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Development of Visuomanual Tracking in 5- to 9-Year-Old Boys

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Visuomanual sinusoidal tracking is investigated in 5- to 9-year-old children. The proportion of successful performances steadily increases with age, but adult proficiency is never attained even by those who can perform the task. Moreover, the progress in proficiency—as measured by systems analysis techniques—is not monotonic and suggests the presence of distinct stages in the development of visuomotor coordination. Qualitative analysis of unsuccessful performance demonstrates that failures cannot be ascribed only to insufficient motor coordination and emphasizes the role of cognitive and representational factors even in such a simple task.

INTRODUCTION

It is generally accepted (cf. Kornblum & Requin, 1984; Schmidt, 1982; Shaffer, 1976, 1981; Viviani & Terzuolo, 1983) that the execution of complex expressive movements—such as drawing, writing, and playing music—requires the interaction of at least two control levels, one which provides the general plan for the movement and another which translates this general plan into an actual motor sequence. Supposedly, the first

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control level is the site of interaction of several sources of information which can be grouped into three categories (Schmidt, 1975, 1982):

1. Expectations about the state and evolution of the environment. These include some knowledge about the neuromuscular and biomechanical properties of the acting body segments.
2. An abstract representation of the intended spatiotemporal form, which can be specified either internally or by an external model via the perceptual system.
3. Templates, permanently stored in motor memory, which provide the building blocks for more complex sequences.

Some of these categories are clearly cognitive in nature. Thus, it is not surprising that from the very inception of motor behavior research (Book, 1908; Bryan, 1892; Bryan & Harter, 1897; Claparède, 1902; Freeman, 1914; Woodworth, 1899) it was explicitly admitted that cognitive structure do play a role in the planning of these complex expressive movements.

The emphasis in the study of relatively simpler movements, and in particular in the study of externally constrained movements such as tracking, has been quite different.

Possibly because of historical reasons, the conceptual framework for these studies draws heavily from the fields of electrical engineering and physics, while the cognitive aspects of the performance are constantly underrated. As a consequence, developmental and motor learning studies in this field are relatively rare (e.g., Bahrick, Fitts, & Briggs, 1957; Briggs, Fitts, & Bahrick, 1957) as compared to those devoted to more complex movements (typing, tapping, two-handed coordination, aiming under visual feedback, etc.).

In a series of developmental studies (Gachoud, Mounoud, Hauert, & Viviani, 1983; Hauert, 1980; Mounoud & Bower, 1974; Mounoud & Hauert, 1982; Mounoud, Mayer, & Hauert, 1979) we sought to emphasize the important role that cognitive factors have in controlling also very simple, everyday movements. In particular, experiments with children (2 to 9 years old) have demonstrated that even the execution of a monoarticular lifting movement depends critically on a number of inferences and expectations concerning the physical properties of the lifted objects and the properties of the motor system itself.

In this paper we pursue the same line of research by considering the development of a simple visuomotor tracking task. Adult performance in tracking both predictable and unpredictable targets has been described in considerable detail (cf. Pew, 1974; Poulton, 1974; Stark, 1968), and several models, mostly inspired by the concept of the servo-mechanism system, have been devised to account for the experimental findings. Studies of children, instead, are relatively rare. Among the recent ones, we remember the work of Pew and Rupp (1971) who considered the behavior of 10-, 13-, and 16-year-old children in tracking unpredictable targets. By considering the responses only in terms of systems analysis (gain and phase curves), these authors have shown a gradual improvement of the temporal aspects of the performance (phase lag) and a change in strategy for the gain control. However, the use of unpredictable targets constrains the subjects to one operational mode (see later) and makes it difficult to explore the age-dependent evolution of the anticipations that the subject makes about the target motion (Poulton, 1952).

Since the main emphasis of the study is on the expectations and cognitive representations involved in the performance, we have only considered predictable sinusoidal targets for which, unlike pseudorandom targets, an abstract representation of the general motor plan must eventually become available.

Magdaleno, Jex, and Johnson (1970) have shown that, in tracking sinusoidal signals, the prediction and generation of pattern of movements become possible at about 0.5 Hz and that this mode of operation, combined with real time corrective actions, is effective up to 1.0 Hz. Thus we decided to test the development of the skill at two frequencies (0.2 and 0.8 Hz) which are definitely lower and higher, respectively, than this critical transition value.

In a previous study (Mounoud et al., 1983) we explored the very early stages of development of visuomanual tracking (3 to 5 years). It was found that an acceptable success rate in the pursuit of a 0.8-Hz sinusoidal target is achieved only for the 5-year-old group. In this study, we then consider the range from 5 to 9 years within which we expect to witness the full development of the skill.

Although systems analysis is used to describe successful performances, equal attention is also paid to the unsuccessful performances which occur frequently in our age range and whose typological analysis reveals the control mechanisms underlying the execution of the task.

METHOD

Subjects

Ten male adults (27.05 ± 2.27 years) and 50 grade school male children from average-income families participated in the experiments. Children were divided into five groups according to their age. The mean (and standard deviation) ages in each group of 10 children were 5.06 (0.14) years, 6.05 (0.15), 6.92 (0.12), 8.04 (0.11), and 9.01 (0.12).

All subjects were right-handed and had normal or corrected-to-normal vision.

Apparatus

Subjects were seated in front of a large translucent screen placed approximately 60 cm from the subject's head (see Fig. 1). The right forearm was comfortably but tightly strapped in a metal splint that could rotate without friction in the horizontal plane. The axis of rotation (P) passed through the elbow so that flexion and extension forearm movements in the horizontal plane could be performed freely within the normal anatomical limits. When the elbow joint was in the relaxed equilibrium position, the forearm was approximately orthogonal to the screen.

Forearm movements were recorded by an angular potentiometer mounted on the axis of rotation of the splint. A white light source mounted at the end of the splint projected a circular (diameter = 15 mm) marker spot on the screen. On the opposite side of the screen was mounted another light source (L) which projected, onto a galvanometer mirror (G), a red circular beam (diameter = 15 mm). By rotating the mirror, it was possible to displace horizontally the red target spot (T) on the screen. Both the signal from the potentiometer and the input command to the galvanometer were recorded on tape.

Task

The task consisted of tracking the displacement of the target spot with the white marker spot by appropriate forearm rotations. Adults were introduced to the task in an informal way. Experiments with children were instead preceded by an extensive familiarization procedure during which emphasis was placed on demonstrating the relation between forearm

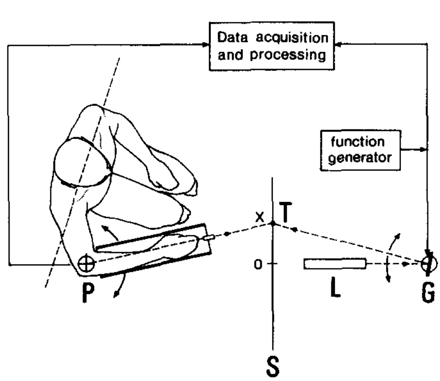

FIG. 1. Schematic view of the experimental setup. By rotating the forearm around the elbow axis the subject controlled the position (x) of the tracking spot on the screen (S). A potentiometer (P) geared on the rotation axis measured the angular displacements of the forearm. A light source (L) and a galvanometric mirror (G) driven by a function generator projected a target spot (T) on the back side of the screen. The angular position of both the forearm and the mirror was recorded on tape for off-line calibration and processing.

rotations and displacements of the marker spot. Moreover, the task was phrased as a skill game with the two spots identified with flying saucers. The aim of the game was to have the two saucers fly very close together and, whenever possible, one on top of the other.

Procedure

Each subject participated in two sessions spaced by no less than 48 h. In the first session, the target spot was animated by a sinusoidal movement at 0.8 Hz. In the second session, the frequency was lowered to 0.2 Hz. In both sessions, the linear amplitude of the movement on the screen was ± 15 cm corresponding to an elbow rotation of approximately ±18°. In all cases we recorded 35 full cycles of target movement, corresponding to 43.75 and 175 s at 0.8 and 0.2 Hz, respectively. However, only the 25 middle cycles (from the 5th to the 30th) were analyzed to eliminate the adaptative phase.

Stimulus and response signals were filtered (cutoff 10 Hz), sampled (204.8 and 51.2 Hz for the higher and lower frequencies, respectively: 256 samples/cycles in both cases), and stored for digital processing.

RESULTS

Adult subjects never had difficulties in performing the task at both frequencies. In contrast, some of the younger children were unable to accomplish the required performance, 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, it was tolerated that the responses had a wrong amplitude or a phase difference with respect to the target, or presented distortions. According to this rather strict criterion, the number of subjects who performed successfully is indicated in Table 1.

Figures 2 and 3 show examples of successful performances at 0.2 and 0.8 Hz, respectively. Each line presents a sample of seven target cycles (dashed line) and the corresponding tracking response (continuous line) for a representative subject from the indicated age group.

At 0.2 Hz, the response contains not only a fundamental sinusoidal

TABLE 1
NUMBER OF SUBJECTS IN EACH AGE GROUP WHO SUCCESSFULLY PERFORMED THE TASK, AT 0.2 AND 0.8 Hz

	Age (years)				
	5	6	7	8	9
0.2 Hz	7	10	10	10	10
0.8 Hz	3	6	8	8	10

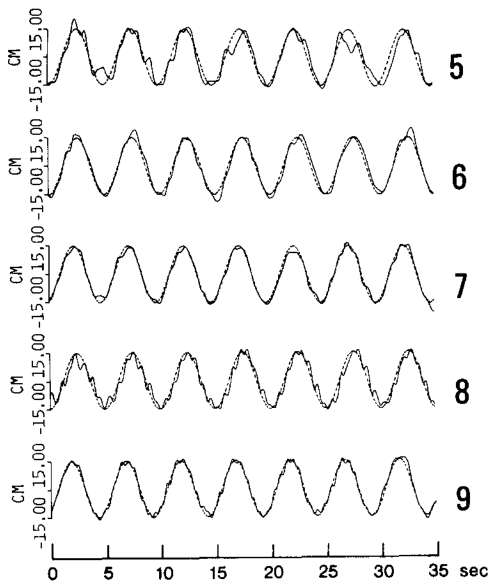

FIG. 2. Typical examples of successful tracking: 0.2 Hz. Each record describes seven full cycles of movement of the target (dashed line) and tracking (continuous line) spot for a representative subject in the indicated age group. Displacements are calibrated in centimeters on the screen. Negative value indicate positions in the right half of the screen.

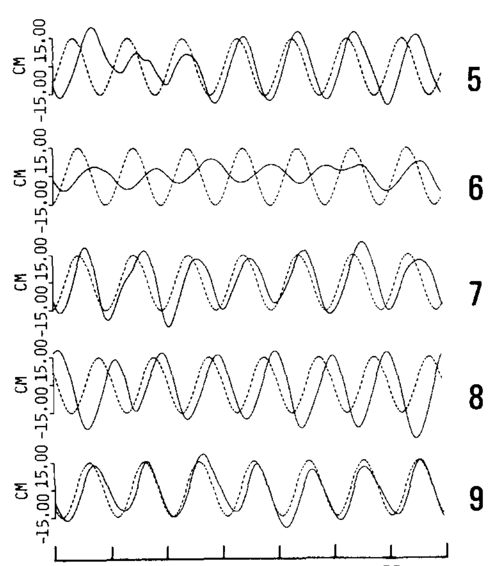

FIG. 3. Typical examples of successful tracking: 0.8 Hz. See Fig. 2.

component at the same frequency of the target but also higher frequency components which are unrelated to the stimulus. The gain and phase of the fundamental are quite similar at all ages and for all subjects. At 0.8 Hz, the responses are quite close to sine waves. However, both the amplitude and phase of the response change considerably across ages and also from subject to subject.

By contrast with the children's data, the tracking performance of adult subjects, not reproduced here, is virtually errorless (gain = 1, phase = 0, little or no harmonic distortion).

Figure 4 shows four selected examples of unsuccessful performances, each of which illustrates one typical kind of failure [(A) 0.2 Hz; (B–D) 0.8 Hz]. Trace A shows the performance of a 5-year-old child who disregards completely the frequency and amplitude information. In some other instances of this behavior, subjects produce a quite stable sinusoidal motion at twice the frequency of the stimulus. Trace B (5-year-old child) illustrates the opposite case in which the movement is much slower than the target. The amplitude is approximately adjusted. In C (6-year-old child), the amplitude information is disregarded and the movement is very small and irregular. Finally, Trace D (6-year-old child) shows an obvious effort to track both amplitude and frequency but the phase relationships are grossly distorted.

Over and above the high-frequency harmonic distortions mentioned above, even the performances classed as successful do show a considerable

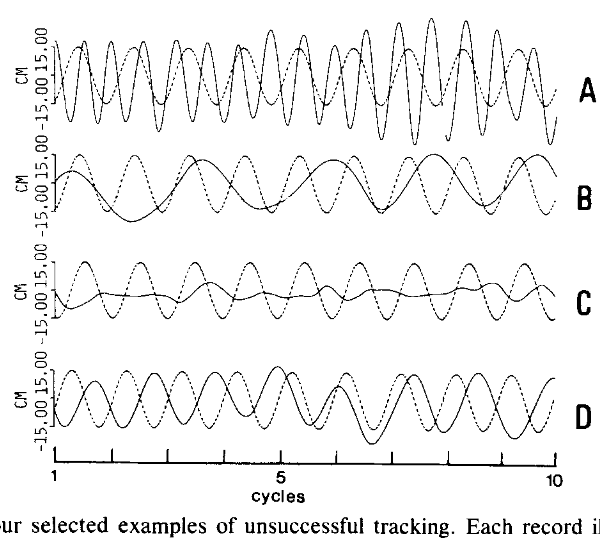

FIG. 4. Four selected examples of unsuccessful tracking. Each record illustrates one type of failure observed in several instances. (A)—5 years: The subject disregards both amplitude and frequency information; (B)—5 years: The amplitude is correct but the frequency information is ignored; (C)—6 years: Low amplitude, irregular movements; occasional efforts to match one target cycle; (D)—6 years: Both amplitude and frequency are correct. During most of the cycles the tracking spot is 180° out of phase.

variability in both amplitude and timing of the cycles. In order to quantify this variability, all successful performances were analyzed cycle by cycle by measuring the instantaneous frequency of the pursuit (i.e., the inverse of the period), the gain (ratio between the peak-to-peak amplitudes of the pursuit and target oscillations), and the phase with respect to the target. Figure 5 shows an example of this type of analysis for two subjects at 0.8 Hz.

Figure 6 shows the results of the same analysis in two 5-year-old subjects whose performances were classified as unsuccessful. The left panels illustrate the case in which the frequency of the movement progressively drifts away from that of the stimulus. At the same time, the amplitude of the response increases. As a result, the phase lag exceeds 360°, which corresponds to losing one complete cycle. In the right panel, the subject strives to maintain the correct frequency. However, the excessive variability may lead to phase shifts which exceed 360° and thereby entail the loss of a cycle. In contrast to the previous example, however, an effort is made to compensate for the loss by increasing the frequency. The fact that the phase lag returns in the original quadrant shows that the effort is successful. Note that, also in this case, variations in frequency are closely correlated with changes in amplitude.

A synthetic appreciation of the deviations from linearity can be obtained by spectral analysis. More specifically, in order to emphasize the measure of high-frequency components in the response, we computed the amplitude

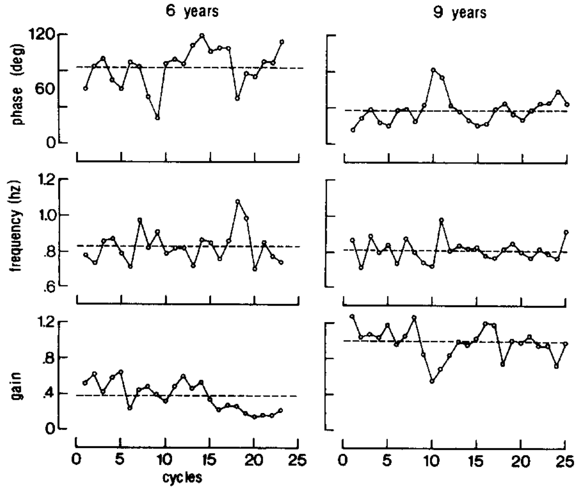

FIG. 5. Cycle-by-cycle analysis of two successful performances: 0.8 Hz. Each plot describes the cycle-by-cycle evolution of the indicated quantities for a representative trial in two subjects. These plots permit one to appreciate the considerable variability that affects even those performances which were classified as successful. On the same scale, an adult performance would produce virtually flat plots.

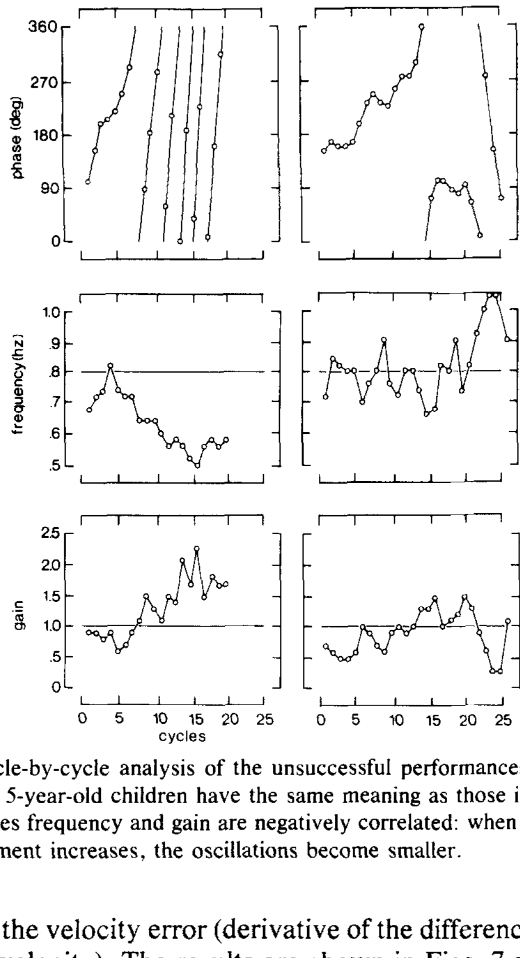

FIG. 6. Cycle-by-cycle analysis of the unsuccessful performances: 0.8 Hz. The plots relative to two 5-year-old children have the same meaning as those in Fig. 5. Notice that in both examples frequency and gain are negatively correlated: when the frequency of the tracking movement increases, the oscillations become smaller.

spectrum of the velocity error (derivative of the difference between target and pursuit velocity). The results are shown in Figs. 7 and 8 for 0.2 and 0.8 Hz, respectively. Notice that the spectral component at the driving frequency is meaningless because it is entirely due to phase differences between target and pursuit. Thus, this component is omitted.

At least three types of nonlinearity emerge from these results. The first type is illustrated by the conspicuous components near target frequency and translates the difficulty of matching the input frequency on each cycle of movements (cf. Fig. 5). This "jitter" decreases with age but remains quite visible even in adult performances. The second type is mostly confined to the very low frequency range for the 0.2-Hz condition and corresponds to large distortions of the movements (see, for instance, the first record in Fig. 2). Finally, the third type is represented by the very distinguishable oscillations with frequencies in the range 1.2–1.7 Hz. These components are generally interpreted as the result of the effect to minimize the tracking error using visual feedback (Poulton, 1974).

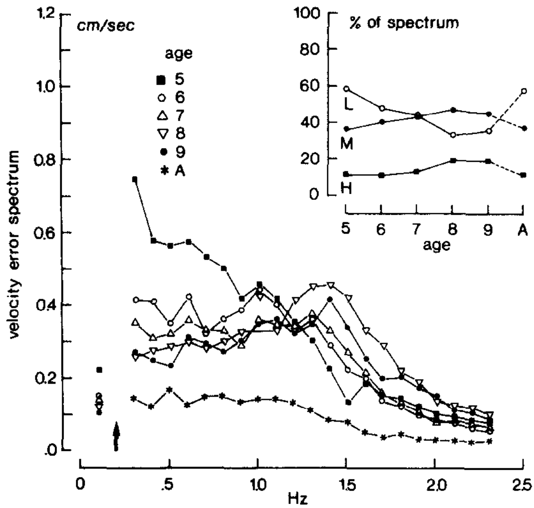

FIG. 7. Frequency analysis of the nonlinear components: 0.2 Hz. Data points represent the amplitude spectrum (resolution 0.1 Hz) of the velocity error (derivative of the difference between target and pursuit). Each data point was obtained by averaging the results of all subjects in the indicated age group who could successfully execute the task. The component at the frequency of the target (arrow) is omitted (see text). Age differences are summarized in the inset in which each data point represents the total amount of nonlinearities in three frequency ranges (L: 0.2–0.9 Hz; M: 1.0–1.6 Hz; H: 1.7–2.3 Hz).

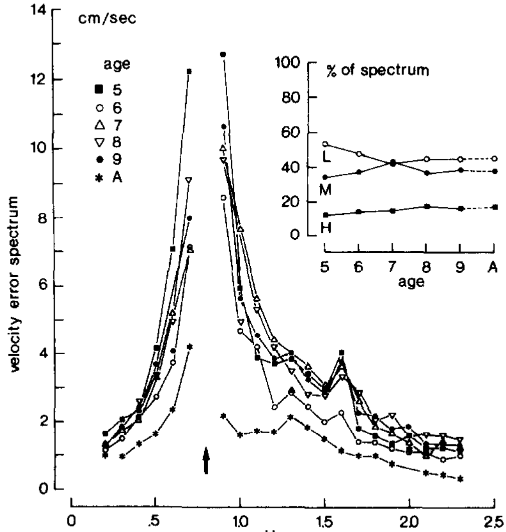

FIG. 8. Frequency analysis of the nonlinear components: 0.8 Hz. See Fig. 7.

Under certain conditions (but not in our experiment) they occur also in adults (Pew, Duffendack, & Fensch, 1967) and are documented even in ramp tracking (Craick & Vince, 1943, 1963; Ellson, Hill, & Gray, 1947).

The results can also be summarized by computing the total spectral components over three adjacent frequency intervals (0.2–0.9: L), (1.0–1.6: M), (1.7–2.3: H). The age evolution of the total spectral power within each of these intervals is shown diagrammatically in the insets to Figs. 7 and 8.

Despite the presence of nonlinear components, the simplest way of characterizing the performances consists of plotting phase and gain of the reponse fundamental versus the average group age (Fig. 9). The gain is defined as the ratio between the amplitude of the fundamental harmonic in the response displacement calculated by Fourier analysis and the amplitude of the target displacement. The phase indicates the delay (lag) of the fundamental harmonic with respect to the target, expressed as a fraction of one complete cycle (360°).

Within the limits of the approximation to linearity exemplified in Figs. 5, 7, and 8, this graph represents the dynamic properties of the tracking for those subjects who can perform the task seem to be independent of age. At 0.8 Hz instead, a 90° phase lag exists for the younger groups, which, with increasing age, approaches monotonically the adult performance. The corresponding evolution of the gain is not monotone. In particular, the 6-year-old children produce movements which are much smaller than those of all other age groups.

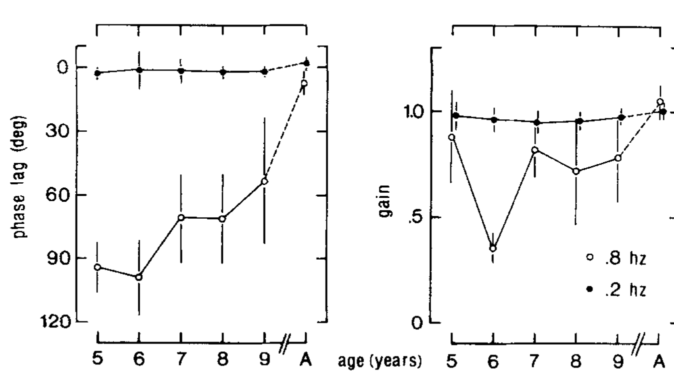

FIG. 9. Gain and phase of the linear components. The left graph represents the phase differences between the target sine wave and the harmonic components of the pursuit with the same frequency of the target. Positive values indicate that the pursuit lags with respect to the target. The right graph represents the ratio between the amplitude of the pursuit and the amplitude of the target. Each data point is the average over all subjects who could successfully execute the task in the indicated age group (A:adult) of the within-trial mean values. Intersubject variability is indicated by vertical bases (± 1 standard deviation).

DISCUSSION

The results have demonstrated the following points:

1. The tracking skill, as described in adults, is acquired progressively over a considerable number of years during childhood. Typical adult performances are not yet attained at the age of 9 years.
2. The evolution with age of the performance involves large changes in both qualitative and quantitative aspects of motor behavior.
3. At all ages considered, the tracking of sine waves by children depends dramatically on target frequency. In contrast, adult performances are largely independent of frequency below 1 Hz (Ellson & Gray, 1948; Noble, Fitts, & Warren, 1955).
4. Within the age limits explored here, the acquisition of the skill cannot be adequately described as a monotonic maturational process. Indeed, at least one major change in operating mode emerges which suggests a possible change in the strategy of perceptuomotor coordination.

All types of tracking necessarily involve some sort of coordinated action by the perceptual and motor systems. For the purposes of this discussion we begin by laying down a highly schematic description of what should be involved in this coordination from a logical standpoint.

One prerequisite for skillful tracking is the capability of representing centrally the trajectory of the target (Krendel & McRuer, 1960). For unpredictable targets such representation can only be piecewise, while in the case of predictable targets, as in our experiments, the entire trajectory can be apprehended as a whole.

The second prerequisite is the capability by the motor control system of producing, piecewise or globally, a copy of the represented target trajectory. The above two conditions are tacitly assumed to be satisfied in normal adults. However, they are not trivial in this context for it is known that the relevant cognitive and motor representations are only progressively established during childhood (Hay, 1979; Piaget, 1946; Pick, 1970). Moreover, even in the case of adults, it is likely that a cognitive representation of repeated patterns more complex than simple sine waves must be acquired progressively.

In addition, one has to postulate a mapping process between cognitive representations and the appropriate motor plans. Specifically, for any given trajectory or segment of a trajectory, this hypothetical process must identify a set of parameters which completely specify the target motion, and translate these parameters into an appropriate setting for the free variables of the motor plan.

A final and logically independent aspect of tracking is the so-called control problem: given the inevitable departures of the pursuit from the intended copy of the target, it is also necessary to postulate the possibility of updating and modifying an ongoing motor plan on the basis of incoming information, that is, to control on line the execution of the movement.

Although very general, the above scheme differs in some significant respect from the conceptual framework implicitly or explicitly assumed in most tracking studies (cf., however, Krendel & McRuer, 1960). In particular, models for tracking based on various analogies with manmade servomechanisms (cf. Poulton, 1974; Stark, 1968; Young & Stark, 1963) never invoke the hypothesis of a cognitive representation for the target motion. Indeed, these models only focus on the control problem mentioned above, which is generally phrased as a classical filtering problem: given the target position and its time derivatives as the input, produce an output (pursuit) which minimizes in some specific sense the position error. Thus the transcoding between the cognitive and motor representations postulated above reduces to a simple functional transformation between a sensory stimulus and a motor command.

As a main point in this discussion we argue that tracking behavior in children supports our logical scheme and—at the same time—is incompatible with any model based on the feedback servocontrol analogy. To be sure, many views of the tracking process can explain the pursuit of a predictable sine wave by adult subjects. Moreover, a servocontrol model can certainly be produced which accounts for one type of failure, observed in younger children and illustrated in Fig. 4C. Here the subject is only capable of producing a very low gain and irregular movement in response to sinusoidal target motion. The other three instances of unsuccessful performances illustrated in Figs. 4A, B, and D are instead in sharp contrast with the basic tenet of the servocontrol models, namely, the input–output, real-time type of operation that they postulate.

In the first two cases the subjects are obviously capable of producing sinusoidal movements with low distortions and stable frequencies. However, they apparently neglect the timing information and do not reproduce the frequency of the target. Most peculiar are those instances where the frequency of the movement is either twice the target frequency or half of it as in Fig. 4B. The performance of a third subject (Fig. 4D) is even more striking insofar as both amplitude and frequency of the pursuit agree with those of the target, but the phase is reversed during almost the entire trial (31.25 s).

These examples of failures, each of which is typical of a behavior observed in several of the younger children, strongly support the view expounded above that tracking is mediated by a cognitive representation of the target movement. Moreover, they also support the contention that the qualifying attributes of the cognitive representation which are mapped into the motor plan are elaborated progressively and independently of each other. Thus, for instance, the representation of the target trajectory by the subject shown in Fig. 4A has only derived from the actual movement the abstract property of being a sine wave: neither the frequency nor the amplitude is considered a qualifying attribute of target movement (cf. also the left panel in Fig. 6). While we cannot rule out the possibility that the problem with the amplitude lies with the calibration of the motor output and not with the cognitive representation, the frequency mismatch certainly cannot be attributed to inadequacy of the motor control. In the case of Subject D in the same figure, the representation of the target movement seems more concrete, but is specified only up to a phase shift. In this case, however, it is also possible that the progressively changing phase relation results from the subject's attempt to match frequency.

It is worth noting in this context that there are other instances of motor behavior in young children which can only be accounted for by assuming different levels of abstraction in the central representation of the movement. Thus, for instance, the peculiar form of disgraphia which apparently results from indifference to mirror reflection (Hécaen & de Ajuriaguerra, 1964) suggests that the internal representation of the letters—both as a motor act and as a percept—is too general to provide the specification of their orientation.

Since at no time during the task do Subjects A, B, and D in Fig. 4 ever bring the spot close to the target in the physical sense, the analysis of the failures can also be summarized as follows. If we accept the notion that the tracking task is generally understood by all subjects—adults and children—as the requirement of remaining "close" to the target, then the judgment of closeness cannot be based on the usual Euclidean metric. Rather, it must be couched in terms of a "metric" appropriate to the conceptual space in which the target movement is represented.

With increasing age, a larger proportion of children perform as adults do, by approaching physically the pursuit and target spot. In line with the above discussion, we conceive of this age-dependent evolution as the expression of a parallel change in the internal representation of the target motion. In the earliest stages of development, only the most salient features of the situation would be abstracted. Thus, for instance, all to-and-fro movements might be subsumed under one representational concept, irrespective of their specific attributes (Mounoud et al., 1983). In later stages these attributes would be progressively discriminated up to the point when each specific target motion can be singled out individually.

We stress that, if correct, this view implies that evolution toward the adult stage is better described as a sequence of discrete steps, each of which entails a redefinition of the relevant representation, than as a smooth refinement process.

An age-dependent evolution can also be documented within the group of children who perform qualitatively as adult controls. The input–output analysis of the pursuit linear component (Fig. 9) discriminates between adult and children only at the highest frequency (0.8 Hz). While the phase diagram shows a monotonic reduction of the phase lag between target and pursuit, which is compatible with the notion of a progressive improvement in the dynamics of the perceptuomotor mapping, the gain diagrams are dramatically discontinuous. This suggests the presence of at least one major modification in the strategy of perceptuomotor coordination occurring between the ages of 6 and 7. In view of 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 may be interpreted not 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 which, however, only becomes effective at a later stage (Bever, 1982).

In order to qualify this suggestion, let us reconsider the nonlinearities of the performance, that is, those harmonic components of the pursuit which are not present in the target movements (Figs. 7 and 8). If we confine our attention to the 0.2-Hz target frequency, it is obvious that the low- and high-frequency nonlinearities have an inverse distribution across ages. In particular, 5-year-old children stand out in this description for they completely lack the high-frequency oscillations, while the low-frequency distortions are much more prominent than at all other ages. It is unlikely that these distortions are due to limitations in motor execution abilities. Indeed, sustained oscillations with a dominant frequency of about 1 Hz are observed in hip, knee, and ankle joints during kicking as early as 4 weeks of age (Thelen & Fisher, 1983). Moreover, recent work by motor control theorists (cf., for instance, Kugler, Kelso, & Turvey, 1982) has pointed out that self-sustained oscillations can be produced by the intrinsic dynamics of the motor system, without assuming a global representation of the movement. On the basis of these considerations, and in line with the previous analysis of the failures, we can tentatively assume that 5-year-old children master the basic motor skill to produce sinusoidal motions (cf. Fig. 4) but, with few exceptions, cannot elaborate a global plan matching the target motion in all its relevant aspects (frequency, amplitude, and phase). Those who perceive that performances such as those in Fig. 4 are inadequate with respect to the task resort to a sequential pursuit strategy in which successive, short segments of trajectory are independently planned and executed. The large low-frequency distortions in their performances would then be the result of this piecemeal assembly of reaction time responses. The high failure rate of the same age group at 0.8 Hz is probably due to the fact that the target period is too short for such strategy to be implemented (Magdaleno, Jex, & Johnson, 1970; Pew, 1974).

The discontinuous mode of operation in pursuing the target subsides before the age of 7 when children fully utilize their previously acquired capability of producing sinusoidal motions. Within this age span, the success rate at 0.8 Hz increases dramatically and the amount of low-frequency distortion decreases by almost 50% (cf. inset to Fig. 7). At the same time, there is a moderate but significant increase in the high-frequency harmonic components which perhaps reflect the increasingly successful efforts to match not only the spatial and temporal aspects of the target separately, but also their specific relationship (kinematics).

The change of strategy requires, however, controlling globally the amplitude of the movement while this parameter is not directly attended to in the discontinuous mode of operation. In fact, it is between 5 and 7 that the intertrial variability of the amplitude decreases the most. Thus, the sharp reduction in gain at 0.8 Hz for the transition age (6 years) (cf. Fig. 9) could be the consequence of the processing load associated with this amplitude control.

In conclusion, the results suggest that, although the necessary motor ability involved in sinusoidal tracking is acquired at a very early stage of development, the construction of the representations appropriate to the fully developed skill requires neglecting temporarily this ability in favor of an altogether different strategy. It is, then, tempting to speculate that the discontinuous strategy is instrumental in the construction of these representations.

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