Timing and Accuracy of Visually Directed Movements in Children: Control of Direction and Amplitude Components

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The reaction times (RTs), movement times (MTs), and final accuracy of hand movements directed towards visual goals were measured in 6-, 8-, and 10-year-old children, using tasks in which direction and amplitude components of movement were distinctly required. The tasks were performed with and without visual feedback of the limb. RTs decreased with age, and were shorter in directional than in amplitude task, in all ages. MTs were the longest at age 8 in both tasks, equally short at ages 6 and 10 in the directional task, the shortest at age 10, and intermediate at age 6, when amplitude had to be regulated. In the amplitude task, the target distance generally affected MTs under both visual conditions, but to a lower degree at age 10 than in the two younger groups. Movement accuracy, which was in all cases higher with visual feedback, showed different developmental trends among the two spatial components: directional accuracy was not different among the three groups of age, whereas amplitude accuracy showed a nonmonotonic development in the nonvisual condition, with an increase between age 6 and age 10, and the lowest level at age 8. In the visual condition, amplitude accuracy did not change with age. The specification of direction seems therefore to predominantly load the preparatory stage of the response. Amplitude specification seems to be more dependent on on-going regulations and to undergo a longer and more complex development, with a critical period around age 8 when a greater propensity for a feedback-based control appears on the two
components. With increasing age, amplitude tends to be specific to a greater extent by a feedforward process. © 1990 Academic Press, Inc.

INTRODUCTION

When studying goal-directed movements, timing and spatial accuracy have been used to investigate control processes involved during the preparatory and execution phases of the response. The relationships between the temporal and spatial parameters of movements during the execution phase were formulated into a law by Fitts (1954). He provided an experimental and a theoretical framework to investigate the level and the type of information to be processed by the motor system to correctly perform a motor skill. Fitts studied back and forth tapping movements on two targets. Target distance and width could be varied, and thus determine an index of difficulty of the task (ID), representing the information load. Movement time (MT) is related to ID according to the formula $MT = a + b \cdot ID$, where $a$ (intercept) and $b$ (slope coefficient) are the empirical regression parameters. Fitts' Law turned out to be a good predictor of hand movement time in a remarkably wide range of tasks. In fact, it frequently accounted for more than 90% of the variance in mean MTs. Although Fitts’ Law was initially based on serial reciprocal tapping movements, it appears to hold for performance on discrete goal-directed movements as well. It was consistent with earlier results on the relationship between MT and amplitude and it was replicated in studies involving discrete pointing movements in adults as well as in developmental studies involving both discrete and serial pointing tasks.

Beyond formulating relationships between MT, target width, and amplitude in serial tapping movements, Fitts’ model is an appropriate theoretical tool for approaching the processes involved in the execution phase of visually directed movements. Indeed, it is consistent with the results of studies investigating the time required for correcting on-going movement on the basis of visual feedback processing (Crossman & Good- eve, 1963; Keele, 1968). Goal-directed movements generally involve ballistic (feedforward) and feedback control processes. Using the Fitts’ paradigm, developmental studies have shown that the intercept coefficient decreases with increasing age, suggesting that a developmental reduction in the “homing” time (feedback processing) takes place. Conversely, the duration of the ballistic phase, revealed by the slope coefficient, remains constant at all ages (Kerr, 1975, 1985; Sugden, 1980). Nevertheless some studies have also shown a reduction in slope coefficient (Hay, 1981; Salmoni & Pascoe, 1978), suggesting that both ballistic and feedback processes could undergo developmental changes. Schel- lekens, Kalverboer, and Scholten (1984), on the basis of a detailed spatio-temporal analysis of visually controlled tapping movements, have shown that with increasing age, the ballistic phase improves in accuracy (close-
ness of approach) with age while duration is kept constant. Such mod-
ifications result in a reduction of the duration and number of movement
elements during the homing phase, which could thus be one of the causes
of the age-related decrease in movement time. It probably facilitates
further integration of this phase into a smooth approach movement.

The same type of spatio-temporal analyses have been made in children
performing discrete visually controlled pointing movements (Van Dellen
& Kalverboer, 1984). Similar developmental trends to Schellekens et al.
(1984) were found, confirming the two-phase models in single movement
control. Other studies, using experimental situations in which visual
feedback was distorted or not involved in on-line regulation, have shown
that the feedforward and feedback components of action develop alter-
ately; stages characterized by dominant ballistic-like control of move-
ment are followed by stages characterized by dominant feedback-based
control which will, in turn, decrease. This alternation has been found
both in infants (McDonnell, 1975; McDonnell & Abraham 1981; Mounoud
& Hauret, 1982) and in children (Gachoud, 1983; Hay, 1979), suggesting
that younger subjects have difficulty integrating feedback information in
the ongoing action.

Developmental trends can also be observed in the preparatory stage
of the response. When reaction times (RTs) are measured per se (without
subsequent oriented movement), they clearly decrease with age, with a
particularly strong effect in the younger ages. On the other hand, RTs
measured as latencies preceding goal-directed movements show much
less marked age-related changes (Bard & Hay, 1983); they are found to
decrease only between the age of 2 to 5, and to remain unchanged
between the age of 5 to 8 (Brown, Sepher, Ettlinger, & Skreczek, 1986).
As suggested by Brown et al. (1986), it is possible that from age 5, more
information processing occurs prior to movement execution, and thus
RT becomes longer than when no subsequent oriented movement is
performed.

Reaching a visual goal in the prehension space requires that the di-
rection and amplitude of the hand movement be correctly specified and
controlled (Paillard, 1985). With regard to movement preprogramming,
several choice RT studies have shown, either by varying direction or
amplitude uncertainty (Fiori, Semjen & Requin, 1974; Megaw, 1972), or
by means of a precuing technique (Bonnet, Requin & Stelmach, 1982;
Rosenbaum, 1980), that directional programming is more time consuming
than amplitude programming, suggesting that on-line regulations are more
involved in amplitude than in directional control. With regard to feedback
processing, it seems that, depending on whether the task requirements
focus on direction or amplitude, visual feedback can be integrated within
different temporal ranges (Hay, Beaubaton, Bard, & Fleury, 1984), and
during different phases of the trajectory (Conti & Beaubaton, 1976): initial
phase under directional control (Bard, Hay, & Fleury, 1985), and final
phase under amplitude control (Beaubaton & Hay, 1986; Carlton, 1981).
From an ontogenetical point of view, directional regulation seems to be
an earlier acquisition than amplitude regulation. Von Hofsten (1982),
when discussing his results on neonate eye-hand coordination, has con-
cluded that the reacting space of the newborn shows a cruder distance
structuring, if any, than direction structuring, since the gain in distance
accuracy when reaching watched objects over unwatched objects is not
very large. In children performing movements without visual feedback,
programming seems to reach its highest efficiency quite early (at about
7 years of age) when directional requirements only are imposed (Bard
& Hay, 1983), whereas it takes longer to develop in pointing tasks in
which both requirements are involved indiscriminately (Hay, 1978). In
such pointing tasks, an early development of accuracy is found, as in a
purely directional task, when it is measured in term of directional error,
showing a linear increment between 2.5 and 8 years of age (Brown et
al., 1986).

Therefore, it seems appropriate to investigate the development of pre-
programming and feedback-based control capacities, using tasks involv-
ing directional and/or amplitude components, thus allowing their re-
spective weighting on movement control in children. For this purpose,
reaction time, movement, and spatial accuracy of target-aiming move-
ments with either direction or amplitude requirements have been ana-
alyzed in children performing directional, amplitude, and directional/
amplitude tasks, with and without visual feedback from their movements
(that is to say, tasks performed in closed- and open-looped conditions).

Since direction specification seems the most time consuming (as al-
ready shown in adults), reaction times should be shorter when only
amplitude requirements are involved in the task than in a purely direc-
tional task. When both requirements are involved together, reaction times
should be longer than in the single component tasks, since additional
information has to be processed to prepare a more complex movement.
Reaction times are expected to decrease with increasing age, whatever
the spatial requirements of the task, and to change according to the
availability of visual feedback since on-line control could replace, at least
partly, anticipatory control under visual conditions.

Movement speed and accuracy are, therefore, liable to modification
with age, but with different developmental trends when amplitude has
to be regulated than in the case of a pure directional control. The rationale
for this hypothesis is that amplitude regulation is more closely concerned
with the development of both feedforward and feedback processes and
with their cooperation than directional control which mostly depends on
feedforward processes. This should be shown by an earlier attainment
of optimal time and accuracy levels with directional rather than amplitude control. Moreover, with amplitude control, the increase of movement time with movement amplitude should be less marked as children grow up, since the ballistic component of movement increases in efficiency.

METHOD

Subjects
Three groups of 6-, 8-, and 10-year-old children (4 boys and 4 girls per group), were used in this study. All were right-handed and had a normal scholastic level. The exact mean age and range for each group was 5.9 years (5 years, 8 months to 6 years, 1 month), 8.1 years (7 years, 8 months to 8 years, 5 months), and 10.2 years (9 years, 11 months to 10 years, 4 months), respectively.

Apparatus
The subjects sat astride an adjustable seat, with his/her chest leaning against a vertical support. In front of this support was a hand lever, extending from the floor between the legs to chin level. The lever, which could be projected from the resting position to a full arm extension, was equipped with a double universal joint at floor level. Two potentiometers perpendicularly attached to the basis of the lever (universal joint) allowed the recording of all frontal and lateral angular displacements. The signal from the potentiometers was digitized with a 12 bits resolution every 3 ms. The potentiometric values corresponding to lever positions were automatically translated into angular or amplitude values.

In front of the subject, a horizontal support was fitted at eye-level with a set of nine targets. Just behind this support, a vertical curved screen served as a visual background. Support and screen were painted matt black. In the directional task, three targets were used, located on an arc of a circle, 300 mm at 0, 20, and 40° of eccentricity in the right hemifield of the subject. In the amplitude task, three targets placed on the sagittal plane at eye-level were used; they were located at 200, 250, and 300 mm from the subject, respectively. Targets were 5 mm-wide, 100 mm-high vertical tubes, made of translucent Plexiglas, lit by green diodes. The room was in dim light. Vision of the hand trajectory could be precluded by a black horizontal screen which could be fixed to the apparatus just above the hand level, and which covered the area of the hand displacements, preventing on-line feedback.

Procedure
Each subject had to perform three types of visuo-manual aiming tasks, holding the lever in his/her right hand and moving back to the resting position at the end of each trial (Fig. 1). In the first, purely directional task (1), the three targets on a frontal plane were used, and the subjects
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Fig. 1. Schema of the three aiming conditions. Black dots represent targets used in a specific condition.

were required to move the lever in the direction of the lit target and to overshoot it, moving their arm from a flexed position to full extension. Angular error and movement time were recorded as the hand crossed the target line. The second task, a pure amplitude task (2), was performed with the three targets located on a sagittal plane. In this case, the lever was laterally locked and could only move in the sagittal plane along the target line. The subjects were then required to push the lever until reaching a position just below the target with the pointer. The amplitude error was recorded as soon as the hand stopped. In the third task (3), the direction and amplitude requirements were combined, the subjects had to move the lever in the accurate direction and stop just below the target. In this case, the directional amplitude aiming errors were recorded.

All three tasks were performed under two visual conditions: one allowing vision of the hand trajectory (providing on-line feedback), the other without vision of the hand (precluding on-line feedback).

For all conditions, the three targets were randomly presented five times. The three tasks were performed by all subjects, in a varied order within each age group. There were resting periods between the presentation of the different tasks during which children were occupied with other sorts of games. The nonvisual condition was always applied before the visual condition, in order to avoid transfer to the task performed without on-line feedback from the on-line feedback execution of the task.

A few practice trials were given to the children before each experimental series on a specific task in order to ensure their understanding of the task; only 3 or 4 trials were necessary for that purpose and children were then provided with knowledge of results (KR) on accuracy and speed of their movement. The practice trials were performed under visual feedback condition because visual familiarization with the entire task environment seemed necessary before precluding vision of the area of the hand displacements. In order to avoid transfer from the practice trials to the nonvisual condition, targets not used for data collection were used.
for practice. In each trial, children were given a verbal preparatory signal ("ready") and, about 1 s later, the target lit up. In all tasks, the targets lit for the entire movement duration. Besides the specific aiming instructions given for each task, children were required to aim as accurately as possible, and they were also encouraged to perform their movement with some briskness. They were not asked to work at their maximum rate since accuracy requirements were stressed, but they were asked not to make hesitating movements. The verbal instructions were "As soon as the target lights up, you have to go and get it; you must be very careful in order to be accurate. But you must not be too slow; it is like "star war," you must shoot it quickly before it goes away, but you must also be very accurate because you have only one shot to get it and you must not miss it." Other scenarios could be told, or in the case where a child wanted to be told another story that he/she preferred, the experimenter could agree with this story if it was likely to work as a context which also could adequately incite the child to be accurate and brisk. The temporal and spatial performance of the subject could be controlled on-line on a monitor. Trials for which MT exceeded 800 ms were cancelled and given again. According to the subject's attentional behavior the instructions could be partly repeated during the session. Irrelevant of the subjects' performance, verbal incentives were given throughout the session (such as "you are good, go on"). No performance feedback, however, was provided throughout the experimental session.

RESULTS

Dependent Variables and Statistical Analyses

Reaction time (RT), movement time (MT), directional error, and amplitude error were the dependent variables. RT was the time from the lighting up of the target to the initiation of the movement, and MT was the time from initiation to end of the movement. Directional error was the left/right angular distance between hand and target measured at the target level. Amplitude error was the forward/backward distance between hand and target measured along the movement axis. Both spatial errors were processed in absolute values as our purpose was to analyze the relative changes in direction and amplitude accuracy according to the experimental factors. It was therefore more appropriate to compare both dimensions in terms of absolute accuracy than to compare systematic (that is, spatially oriented) error on both axes.

In order to avoid any contamination from visual feedback on programming (closed loop vs. open loop), all subjects first performed the open-loop condition. To make sure that no learning occurred during this condition we ran, on the errors scores, an analysis of variance according to block of trials (5 blocks of 3 trials) and age (6, 8, 10 years). For
directional errors, no significant practice effect was found on the single task condition (1), $F(4, 84) = 2.24, p < .07$; however, in the combined task (3), the practice effect was significant, showing a deterioration across blocks, $F(4, 84) = 3.01, p < .02$ (Fig. 2), the post hoc analysis showing that block 4 error scores were significantly higher than those from block 2. For amplitude errors, no significant difference was found in the single (2) or combined tasks (3), $F(4, 84) = 1.04, F(4, 84) = 0.18$ (Fig. 3). No age or interaction effect was significant. Therefore, the lack of improvement suggests that performing the open-loop condition first did not contribute to any improvement observed in the visual condition. Similarly, the gender effect was not significant and the data for boys and girls have been collapsed.

All errors presented in this section were submitted to a Group (3), by Task (3) by Vision (2), and by Target (when appropriate) ANOVA, with repeated measures on the last three factors. Age was a between-subjects measure (Hoc, 1983; Rouanet & Lépine, 1977). Reaction times and movement times were analyzed with respect to Age, Task, and Vision.

**Timing**

*Reaction times* (see Table 1) decreased with age (707, 609, and 577 ms on average for the 6-, 8-, and 10-year olds, respectively; $F(2, 21) = 4.40, p < .05$). No significant Age $\times$ Task interaction was found; $F(4, 42) = 1.01 p < .05$. Whatever the age, the Task factor affected RTs significantly; $F(2, 42) = 5.98 p < .01$. The longest RTs were found in the Direction task and the shortest in the Amplitude task. Comparing the RTs between tasks showed that the difference between Direction

![Fig. 2. Directional error of movements in task 4 (continuous lines) and task 3 (dotted lines) in the open-loop condition, according to block of trials.](image_url)
and Amplitude tasks was significant; $F(1, 21) = 14.78, p < .001$, whereas the difference between Direction and Combined tasks was not, $F(1, 21) = 1.17$. RTs were shorter in the visual than in the non-visual condition (595 vs. 666 ms; $F(1, 21) = 7.89, p < .025$. A significant interaction of Task $\times$ Vision, $F(2, 42) = 6.39, p < .01$, shows that vision of movement induced shorter RTs only in Amplitude and Combined tasks, whereas RTs were equally long in the single Direction task in both vision conditions. No significant interaction was found between Age and Vision $F(2, 21) = 0.84$. RTs were not affected by the Target factor in any of the tasks.

Movement times were analyzed together for the Direction (1) and Combined (3) tasks in which the target distances were identical, and

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<th>10</th>
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<td>669</td>
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<tr>
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separately for the Amplitude task (2) in which the target distance was varied. The data from the tasks with a single target distance (1 and 3) are presented in Fig. 4. MTs were significantly shorter in the single Direction task than in the Combined task; $F(1, 21) = 25.98, p < .001$. The visual condition induced shorter MTs than the nonvisual condition $F(1, 21) = 6.19, p < .025$. Target location had no significant effect on MTs, $F(4, 42) = 3.16, p > .05$. No interactions were found between Task, Vision, and Target factors. MTs differed significantly with age, $F(2, 21) = 4.68, p < .025$; on average, the 8-year-olds performed with the longest MTs, the 10-year-olds with the shortest. The 6-year-olds had intermediate MTs. This is shown by a significant quadratic component on the Age effect in a trend analysis, $F(1, 21) = 6.36 p < .025$. This developmental trend was task-dependent as shown by a significant Age $\times$ Task interaction; $F(2, 21) = 5.07, p < .025$. This means that the difference in MTs between the Direction and Combined tasks was much greater in the 6-year-old group than in the two older groups: consequently, in both visual conditions, the MTs performed by the 6-year-olds were as short as the 10-year-olds’ MTs in the single Direction task and they were as long as the 8-year-olds’ MTs in the Combined task. This task-dependent effect of age is shown in a task-specific trend analysis on the Age effect, by a significant quadratic component, $F(1, 21) = 6.83, p < .025$, (and no linear component) in the Directional task, and a linear component, $F(1, 14) = 10.83, p < .01$, (and nonquadratic component) in the Combined task.

![Fig. 4. Movement times in task 1 (striped) and task 3 (white) in the two visual feedback conditions, with respect to age.](image-url)
The data from the Amplitude task are presented on Fig. 5. MTs increased with the target distance as shown by a significant Target effect, $F(2, 42) = 60.40, p < .001$, and they were not influenced by Vision, $F(1, 21) = 0.67$. MTs differed significantly with age, $F(2, 21) = 9.25, p < .01$; the 8-year-olds performed with longer MTs than the 6- and the 10-year-olds. This is shown by a significant quadratic component on the Age effect, $F(1, 21) = 16.88, p < .001$. Interactions were found between Age and Targets, $F(4, 42) = 2.74, p < .05$, and between Age and Vision, $F(2, 21) = 8.39, p < .05$. The Age $\times$ Target interaction seems mainly due to the fact that the 10-year-olds showed less differences in MTs according to the target distance than the two younger groups. The Age $\times$ Vision interaction is due to the fact that the 10-year-olds showed shorter MTs in the Vision than in the No-Vision condition, whereas the two younger groups showed slightly longer MTs in the Vision than in the No-Vision condition. No interaction was found between Target and Vision; $F(2, 42) = 1.67$.

**Spatial Accuracy**

Aiming accuracy was measured in terms of absolute terminal errors. For both direction and amplitude errors, scores were allotted on the single tasks (1 or 2) and the combined task (3). They are presented together in Fig. 4.

**Direction.** The directional error (Fig. 6), in terms of main effects, did not change significantly with age, $F(2, 21) = 0.31$, nor with targets, $F(2,$

![Fig. 5. Movement times in task 2 in the two visual feedback conditions, with respect to target distance and age.](image-url)
42) = 0.55, and there was no significant difference between tasks with the single and combined dimensions, $F(1, 21) = 3.82$. The only significant change in performance was related to the visual feedback conditions, $F(1, 21) = 46.55, p < .001$, since vision of the hand improved angular accuracy in all age groups and on both single and combined tasks. No significant interactions were found between any of the factors.

**Amplitude.** More main effects were found on amplitude error, as shown by Fig. 7. Age significantly affected performance as a main effect, $F(2,
21) = 3.96 \( p < .05 \), since amplitude error decreased between 6 and 10 years of age on average. Accuracy was higher in the visual feedback condition than in the no-vision condition; \( F(1, 21) = 83.63, p < .001 \). Task also affected performance as a main effect, \( F(1, 21) = 7.77, p < .025 \), since error was higher in the Amplitude task than in the Combined task on average. But the Age and Task effects were highly vision-dependent, as shown by significant interactions between Age and Vision, \( F(2, 21) = 5.76, p < .025 \), and between Task and Vision, \( F(1, 21) = 4.87, p < .025 \). This means that Age and Task effects were essentially due to modifications in performance under the no-vision conditions. Thus the Age effect consisted of a decrease in error without vision from 6 to 10 years of age as shown by a linear component under this condition whereas no linear component was found under the Vision condition. Similarly, the overall Age \( \times \) Task interaction \( F(2, 21) = 4.93, p < .025 \), was apparent only under the nonvisual condition as shown by the triple Age \( \times \) Task \( \times \) Vision interaction, \( F(2, 21) = 5.45, p < .025 \). It consisted in different trends on the Age effect between Amplitude and Combined tasks under the nonvisual condition. The 8-year-olds performed with greater errors than the 6- and 10-year-olds in the Amplitude task without vision (significant quadratic component, \( F(1, 21) = 7.48, p < .025 \)). In the Combined task under the nonvisual condition, the amplitude errors decreased linearly with age (significant linear component, \( F(1, 14) = 17.47, p < .001 \)).

**Timing**

*Reaction times.* The decreased RTs with increasing age is a known result, even in the case of latencies preceding goal-directed movements, as shown by Brown et al. (1986). However, they found a stabilization of RTs between 5 and 8 years of age, whereas our data show that the RTs tend to level off only between 8 and 10 years of age, particularly in the visual condition. This could be explained by the temporal instructions which were different between the two studies. In Brown et al.’s study, spatial accuracy was emphasized and children were asked “to touch the target as accurately as possible and to take their time in doing so,” whereas in our experiment, the instructions also emphasized speed of movement. The children’s reactions to temporal pressure probably vary with age, and the 8-year-old children might have performed with shorter RTs than the younger ones when under temporal constraint, and with equal RTs when they had no such constraint.

In the singly performed directional or amplitude task, RTs were systemically longer for direction than for amplitude, and an additional amplitude requirement did not cause any RT increase over the single directional task. These data are consistent with studies on adults (Bonnet, et al., 1982; Fiori et al., 1974; Megaw, 1972; Rosenbaum, 1980) which showed that the specification of direction and amplitude parameters of
movement are not equally time-consuming, and could thus mainly involve different stages of the response process. The role of vision might also be interpreted within the same conceptual framework. Since direction parameter of movement is mostly specified at a preprogramming level, the availability of feedback has little influence on the preprogramming time. On the contrary, subjects might try to preprogram their movement amplitude when visual feedback is not available, yielding a longer preprogramming time in the amplitude task under the no-vision than the vision condition.

**Movement times.** Unlike RTs, MTs did not change linearly with age. MTs were systematically shorter in the single Direction task, which is not surprising since this task could be performed without final braking. But the differences in MTs between Direction and Combined tasks were much more pronounced with the 6-year-olds, so much so that this age group behaved like the 10-year-olds in the single Direction task and like the 8-year-olds in the Combined task that involved braking and stopping on the target. The longer Mts observed in the no-vision condition for the direction and the combined tasks is consistent with Brown et al. (1986)'s data since the "partial visual information" condition in their study (dark room and target lit for 3 s, that is, for the entire MT) is comparable to our "no-vision" condition. One interpretation could be that, in the no-vision condition, subjects (particularly the older ones), try to control their movement trajectory on the basis of proprioceptive information and make on-line comparisons between the successively felt positions of their hand and the seen position of the target. This type of visuo-proprrioceptive guidance is probably more time-consuming than movement guidance performed within the same (visual) modality on the basis of the relative target and hand positions, when visual feedback is available. This interpretation would be consistent with the results obtained by Brown et al. (1986) in their "reduced visual information" condition (dark room), in which the target light went out on movement initiation. This condition induced the shortest MTs. This could be due to the fact that it was impossible to perform visuo-proprrioceptive comparisons between hand and target positions in order to compensate for the absence of visual feedback in this condition, since visual information on the target was not available during movement.

In the single Amplitude task (2), the target distance affected MTs at all ages and under both visual feedback conditions. But the slope of the amplitude-vision function was less marked for the 10-year-olds than for the two younger groups, which is consistent with the age-related differences found in MTs in the Combined task (3), and suggests an increasing efficiency in ballistic distance covering phase between 8 and 10 years of age. This is consistent with the developmental studies on Fitts' Law which show decreasing slope of the MT-ID function as children grow up. Older children tend to move according to an isochrony principle
which consists in adapting their movement velocity to the amplitude to be covered.

**Spatial Accuracy**

*Direction.* Specification of the directional parameter in the absence of visual feedback seems to be fairly accurate early on during development, since mean error was only around $3^\circ$ at 6 years of age and did not show any major changes afterwards. In agreement with previously mentioned studies, directional accuracy thus seems to depend on quite elementary and early functional mechanisms. This does not exclude the possibility that directional accuracy may be subjected to a developed type of control such as visual guidance. Introducing an additional amplitude requirement (task 3) does not affect directional accuracy whatever the visual feedback condition, suggesting the existence of specific channels. In the case of the visual feedback condition, this compatibility could moreover be attributed to the fact that visual regulation of the two dimensions does not involve the same phases of movement trajectory, as suggested by the studies on adults already mentioned.

The absence of age-related changes in directional accuracy, particularly when visual feedback is not available, might be due to the fact that, in our experiment, the task was performed without any sort of feedback on terminal error.

*Amplitude.* Regulation of amplitude seems to develop in a different manner, with respect to terminal accuracy. Specification of the amplitude parameter in the absence of visual feedback reflects a nonmonotonic development, as previously encountered with pointing tasks in which both requirements were combined. In contrast, visually controlled movements tend to be equally accurate at all ages. However, the fact that higher error scores were obtained in the single Amplitude task than in the Combined task at 8 and 10 years of age is paradoxical. The decrease in performance level at age 8 seems to be related to the need for regulation, which is made particularly difficult at this age by the lack of visual feedback, not yet easily compensated for by proprioceptive feedback. If we hypothesize that this factor had no influence on amplitude accuracy in the Combined task, then another interpretation would be needed. It may be that amplitude regulation tends, with increasing age, to be undertaken at the preprogramming level when it has to be controlled simultaneously with direction. In conclusion, we propose that specification of the spatial parameters of aiming movements undergoes a longer and more complex development with regard to amplitude than to direction, with important changes of strategy occurring around the age of 8. Both dimensions seem to be predominantly specified at different stages in the response process, which is consistent with previous studies in adults (Bonnet et al., 1982). Specification of direction seems to predominantly load the preparatory stage of the response, compared to amplitude
specification. Amplitude seems to be more dependent on on-going regulations than direction, and hence on the maturation of braking which allows a modulation of velocity as required by integration of feedback information. From the differences in MTs observed between tasks, it is clear that there is a particular difficulty in braking at age 6. The 8-year-olds show greater propensity for feedback control, as shown by their important inaccuracy in the amplitude task when performed without vision. This results in an improvement in the efficiency in the distance-covering phase that occurs only between 8 and 10 years of age, as shown by the MTs slopes with respect to target distance. Hence, with increasing age (and particularly at age 10), amplitude specification tends to be mainly regulated by the feedforward process.

REFERENCES


