Relationships Between Perception and Action

Current Approaches

Edited by

O. Neumann and W. Prinz

With Contributions by

P. Bieri · B. Bridgeman · H. Cruse · J. Dean · C.-A. Hauert
H. Heuer · D. G. MacKay · D. W. Massaro · P. Mounoud
O. Neumann · W. Prinz · E. Scheerer · R. A. Schmidt
A. H. C. van der Heijden · A. Vinter · P.-G. Zanone

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Development of Motor Control in the Child: Theoretical and Experimental Approaches

C.-A. HAUERT, P.-G. ZANONE, and P. MOUNOUD

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Introduction

This chapter is concerned with some general aspects of the ontogenetic development of motor planning and control in the child. According to classical theories on human development, psychologists describe the age of 2 years as a transition between two main steps in child development. However, this age can in no case be considered as an "endpoint" in the perceptuo-motor development, nor as a "startingpoint."

This preliminary remark is important if one considers the following apparent paradox. The perceptuo-motor coordinations the child exhibits at 2 years of age, as a result of his/her first development, are very numerous and fairly well adapted to many dimensions of the environment. As a matter of fact, compared with the neonate, the 2-year-old child is able to walk and run efficiently, or is able to grasp objects very accurately in a wide variety of situation with one hand or the coordinated activity of both hands, and so on (for a review, see Mounoud, Vinter & Hauert, 1985). But compared with a 9-year-old child, for example, he/she looks like a very incompetent, awkward, deficient "producer" and "controller" of perceptuo-motor behaviours. This remark holds true for a 9-year-old child compared with adult. In this chapter, we will try to provide some theoretical elements to discuss the way in which perceptuo-motor behaviours develop during childhood.

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As shown in many ontogenetic studies, children manifest dramatic changes in their actions from birth to adulthood. Some of these changes are qualitative, other are quantitative. If one accepts that the physical external world is in some way invariable, the question of the origin of these changes arises. With respect to this question, two theoretically opposed options can be distinguished. In the first one, these changes are assimilated to a maturational, physical, and neurobiological process allowing the subject to control his/her perceptuo-motor systems with increasing accuracy, and to coordinate them more and more adequately. We will try to argue for a second option that views maturation as a necessary but not sufficient condition to yield the changes occurring in perceptuo-motor development. Perceptuo-motor coordinations imply anticipatory and corrective adaptive mechanisms. In our opinion, such mechanisms depend on mediational-representational processes, enabling the subject to elaborate the relevant information involved before as well as during every motor task. Such an assumption has to be discussed at the theoretical level (for a general discussion about the relationship between cognitive and motor skills, see Mounoud 1986). On the other hand, this assumption has consequences at the methodological level: the most pertinent situations to assess the ontogenetic development of perceptuo-motor skills and address the issue of its nature have to present dimensions which can be clearly anticipated.

Theoretical Background

At the moment, literature devoted to human motor control in adults provides a consensual figure of the perceptuo-motor system as a hierarchical organization (Adams, 1976; Bernstein, 1967; Gentile, 1972; Keele, 1982; Newell, 1978; Paillard, 1980; Pew, 1974b; Schmidt, 1982; Shaffer, 1982). However, the definition of the very nature of the different organizational levels remains an open question. In Paillard's concept, for example - one of the most general models now available - the three lower levels of the perceptuo-motor hierarchy are conceived as follows: "servo-motor" control (first level, reflex control), "self-regulation" (second level, prewired programs of movements), "auto-adaptive" loops (third level, automatic adaptive process of prewired programs). In such a framework, if a low-level control mechanism cannot manage at a given movement - and in this case only - this function is run by the immediately superior level of control. Mediational processes do not arise in any of these three levels, which can certainly account for the major part of the perceptuo-motor competences of the subject. The fourth level, namely the "cognitive auto-organization," would only be involved in the conscious determination of the intended action. As a consequence, motor skills are implicitly considered as automatic, since their planning and control do not imply the so-called conscious "cognitive" level.

General Thesis

Our own thesis is based on experimental studies carried out from a developmental perspective. It also assumes different modes of motor control. However, only one of these consists, at some stages of the adaptive processes, in an automatized motor control. If the actual performance is considered, independent of its acquisition, such an automatization might suggest a complete lack of any cognitive mechanisms in the control of skills that would thereby exhibit an illusory automatic aspect. We will try to show that the different modes of action control are based on a general process that deals with the predictable aspects of the situations in which the actions have to be performed. Consequently, this process involves internal representations of the properties of the situations, whatever the general level of ontogenetic development or the specific level of acquisition of a given perceptuo-motor skill. Let us note here that the importance of an anticipatory process for action is accepted by many authors and is a basic postulate of Gibsonian theory (cf. Turvey & Kugler, 1984). From this point of view (Gibson, 1961), however, preparation for action should be limited to a nonmediational process that simply picks up the relevant environmental properties (affordances).

It is important to point out that the authors who regard perceptuo-motor coordinations as isolated functions, or who consider that they are not cognitively mediated (e.g. Adams, 1981; Kelso & Wallace, 1978; Paillard, 1980; or all the supporters of the "natural/dynamic approach", see Kugler, Kelso & Turvey, 1982) use the concept of cognition in a very restrictive sense. In their view, cognition consists in conscious and intentional operations that precede, accompany, or follow movement. In other words, all the mechanisms that are not linked to a clearly conscious experience, and whose contents cannot be "thematizable" or "expressible" (i.e., potentially a topic of discourse for the subject) are, by definition, of a necessarily non-cognitive and purely biological nature. Now, if carried to extremes, such a standpoint leads to absurd statements: any speech production, for example, would be considered as a purely biological activity! Actually, such misunderstandings are likely to originate in that the authors arguing for a biological concept of perceptuo-motor processes always assimilate automatized with automatic behaviours. MacKay (1984, p. 183) sums up the whole situation when he points out that, "1. Not all motor activities are conscious action; 2. not all sensory information-processing mediates conscious experience." Along the same lines, Newell and Barclay (1982, p. 205) state that, "Much of our knowledge about action is apparently tacit. By requesting subjects to be explicit on knowledge about action, an erroneous conceptualization could emerge."

From such a biological point of view, perceptuo-motor coordinations would be regulated by prewired programs, capable of an automatic adaptation to the changing conditions of their execution. Moreover, there would be several behaviours considered as basically automatic (walking, for example), that is, workable under the sole control of biologically determined levels. In our opinion, whereas motor behaviours under automatized control do exist in the spontaneous repertoire of the human subject, this repertoire does not include automatic behaviours. In human adults, Roll (1981) emphasizes the dramatic modifications that psychological factors can introduce in so-called automatic neurophysiological reactions (such as postural reflexes, segmental reflexes, the illusion of self-movement, etc.). He notes that, "It is classical that the occurrence of a 'functional stretch reflex' in a human subject depends on the instruction given to the subject not to interfere with, nor to resist the muscular stretching .... In the same way, in the postural control of an upright position in humans, the gain of rapid responses to stretch of the soleus muscle could depend only on the presence or absence in front of the subject of a support he could get hold of if he lost his balance" (p. 151, our translation). Thus, purely automatic behaviours are likely to occur only in artificial situations. To make ourselves clear, in no way can walking of a spinal cat (for example, Grillner, 1975) be compared to natural walking: the latter is an automatized activity since, in spite of its automatic appearance, it remains coercible and modulable. On the contrary, a spinal cat does not walk. If electrically or chemically stimulated, it may show coordinated patterns of body segments that would never allow it to catch a mouse.

Toward a Broad Concept of Cognition and Its Implication in Movement

Our thesis claims that cognition, as a conscious or unconscious process, in involved in planning, executing, and controlling every perceptuo-motor activity, even nociceptive reflexes, at least in adults (Cohen, Cranney & Hoffman, 1983). We conceive of cognition as ensuring the following functions: mediation of nervous signals by means of one or several internal codes (transformation of neural signals in information through a coding process), storage of the coded contents, generation of new contents by internal activity (anticipation, i.e., activity linking antecedents and consequents even in absence of specific external stimulus), activation or inhibition of such internal contents (choice, decision). The crucial point here is the first statement. As far as the concept of information is concerned, we reject the usual implicit assumption that nervous signals contain per se any relevant information for the perceptuo-motor system. Instead, information must be viewed as internal contents created by the system on the basis of incoming sensorial data with respect to the previous experiences. An argument for such a standpoint can be found in the changes of meanings (perception) of identical nervous events (sensation) occurring with age and individual features.

With regard to the topic of motor behaviour, this definition leads to a particular figure of the perceptuo-motor system as multilevel organization (Zanone & Hauert, 1987). Let us recall briefly the main aspects of our point of view. The highest level of this organization sets the nonmetrical aspects of movement: which body segments are involved; in what spatial direction is their trajectory going to develop, or in what sequence of directions; what is the final goal of the movement? Once these aspects are determined as a procedure, a general motor program (GMP) is selected. The notion of a GMP (Schmidt, 1975) designates a set of motor coordinations underlying a class of movements and is comparable to several classical concepts in the field: the motor engram (Bartlett, 1932; Pew, 1974a,b), the central program (Brooks, 1974), the motor scheme as discussed by Piaget (1936), or the motor control structure (cf. Cruse, Dean & Heuer, this volume). The GMP has to be conceived of as a rather abstract structure whose mutable parameters, from our point of view, are biomechanical (muscles and joints, i.e., the elements of a "coordinative structure" as defined by Kelso, Southard & Goodman, 1979), spatial (movement amplitude and trajectory), temporal (movement duration), kinematic (velocity and acceleration) and dynamic (intensity of active and passive forces). In this respect, let us recall Bernstein's famous example (1967) of the so-called motor equivalence in signature (see also Merton, 1972; Viviani & Terzuolo, 1982): the spatio-temporal characteristics of its components are invariant according to a homothetic principle across widely varying biomechanical, spatial, and temporal conditions of execution.

The actual matching of the movement with the spatio-temporal requirements of the task implies the anticipated instantiation of the mutable parameters of the GMP, allowing the initiation of the intended motor sequence. Then, as a function of the action outcome, an eventual updating of the GMP may occur that entails the generation of corrections during the ongoing movement. More specifically, procedural corrections lead to modifications in the nonmetrical aspects of movement, while instantiation corrections are related to changes in its spatio-temporal characteristics. Now, both instantiation and updating suppose the compilation of several sources of information - as defined above - pertaining to, on the one hand, the characteristics of the experimental situation and, on the other hand, to the biomechanical properties of the involved bodily segments.

GMP Instantiation

To discuss the process of GMP instantiation, the notion of a schema as defined by Schmidt (1975, 1976, 1982) is very powerful. Let us recall that, from Schmidt's point of view, a "recall schema" is supposed to be available to the subject. Such a schema is a kind of motor memory of the functional relationship (or rule, according to Shapiro & Schmidt, 1982) that has been progressively built during past experiences among: (a) the extero- and proprioceptive afferences ("the initial conditions;" IC); (b) the desired goals of action; (c) and the instantiation of the GMP. The recall schema is able, from this rule, to inter- or extrapolate a specific GMP instantiation for the actual action. In addition to the recall schema, the subject possesses another schema that is related to the sensory aspects of his/her actions: the "recognition schema," a sensory memory of the functional relationship between: (a) past IC; (b) the goals of actions; (c) and the past sensory consequences of actions. From this memory trace, the recognition schema generates the expected sensory consequences of the intended movement that provide a clear internal reference for the control of movement. Finally, a comparator is deemed to process the actual sensory consequences with respect to this reference, and to trigger an error signal in case of mismatch. It must be highlighted that a correction is then generated if, and only if, such a mismatch is detected with respect tot he *expected* sensory consequences of the ongoing movement.

From our point of view, these mechanisms have clearly cognitive dimensions. Indeed, the definition of the action procedure is a cognitive process. Then, the second source of information for both schemata, the IC, arises through an internal coding of the actual sensory consequences. Clearly enough, the schemata do not process directly the properties of the environment but internal translations of these. Thus, whatever the motor control mode, a movement never translates any intrinsic property of the recall or recognition schemata, but rather the very nature of the information on which they work.

According to these considerations, whatever movement an individual is asked to execute, preparation for action as well as its control are based on subjective internal representations of the goal and of the initial conditions of the intended movement.

GMP Updating

Let us recall that GMP updating, that is, changing some of its parameters during the execution of movement, may only result from the previous triggering of an error message by the comparator, following some mismatch between actual and expected sensory consequences. This point is particularly important insofar as it leads to a fundamental change in the way to conceive of the mechanisms responsible for motor control. The classical framework of engineering and cybernetics distinguishes several modes of movement control that have been nicely classified in three categories according to Cruse et al. (this volume). Their typology among "advance processing of sensory information," "intermittent processing of sensory information," and "continuous processing of sensory information" allows an understanding of when information is used by the system to control the to-be-executed or the current movement. Along with the argument about the concept of information we discussed above, the question remains of why some supplementary information is necessary during the execution of the movement. Two possibilities have to be envisaged. On the one hand, the actual performance did not follow the intended plan resulting from an advance processing of information because of some unexpected perturbations. A mismatch is then detected by the comparator that may entail a correction based on new token of information. On the other hand, the movement was consistent with its initial plan, but did not fulfill the intended goal. In the former case, a departure occurred with respect to the internal reference for the movement provided by the recognition schema, while, in the latter case, some gap was detected between the actual outcome of movement and the expected consequence on the environment. Whatever its origin, the crucial point is the occurrence of some mismatch between actual and expected sensory consequences. In other words, the issue is no longer at what rate sensory consequences are processed by the system, but at what time they become meaningful, namely when they are no longer consistent with the expected consequences of the action.

At a behavioral level, this distinction is somewhat confusing. Brooks, Cooke, and Thomas (1973) proposed a classification of movements into two categories according to their kinematics: continuous movements, characterized by a sequence of only one acceleration phase and one deceleration phase; and discontinuous movements, in which numerous sequences of this kind can be identified. Discontinuity of movement is attributed to the presence of one or several corrections and is then the behavioral clue of GMP updating. This means that some mismatch had been intermittently detected, but does not indicate at what rate the sensory consequences have been processed: as a matter of fact, continuous, as well as intermittent processing could have resulted in triggering a mismatch message; one may only discard pure advance processing. Conversely, continuous movements can be the consequence of any kind of processing. However, if no mismatch is detected, the resulting movement is ballistic (i.e., as traditionally defined, only one peak of velocity) and is due to pure advance processing, whereas it is continuous but nonballistic (i.e., modulations in both acceleration and deceleration phases) in cases of slight corrections following mismatch detections. Finally, larger corrections can result in discontinuous movements as well.

One must admit that continuous processing of sensory consequences can only be possible if the expected consequences of movement, with which the sensory consequences are to be compared, are defined for the entire course of the intended movement. On the other hand, nonballistic continuous movements are more probable when a continuous comparison between expected and actual sensory consequences prevents the occurrence of too large a mismatch.

Conversely, piecemeal, or incorrect expectations are likely to result in discontinuous movements because of the need for major corrections.

In terms of internal representations, the functional significance of such distinctions can be understood as follows (Hauert, 1980): discontinuous movement indicates a high level of uncertainty with respect to some or all dimensions of the situation, that is, a weak internal model of the action to be executed. The system needs to sample relevant information during the movement. Instead, a continuous movement indicates that the situation is sufficiently predictable, that is, the system has at its disposal a well-defined internal model. Slight corrections may nevertheless occur during a continuous movement, depending directly on such an internal model. Finally, a continuous ballistic movement witnesses a total certainty with respect to all the relevant dimensions of the situation. Obviously enough,such a certainty only translates the subject's point of view and may be, in reality, completely erroneous.

The Developmental Perspective

Following the above general assumptions, it becomes interesting to consider the perception-action relationships from the developmental perspective. Indeed, cognitive developmental psychology has clearly demonstrated that internal representations of reality are constructed by the subject him-/herself during the entire ontogeny (e.g., Piaget & Inhelder, 1941). At some steps of this construction, these internal representations are obviously complete and faithful with respect to the reality they mediate. At other steps, they are incomplete and distorted reflections of reality. But we have assumed that, in all cases, such representations are the inputs of the recall and recognition schemata. Now, the GMP responsible for a specific action is instantiated in a more or less complete and adequate way, to the same extent as these representations are complete and reliable according to developmental level. In parallel, the comparator is provided with a weak or strong internal model of the expected consequences of the movement by the recognition schema. As a consequence, some characteristics of the child's movements are expected to evolve qualitatively and not only quantitatively with age.

At the moment, literature about child development provides some experimental evidence for such developmental changes (Hay, 1979; Mounoud, 1983; Mounoud, Viviani, Hauert, & Guyon, 1985; Vinter, 1985; White, Castle, & Held, 1964) resulting from modifications with age in the mode of perceptuo-motor control. The available results suggest that a given perceptuo-motor behaviour evolves with age through a fixed temporal sequence: (a) movement control is based on an advance processing of sensory information; (b) it is assumed through discontinuous control; and (c) it becomes continuous. Moreover, such a sequence is likely to occur several times during ontogeny according to the different representational capacities that appear at different ages (for a discussion, see Mounoud, 1983).

The previous hypothetical considerations will be illustrated by two series of experimental studies that can be distinguished by the constraints they exert on the action. The first one concerns the development of visuo-manual pointing tasks, that is, situations mainly characterized by spatial constraints (orientation and location of various targets). The second series is interested in the development of visuo-manual tracking behaviour, that is, situations with spatio-temporal constraints (trajectory and kinematics of a moving target).

Methodologically, the common characteristic of these experimental paradigms is that the subject is presumably exposed to partly or totally predictable stimuli. Let us recall that all the data related to the development of perceptuo-motor skills in unpredictable situations exhibit progressive and monotonous increases in performance until adulthood. In the case of unpredictable visuo-manual tracking (Pew & Rupp, 1971), performance improves progressively with age, probably because such a task implies, by definition, the use of a discontinuous control of movement since no, or few, expectations may be available about the target motion. Thus, as far as ontogeny is concerned, the conclusions of this kind of study are very limited.

Visuo-manual Pointing Studies

Most developmental studies on pointing tasks are based on Fitts paradigm (i.e., a reciprocal tapping task under speed and precision constraints) (Connolly, Brown, & Bassett, 1968; Hay, 1981; Kerr, 1975; Salmoni, 1983; Sugden, 1980; Schellekens, Kalverboer, & Scholten, 1984). From a global survey, all these experiments converge to show a decrease in movement time with age, related to an increase in the mean velocity. In these studies, subjects are considered as information processors of limited capacity and, from this point of view, the decrease in movement time is interpreted as a progressive increase in the processing capacity with age.

Other studies on pointing tasks from a developmental point of view have attempted to assess experimentally the main theoretical postulates of schema theory (Schmidt, 1975, 1976), especially the effect of practice on schemata formation (Carson & Wiegand, 1979; Kelso & Norman, 1978; Kerr & Booth, 1977; cf. Shapiro & Schmidt, 1982, for a review). The question was asked whether variability in training favored performance in a new experimental situation - the so-called novelty problem - as assumed by Schmidt's prediction. As a matter of fact, the results of these experiments largely support this assumption.

Nevertheless, it is worth noticing that all the above results roughly sought to compare adult and child performance. Thus, the age scale is investigated using very large steps, if any. From our point of view, it may be suggested that such a gross observation along the age dimension could not lead to a real comprehension of the acquisition of pointing skills. Furthermore, this method is inappropriate to show any "U-shaped" evolutions that are reputed to occur within very narrow age intervals (Bever, 1982; Strauss, 1984).

In a study by Hay (1978), 4-11-year-old children and adults were asked to perform a visuo-manual directional pointing task without seeing their limb. Such a movement is usually defined as an open-loop task, implying visually triggered movement (White et al., 1964) or, according to the definition of Cruse et al. (this volume), relying on pure advance processing of visual information. In one experimental condition, subjects had to actively point their fingertips as accurately as possible in the direction of a light target using a horizontal swing of the arm. In a second condition, the arm was passively moved by the experimenter until the subject felt it just under the target and said "stop."

The results are very striking: in the active condition, children under 7 years showed a little undershoot - almost similar to adult performance. At the ages of 7 and 8 years, movement accuracy suddenly decreased and then progressively attained an almost adult level of performance until the age of 11. In the passive condition, accuracy showed a similar evolution across ages, but was lower than in the active condition, particularly in the older children.

This nonmonotonous trend in the acquisition of an open-loop pointing task is interpreted as the consequence of the appearance, at the age of 7 years of what the author calls "visual guidance" mechanisms in motor control, that is, a control based on an intermittent or continuous processing of visual information. Under this postulate, younger children - aged 4-6 years - produce mainly triggered or ballistic movements. Thus, they do not need any kind of information processing during the movement. On the contrary, the 7-year-old children are disturbed, because they do need the nonexistent visual information to monitor their arm position. The increased accuracy that is observed from this age onwards manifests the progressive use of proprioceptive cues to compensate for the lack of visual afferences. Such a process is assumed to require several years of perceptuo-motor experience. Once it is achieved, movement can be continuously controlled on the basis of a well-defined internal reference.

In a second experiment, Hay (1979) attempted to verify her hypothesis by defining more precisely the spatio-temporal characteristics of pointing movements in 5-11-year-old children. The procedure and the apparatus were the same as above. The results of this study confirmed the previous findings with respect to the evolution of movement accuracy in an open-loop pointing task, showing a less accurate performance at the age of 7. In a more detailed analysis, movements were classified into two gross categories according to their spatio-temporal characteristics. The first type included ballistic movements that showed only a sudden deceleration near the end of the movement. The second class included movements with one or several breaking activities either in the final part of the movement, leaving the initial ballistic phase undisturbed, or during the entire movement, reducing or even abolishing the ballistic phase. This dichotomy corresponds to our distinction between ballistic, on the one hand, and continuously or discontinuously controlled movement, on the other hand (see "GMP Updating").

From the developmental point of view, ballistic movements represent more than 60% of 5-year-olds' movements. This finding supports the postulate of a ballistic type of behaviour at this age, that is, based on advance processing of sensory information. Moreover, this type of movement disappears almost completely from the motor behaviour of older children. On the contrary, the rate of controlled movements increases steadily from the age of 7 years.

This classification, based on kinematic parameters, was confirmed by analyzing children's performance in a pointing task with the visual field rotated by wearing prismatic glasses (Hay, 1979). In this situation, the projected pointing movement had to be corrected to compensate for the apparent displacement of the target.

The moment of the onset of the trajectory correction in the ongoing movement varied as a function of age. At the age of 5 years, the correction occurred late, even after the pointing movement was completely achieved. This suggests that there is almost no visual guidance at this age. On the contrary, the 7-year-olds corrected their movement in half the time it took the 5-year-olds, whereas older children showed an intermediate moment of correction occurrence. These results provide some evidence that pointing movements are essentially ballistic at the age of 5, whereas they are mainly controlled at the age of 7. Nevertheless, highly efficient control does not occur before the age of 11 years.

From the two experiments by Hay, it could be argued that the observed evolution is paradigmatic of a general developmental trend. Thus, a general description of the evolution between the ages of 5 and 9 years can be attempted. First, there is a predominance of ballistic behaviours at the age of 5, that is, a predominance of an advance processing of sensory information. Then, a discontinuous control mode appears at the age of 7. Finally, from the age of 8, a continuous control mode gradually replaces the discontinuous one.

Visuo-manual Tracking Studies

Interestingly, a comparable developmental sequence can be found in a second experimental situation, that is, visuo-manual tracking of a simple predictable stimulus. Adult performance in tracking both predictable and unpredictable targets has been described in detail (cf. Ellson & Gray, 1948; Noble, Fitts & Warren, 1955; Pew, 1974a,b; Poulton, 1974; Stark, 1968). Several models, based on the concept of a servo-system (reduction of error on the basis of a continuous or intermittent processing of sensory information), have been devised to account for the experimental findings. Studies with children, however, are few. Let us recall the work of Pew and Rupp (1971) who investigated the performances of 10-, 13-, and 16-year-old children in tracking unpredictable targets. As mentioned above, the use of unpredictable targets necessarily constrains the subject to a discontinuous control mode and makes it difficult to explore the age-dependent evolution of the anticipations he/she can make about the target motion (Poulton, 1952) in order to instantiate the selected GMP.

Since we are interested in cognitive representations involved in perceptuo-motor coordinations, we have only considered predictable sinusoidal targets for which, unlike pseudorandom targets, an internal model could eventually be elaborated by the subjects. Indeed, Magdaleno, Jex, and Johnson (1970) showed that, while a feedback control mode may allow a successful pursuit of a target under a 0.5-Hz frequency, such a strategy cannot operate in tracking targets of frequency higher than 0.5-Hz. As a matter of fact, prediction and generation of a movement pattern are then required. Thus, the acquisition of tracking behaviour at two frequencies (0.2-Hz and 0.8-Hz) which are, respectively, lower and higher than this critical transition value has been studied (Mounoud, Viviani, et al., 1985).

Subjects were sitting in front of a screen on which it was possible to displace a red target spot horizontally (± 15 cm). The right forearm was fixed in a metal splint that could rotate in the same plane as the target. Forearm movements were recorded by an angular potentiometer mounted on the axis of rotation of the splint. A white light source at the end of the splint projected a circular marker spot on the screen. The task was to track the displacement of the target at 0.2 and 0.8 Hz with the white marker spot using forearm rotations during 35 full cycles of the target.

Adult subjects did not have difficulties in performing the task at either frequency. By contrast, some of the younger children were unable to accomplish the required task, especially at the higher frequency. By convention, a performance was defined as correct if, and only if, each stimulus cycle resulted in a response cycle. However, responses having the wrong amplitude or a phase difference with respect to the target, or showing distortions were tolerated. According to this criterion, the percentage of subjects who performed the task successfully was as shown in Table 1. Even the successful performances show a considerable variability in both amplitude and timing of the responses. In order to quantify this variability, the responses were analyzed cycle by cycle by measuring the gain (ration between the peak-to-peak amplitudes of the pursuit and target oscillations) and the phase lag with respect to the target. Phase lag indicates the temporal delay of fun-

Table 1. Percentage of subjects in each age group (n = 10) who performed the visuo-manual tracking task successfully at 0.2 Hz and 0.8 Hz, respectively

Age (years)		5	6	7	8	9
Frequency	0.2 Hz	70	100	100	100	100
	0.8 Hz	30	60	80	80	100

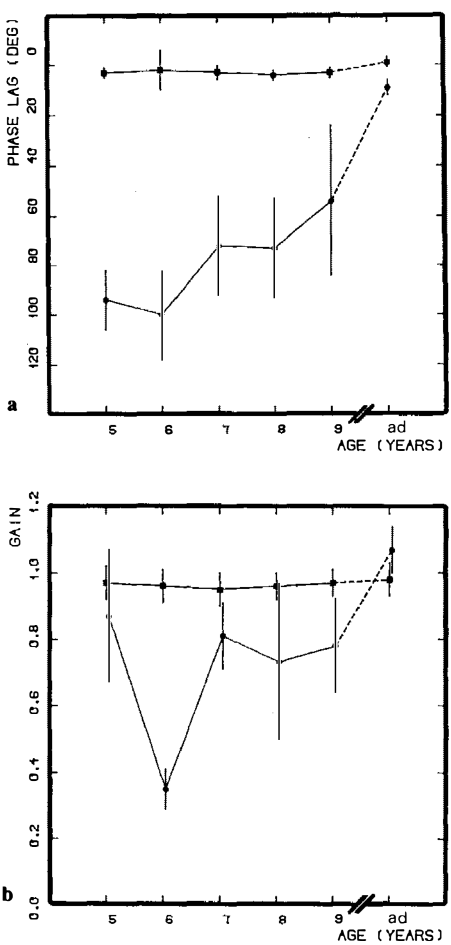

Fig. 1 a,b. *Gain and phase of the linear components.* **a** The phase differences between the target sinewave and the harmonic components of the pursuit with the same frequency of the target. Positive values indicate that the pursuit lags with respect to the target. **b** The ratio between the amplitude of the pursuit and the amplitude of the target. Each data point is the average of all subjects in the indicated age group who could execute the task successfully (*ad,* adult) of the within-trial mean values. Intersubject variability is indicated by *vertical bars* (± 1 standard deviation). *Squares,* 0.2 Hz; *circles,* 0.8 Hz. (From Mounoud, Viviani, et al., 1985)

damental harmonic of the response with respect to the target, expressed as a fraction of one complete cycle (360°).

Performances can be characterized by plotting the phase lag and gain of the response as a function of age. Figure 1 represents the dynamic properties of the tracking system at the two selected frequencies. At 0.2 Hz, the dynamics for those subjects who could perform the task seem to be independent of age. At 0.8 Hz, a 90° phase lag exists for the younger groups, which, with increasing age, monotonously approaches adult performance. The evolution of gain looks more complex. In particular, the 6-year-old children systematically (see the very low intersubject variability) produce movements which are much smaller than those of all other age groups. On the other hand, an evolution is no longer observed between 7 and 9 years.

However, successful performances show qualitative distortions with respect to a pure sinewave. The deviation from such a model - assumed to be related to fast corrections in the response - can be appreciated by spectral analysis, that is, by an analysis of its frequency components (Fourier analysis). In order to emphasize the distortions contained in the response, this analysis was carried out with respect to the instantaneous error between target and response velocities.

At least three types of distortions appear from the results of this analysis. The two first types are related to the components near the two target frequencies and indicate the difficulty of reproducing precisely the input frequency on each cycle of movements. The third type is represented by oscillations within the frequency range of 1.2-1.7 Hz. These components can be interpreted as the result of the effort to minimize the tracking error by a processing of visual information (Poulton, 1974). Under certain conditions (but not in our experiment), they also occur in adults (Pew, Duffendack, & Fensch, 1967) and are documented in ramp tracking too (Craik & Vince, 1963; Ellson, Hill & Gray, 1947).

These results can be summarized by grouping the total relative spectral components within three frequency intervals 0.2-0.9 Hz: low, 1.0-1.6 Hz: medium, 1.7-2.3 Hz: high. The age-related evolution of the total spectral power within each interval is shown in Fig. 2.

To summarize, Fig. 2 shows a clear decreasing trend for the low-frequency components, while high-frequency components increase with age.

The results demonstrate the following points: the tracking skill, as described in adults, is acquired progressively over a considerable number of years during childhood and cannot be adequately reduced to a monotonous maturational process. Typical adult performances are not yet attained at the age of 9 years. The evolution with age of the performance involves large changes in both qualitative and quantitative aspects of motor behaviour. Indeed, as we will try to speculate in the following discussion, at least one major change in control mode occurs at around 7 years of age that suggests a possible change in the strategy of perceptuo-motor coordination.

All types of tracking necessarily involve some kind of coordination between perceptual and motor systems. For the purpose of this discussion, we will begin by laying down a schematic description of what should be involved in this coordination from a logical standpoint.

One prerequisite for skillful tracking is the ability to represent centrally the trajectory of the target (Krendel & McRuer, 1960). For unpredictable targets, such a representation can only be piecemeal, while in the case of predictable targets, as

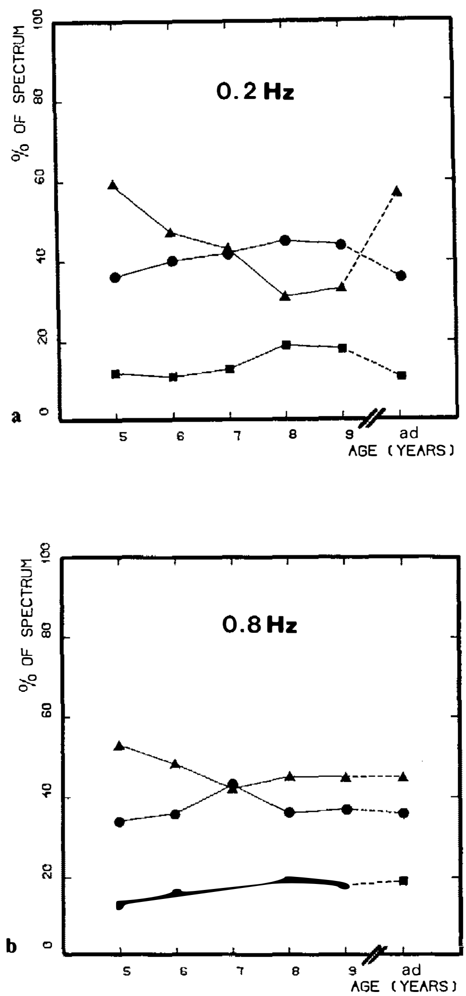

Fig. 2 a, b. *Frequency analysis of the nonlinear components.* Distortions in tracking a 0.2-Hz (**a**) and a 0.8-Hz (**b**) target with respect to age. Each *data point* represents the total relative amount of nonlinearities within three frequency intervals (*triangles*, low - 0.2-0.9 Hz; *circles*, medium - 1.0-1.6 Hz; *squares*, high - 1.7-2.3 Hz; *ad*, adult. (From Mounoud, Viviani, et al., 1985)

in our experiments, the entire trajectory can be apprehended as a whole. The second prerequisite is the subject's ability to build an appropriate procedure that reproduces the represented target trajectory. The above two conditions are tacitly assumed to be satisfied in normal adults. However, they are not trivial in children, for the relevant representations are only progressively established during childhood.

In addition, we assume that the motor system is able to select a GMP, to identify a set of parameters that completely specify the target motion, and to match these parameters into an appropriate setting for the mutable variables of the GMP (see Prinz, this volume, for a discussion of the concept of matching). We assume that the recall schema is responsible for these two functions.

Nevertheless, the actual pursuit will inevitably show some errors with respect to target motion. Therefore, we must postulate the possibility of updating the ongoing motor program on the basis of incoming information. Detecting these errors indirectly involves the recognition schema.

It must be stressed that classical models about tracking behaviour (cf. Young & Stark, 1963; Stark, 1968; Poulton, 1974) view the control problem mentioned above as a simple functional transformation from a sensory stimulus to a motor output. On the contrary, our concept implies a mediate matching between the perceptual and motor representations in planning and instantiating the motor command. Thus, the age-dependent evolution observed in tracking has to be considered as the expression of a concomitant change in the internal representation of the target motion. This leads to the conclusion that evolution toward adult behaviour is better described as a sequence of discrete steps, each one of which entails a (re)definition of the relevant representation, than as a smooth refinement process.

The input-output analysis of the pursuit linear component (Fig. 1) only discriminates adults and children at the highest frequency (0.8 Hz). Whereas the phase lag diagram indicates a monotonous reduction of the temporal delay between target and pursuit, which is compatible with the notion of a progressive improvement in the dynamics of the perceptuo-motor coordinations, the gain diagram is obviously discontinuous. This suggests the presence of at least one major modification in the strategy of perceptuo-motor coordination occurring between the ages of 6 and 7 years. With regard to the considerable improvement observed in 7-year-old children for both phase and gain, the sharp reduction in movement amplitude at the age of 6 cannot be interpreted as a regression from the level already attained at 5, but rather as the price to be paid when replacing one strategy with a better one that, however, only becomes effective at a later stage.

As a cue of this change, let us consider the distortions of performance at 0.2 Hz target frequency (cf. Fig. 2). Obviously, the low- and high-frequency nonlinearities show inverse tendencies with age. In particular, the 5-year-old boys stand out in this description, as they completely lack in high-frequency oscillations, while the low-frequency distortions are by far the most prominent with respect to all other ages. It is unlikely that these distortions are due to limitations in the motor execution abilities. On the basis of these considerations, we can tentatively assume that 5-year-old children master the basic motor skill to produce sinusoidal motions but, with few exceptions, cannot elaborate a global representation of the target motion in all its relevant aspects (frequency, amplitude, and phase). They resort to a sequential pursuit strategy in which successive, short segments of trajectory are independently planned and executed as independent ballistic movements. The large low-frequency distortions in their performances would then be a by-product of this piecemeal concatenation of responses separated by a reaction time. The high failure rate in the same age group at 0.8 Hz is probably due to the fact that the duration of the target period is too short for such a strategy to be operational (Magdaleno et al., 1970; Pew, 1974a,b). Instead, unsuccessful performances consist in true sinusoidal movements, but at a wrong frequency and/or with a wrong amplitude. However, from the point of view of the child, he/she feels that the task has been perfectly performed. This is a strong indication of a purely advance processing of sensory information at this age.

This mode of motor control subsides before the age of 7, as children can utilize the acquired ability to produce sinusoidal motions. Within this age span, the success rate at 0.8 Hz increases sharply and the amount of low-frequency distortions decreases. At the same time, there is moderate increase of the high-frequency harmonic components, which perhaps reflect the more numerous efforts to reproduce the temporal aspects of the target through a continuous processing of visual information. This strategy allows the sharp decrease in phase lag observed between 6 and 7 years. The pronounced reduction in gain at 0.8 Hz at the transitional age (6 years) could be the consequence of the processing load associated with the implementation of this frequency control through a temporarily discontinuous processing of visual information.

In conclusion, the results suggest that, although the basic motor ability involved in sinusoidal tracking is acquired very early in ontogeny, the construction of internal representations that would be appropriate to the fully developed skill requires the temporary neglect of this ability in favor of an altogether different strategy. It is then tempting to speculate that the transitory discontinuous control mode observed at the age of 6 is instrumental in the construction of these representations.

Conclusions

From a developmental point of view, the relationships between perception and action evolve in a very complex way. It seems clear that development cannot be seen as a progressive improvement in the planning of movement and the processing of sensory information. The nature of the changes occurring within the age range considered is not only determined by maturational factors that are intrinsic to the perceptuo-motor system. The results presented and discussed here strongly suggest that the construction of internal representations of the various properties of the physical world allows adapted executions of perceptuo-motor skills.

If one considers the developmental sequence described with respect to the skills discussed in this chapter, a striking similarity emerges. Each sequence is a succession of steps in which the child resorts to three different modes of perceptuo-motor control. As a matter of fact, the order of occurrence of these modes is rather clearly defined: the first step around 5-6 years, the child produces predominantly movements based on an advance processing of information that may or not attain the desired outcome. In the second step (about 6-7 years), action is temporarily controlled through a discontinuous mode of information processing. Finally (from 7-8 years), motor control becomes progressively carried out by a continuous mode of information processing. Let us emphasize the fact that this sequence is contingent on the actual prediction the child is able to make about the situation.

Finally, we must stress that this developmental sequence may be delayed for 1-2 years in the age scale, presumable because of some specific dimensions of reality that must be cognitively elaborated for a particular skill. From this point of view, development of the motor system per se seems a somewhat anecdotal factor if one expects to understand the acquisition of perceptuo-motor behaviours in children.

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