processes in each cerebral hemisphere, which is in agreement with studies on prism adaptation in normal adults (Martin & Newman, 1980; Redding & Wallace, 1988) and studies on the visuo-manual performance of brain-damaged (Jeannerod, 1986; Perenin & Vighetto, 1988; Rondot, de Recondo, & Ribadeau Dumas, 1977) and split-brain patients (Gazzaniga, 1970).

At this point, two questions may be raised: (1) Why the results show an asymmetry for CE and not for RT? and (2) why the temporary increase of CE, as documented in the literature, can be observed in unrestrained visual conditions of target presentation (i.e., not lateralized targets)? We may attempt to give a common explanation to these two questions. Indeed, it seems that both questions can be answered by assuming that the visuo-manual linking process of the left cerebral hemisphere plays a major role in the aiming task. Studies on apraxia (Heilman, 1979) and optic ataxia (Perenin & Vighetto, 1988) support this assumption; both lines of evidence reveal the prevailing role of the visuo-manual processes located in the left cerebral hemisphere. Change in the properties of this process seem to occur at about 8 years of age. This change produces a temporary perturbation of the efficiency of the process. Now, if this process has a major weight in the system, it may affect (1) the onset of the motor response in every condition tested in Experiment 1, and (2) the spatial precision of the motor response in conditions of unrestrained target presentation. In other words, the hypothesis is that when targets are presented in free vision, the left cerebral process does the conversion from visual to motor coordinates, at least from 8 years on, and CE reflects its properties. Instead, in the particular case of lateralized visual targets the visuo-motor conversion is performed by the hemisphere receiving the input, hence, the difference of spatial accuracy according to the visual field of presentation. However, even in this case, the prevailing left cerebral process affect the processing performance of the system, which is reflected by RT.

The general conclusion drawn from the results of the three experiments is that the non-monotonic changes observed were related to the process linking, in the left cerebral hemisphere, visual to motor coordinates. Age-related trends like these should not be observed if this process consists of simple prewired input-output linkage. Such results strongly suggest that some qualitative transformations in the operations responsible for the visual-motor coordination take place during the child development. Other experiments are required to pinpoint what operations that process acquires or lose during childhood. Given that these operations mediate the visuo-motor coordination, they may be considered as functional representations of the relations between properties of the environment and of the motor system (Mounoud et al., 1985). In other words, these results reveal transformations of these functional representations during childhood.

REFERENCES

Allen, M. 1983. Models of hemispheric specialization. *Psychological Bulletin,* **93,** 73–104.

Bard, C., Hay, L., & Fleury, M. 1990. Timing and accuracy of visually directed movements in children: Control of direction and amplitude components. *Journal of Experimental Child Psychology,* **50,** 102–118.

Brinkman, J., & Kuypers, H. G. J. M. 1973. Cerebral control of contralateral and ipsilateral arm, hand and finger movements in the split-brain rhesus monkey. *Brain,* **96,** 653–674.

Brooks, V. B. 1974. Some examples of programmed limb movements. *Brain Research,* **71,** 299–308.

Brown, J. V., Sepehr, M. M., Ettlinger, G., & Skreczek, W. 1986. The accuracy of aimed movements to visual targets during development: The role of visual information. *Journal of Experimental Child Psychology,* **141,** 443–460.

Bryden, M. P. 1977. Measuring handedness with questionnaires. *Neuropsychologia,* **15,** 617–624.

Conel, J. 1939–1967. *The postnatal development of the human cerebral cortex.* Harvard University Press, Cambridge MA. (Vols. 1–8).

Connolly, K. J., Brown, K., & Basset, E. 1968. Developmental changes in some components of a motor skill. *British Journal of Psychology,* **59,** 305–314.

Fayt, C., Minet, M., & Schepens, N. 1993. Children's and adults' learning of a visuomanual coordination: Role of ongoing visual feedback and of spatial errors as a function of age. *Perceptual and Motor Skills,* **77,** 659–669.

Gazzaniga, M. S. 1970. *The bisected brain.* New York: Appleton-Century-Crofts.

Goodale, M. A., Pélisson, D., & Prablanc, C. 1986. Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature,* **320,** 748–750.

Hay, L. 1978. Accuracy of children on an open-loop pointing task. *Perceptual and Motor Skills,* **47,** 1079–1082.

Hay, L. 1979. Spatial-temporal analysis of movements in children: Motor programs versus feedback in the development of reaching. *Journal of Motor Behavior,* **11,** 189–200.

Hay, L. 1981. The effect of amplitude and accuracy requirements on movement time in children. *Journal of Motor Behavior,* **13,** 177–186.

Hay, L., Bard, C., Fleury, M., & Teasdale, N. 1991. Kinematics of aiming in direction and amplitude: A developmental study. *Acta Psychologica,* **77,** 203–215.

Heilman, K. M. 1979. Apraxia. In K. M. Heilman, and E. Valenstein (Eds.), *Clinical neuropsychology.* New York: Oxford University Press. Pp. 159–185.

Hofsten, C. von, & Rösblad, B. 1988. The integration of sensory information in the development of precise manual pointing. *Neuropsychologia,* **26,** 805–821.

Holland, B. A., Haas, D. K., Norman, D., Brant-Zawadski, M., & Newton, T. H. 1986. MRI of normal brain maturation. *American Journal of Neuroradiology,* **7,** 201–208.

Honda, H. 1990. Eye movements to a visual stimulus flashed before, during or after a saccade. In M. Jeannerod (Ed.), *Attention and Performance XIII*. Hillsdale, NJ: Erlbaum. Pp. 567–582.

Jeannerod, M. 1986. Mechanisms of visuomotor coordination: A study in normal and brain-damaged subjects. *Neuropsychologia,* **24,** 41–78.

Kerr, R. 1975. Movement control and maturation in elementary-grade children. *Perceptual and Motor Skills,* **41,** 151–154.

Martin, L. M., & Newman, C. V. 1980. Simultaneous right- and left-hand adaptation in opposite lateral directions following bidirectional optical displacement. *Bulletin of the Psychonomic Society,* **16,** 432–434.

Milner, T. E. 1986. Controlling velocity in rapid movements. *Journal of Motor Behavior,* **18,** 147–161.

Moscovitch, M. 1986. Afferent and efferent models of visual perceptual asymmetries: Theoretical and empirical implications. *Neuropsychologia,* **24,** 91–114.

Mounoud, P., Viviani, P., Hauert, C. A., & Guyon, J. 1985. Development of visuomanual tracking in 5- to 9-year-old boys. *Journal of Experimental Child Psychology,* **40,** 115–132.

Perenin, M. T., & Vighetto, A. 1988. Optic ataxia: A specific disruption in visuomotor mechanisms. I. Different aspects of the deficit in reaching for objects. *Brain,* **111,** 643–674.

Rabiner, L. R., & Gold, B. 1975. *Theory and application of digital signal processing.* New Jersey: Prentice–Hall.

Rabinowicz, T., Leuba, G., & Heumann, D. 1977. Morphologic maturation of the brain: A quantitative study. In S. R. Berenberg (Ed.), *Brain. Fetal and infant.* The Hague: Martinus Nijhoff. Pp. 28–53.

Redding, G. M., & Wallace, B. 1988. Components of prism adaptation in terminal and concurrent exposure: Organization of the eye hand coordination loop. *Perception & Psychophysics,* **44,** 59–68.

Rondot, P., de Recondot, J., & Ribadeau Dumas, J. L. 1977. Visuomotor ataxia. *Brain,* **100,** 355–376.

Salmoni, A. W. 1983. A descriptive analysis of children performing Fitts' reciprocal tapping task. *Journal of Human Movement Studies,* **9,** 81–95.

Schellekens, J. M. H., Kalverboer, A. F., & Scholten, C. A. 1984. The micro-structure of tapping movements in children. *Journal of Motor Behavior,* **6,** 20–32.

Sternberg, S. 1969. The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica,* **30,** 276–314.

Sugden, D. A. 1980. Movement speed in children. *Journal of Motor Behavior,* **12,** 125–132.

Thatcher, R. W., Walker, R. A., & Giudice, S. 1987. Human cerebral hemispheres develop at different rates and ages. *Science,* **236,** 1110–1113.

Vinter, A., & Mounoud, P. 1991. Isochrony and accuracy of drawing movements in children: Effects of age and context. In J. Wann, A. M. Wing and N. Sõvik (Eds.), *Development of graphic skills.* London: Academic Press. Pp. 113–134.

Viviani, P., & Schneider R. 1991. A developmental study of the relationship between geometry and kinematics in drawing movements. *Journal of Experimental Psychology: Human Perception and Performance,* **17,** 198–218.

Viviani, P., & Zanone, P. G. 1988. Spontaneous covariations of movement parameters in 5- to 7-year-old boys. *Journal of Motor Behavior,* **20,** 5–16.

Yakovlev, P. I. & Lecours, A. R. 1967. The myelogenetic cycles of regional maturation of the brain. In A. Minkowski (Ed.), *Regional development of the brain in early life.* Oxford: Blackwell Scientific Publications. Pp. 3–70.