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Development of prehension movements in children: a kinematic study

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Abstract To evaluate the normal development of functional hand motor skill, the kinematics of prehension movements were analyzed in 54 healthy children (age 4–12 years). The subjects repeatedly reached out for cylindrical target objects and grasped them with a precision grip of their dominant hand. The trajectory of the reaching hand and the finger aperture were monitored by optoelectronic motion analysis. To obtain comparable conditions for the different age groups, the experimental setup was scaled according to the individual body proportions of each subject. Within the investigated age range, neither the movement duration nor the normalized (according to body proportions) peak spatial velocity of the reaching hand changed significantly. However, the hand trajectory straightened and the coordination between hand transport and grip formation improved, resulting in smooth and stereotyped kinematic profiles at the age of 12 years. The younger children opened their grip relatively wider than the older ones, thus grasping with a higher safety margin. The dependence on visual control of the movement declined during motor development. Only the oldest childen were able to scale the grip aperture adequately, according to various sizes of the target objects, when visual control of the movement was lacking. The results suggest that the development of prehensile skills during childhood lasts until the end of the first decade of life. This functional maturation is discussed in relation to the development of neuronal pathways.

Key words Prehension · Arm movement · Children · Grasp · Motor learning

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Introduction

Reaching out to grasp an object combines two movement components: spatial positioning of the arm and hand (hand transport), involving proximal muscles acting on the shoulder and elbow joints, and preshaping of the fingers (grip formation) according to the size and shape of the object, involving more distal muscles (Jeannerod 1984). Experiments in primates suggest that distinct neural systems are involved in the planning of hand transport and grip formation. Spatial positioning of the arm and preshaping of the grip seem to be coded predominantly in different areas of the premotor cortex, which are linked to distinct regions of the posterior parietal lobe (Jeannerod et al. 1995; Rizzolatti et al. 1997). Furthermore, hand transport is organized bilaterally and can thus be steered by the ipsilateral brain hemisphere (Brinkman and Kuypers 1973), whereas precise grasping depends on the integrity of crossed corticospinal pathways projecting from the contralateral motor cortex (Porter and Lemon 1993).

Nevertheless, hand transport and grip formation must be precisely coordinated to ensure efficient prehension. Hoff and Arbib (1993) have proposed the existence of a superordinate control program responsible for the coordination of reaching and grasping. Such a control is reflected by the stereotyped kinematic features of prehension movements in human adults (Jeannerod 1984). Hand transport is characterized by smooth, approximately bell-shaped velocity profiles and straight trajectories of the reaching hand (Georgopoulos 1986). Grip formation is coordinated with transport in such a way that maximum grip aperture is reached in the deceleration phase of the reach, at about two-thirds of the movement duration (Jakobson and Goodale 1991; Chieffi and Gentilucci 1993). Errors of hand transport which may occur during prehension without visual guidance are compensated by a widening of the grip aperture (Wing et al. 1986). The velocity of hand transport varies with target distance and the grip is preshaped according to the object size (Jeannerod 1984; Chieffi and Gentilucci 1993).

Table 1 Body height and weight, arm length, finger span in the different age groups (interindividual means and SD)

Age (range in months)	48–51 (4 years) (*n*=12)	60–63 (5 years) (*n*=14)	84–87 (7 years) (*n*=14)	144–147 (12 years) (*n*=14)
Body height (cm)	105.1±2.2	113.1±4.3	125.3±4.7	154.5±6.1
Weight (kg)	16.8±1.9	18.5±4.3	25.6±4.5	42.4±6.4
Arm length (cm)	32.3±1.3	34.5±2.0	40.0±2.1	51.4±1.5
Finger span (cm)	9.8±0.7	10.6±0.9	11.7±1.0	14.3±1.1

A smooth coordination of reaching and grasping is not innate but evolves gradually during ontogeny (Jeannerod 1986). However, compared to the numerous analyses of prehension in human adults, few kinematic data are available concerning the development of this motor skill in children. In infants at an age of 4 months, the first functional reaches display circuitous trajectories (Fetters and Todd 1987) which are composed of several acceleration-deceleration segments (movement units). A straightening of the trajectories and a decreasing number of movement units per reach have been found in longitudinal studies of infants up to the age of 9 months by von Hofsten (1979, 1991). At this age the infants tend to adjust their grip size according to the object size, but preshaping is much less differentiated than in mature grasping and is poorly coordinated with hand transport (Hofsten and Rönnqvist 1988). Konczak and coworkers (1995, 1997) recently analyzed the kinematics and dynamics of reaching movements in children up to an age of 3 years. The improvement in transport kinematics was mirrored by an increasingly smooth and efficient muscular torque production. However, the authors noted that differences in spatial layout and precision of velocity control may still exist between 3-year-old children and adults (Konczak and Dichgans 1997). Data on older children are lacking so far.

In the present cross-sectional study, comprising two experiments, a detailed kinematic analysis of reaching and grasping was performed in healthy 4- to 12-year-old children to describe the development and refinement of these motor skills. In the first experiment, object size and distance were kept constant within each subject, and were scaled according to the body proportions to obtain comparable data for the different age groups. It was expected that maturation of hand transport would result in faster movements with straighter trajectories, smoother velocity profiles, and a decreasing number of movement units per reach. A maturing synergy of hand transport and grip formation would be reflected by an increasingly stable temporal coupling of the two movement components. In the second experiment, target size and distance were varied systematically in each subject to analyze the ensuing adaptations of motor performance. Prehension trials executed with and without vision of both target object and hand were compared. This may show whether children memorize the object's properties correctly to adjust their grip accordingly when visual guidance is lacking. The present study complements the existing kinematic data of normal motor development, since the reach-to-grasp movement has been analyzed in young children and adults but not at intermediate age levels.

Experiment 1

Materials and methods

Subjects

A total of 54 healthy children aged 4–12 years took part in this study. They were recruited from nursery and primary schools after approval of the local authorities and the ethics committee. All children and parents gave their informed consent prior to participation. Mental and motor development of the children was assessed by physical examination and by standardized testing procedures. Cognitive functions were examined using the Kaufman Assessment Battery for Children (Melchers and Preuß 1991). A movement assessment test for children (Schilling and Kiphardt 1974) was used to evaluate global motor functions such as balance, strength, and coordination. Children who scored below one standard deviation of the norm in either test were excluded. The subjects were then divided into four age groups, with equal distribution of gender. Body height and weight, arm length (AL, distance between acromion and styloid process of the radius), and maximum finger span (FS; distance between the pads of the thumb and index finger of the spread hand) were measured to adjust the experimental setup for each subject (Table 1). Ninety percent of the participants were right-handed as determined with a standardized questionnaire (Oldfield 1971); the others were left-handed or ambidextrous.

Procedure

The children sat in an adjustable chair, facing a dark table surface (100×70 cm). At the beginning of each trial, the dominant hand and half of the forearm rested on the table in a semiprone position in front of the shoulder. The thumb and index finger were in pinch position, touching a half-spherical knob (diameter 1 cm) which marked the starting point on the table surface. The shoulder was in a neutral posture (neither abducted nor adducted), the humerus aligned parallel to the trunk, and the elbow was flexed by about 90°. The forearm axis was aligned forward in the direction of the reach. In a given trial, a target object was placed on the working surface in front of the shoulder joint, so that the grasping hand advanced along a parasagittal plane. The objects were white upright plastic cylinders. Cylinder size and target distance were scaled proportionate to the individual's FS and AL to obtain comparable conditions for the different children. The diameter of the dowels was 10% of the FS (gradation interval 1 mm), and their height was 25% of the FS. The distance between starting point and target was 60% of the AL.

The children were instructed to reach and grasp the object with thumb and index finger, pick it up, and place it beside the starting point. This was demonstrated and practiced several times before data collection started. A short acoustic signal (ding) gave the command to start the movement. Reacting as quickly as possible was not emphasized, but the children were told to move at a nor-

Table 2 Prehension in the visual condition: interindividual means (±SD) of kinematic parameters in the different age groups

Age	4 years	5 years	7 years	12 years
Movement initiation time (ms)	670±216	495±118	462±158	399±118
Movement duration (ms)	839±189	779±174	776±156	685±130
SD of movement duration (ms)	164±63	128±43	131±46	70±27
Transport parameters				
Peak transport velocity (cm/s)	65.4±8.4	69.7±14	79.2±14.9	98.8±13.8
Time to peak velocity (ms)	297±64	294±60	300±49	293±67
Relative time (% of movement duration)	36.2±9.8	40.2±8.4	39.6±8.6	42.5±6.2
Time to peak deceleration (ms)	496±125	479±82	463±68	456±98
Relative time (% of movement duration)	59±14.3	62.5±13.9	61.3±12.6	67.5±9.1
Straightness ratio	1.31±0.15	1.27±0.12	1.20±0.05	1.10±0.06
Number of transport subunits	2.1±0.6	1.9±0.4	1.4±0.4	1.1±0.2
Grasp parameters				
Maximum grip aperture (cm)	5.18±0.91	5.35±0.69	5.60±0.85	6.52±0.96
Normalized grip aperture (percentage of the finger span)	52.9±6.2	50.7±6.5	47.9±7.2	45.4±6.7
Time to max. grip aperture (ms)	536±103	454±75	449±81	465±98
Relative time (% of movement duration)	63.4±16	59.2±13.9	59.5±12.9	67.8±8.7

mal and comfortable speed, as if "reaching for a building brick on the table." Ten trials took place under normal room-lit conditions, and ten subsequent trials were performed without visual control in each subject. In this no-vision condition the children saw the target object prior to the start signal. The light was then extinguished concurrently with the start signal for about 5 s, so the object had to be grasped in complete darkness. Thus a motor task and a spatial memory task were combined in the no-vision condition.

Recording and evaluation of kinematic data

An optoelectronic motion analysis system (Qualisys, Partille, Sweden) was used, consisting of two cameras equipped with infrared light emitting diodes (IRED) and videoprocessors. The light was reflected by three passive light-weight half-spherical markers (diameter 0.5 cm). These were attached to the wrist at the styloid process of the radius, to the nail of the thumb (ulnar side), and to the nail of the index finger (radial side). The three-dimensional coordinates of the marker centroids were recorded with a sampling frequency of 50 Hz by the videoprocessors. Within the calibrated cubic workspace (edge length 0.5 m) the spatial error of a stationary marker was 0.4 mm. The coordinate data were low-pass filtered (second order Butterworth, cutoff frequency 20 Hz), and transferred to a PC for the calculation of kinematic parameters. The moment when the object was grasped and lifted more than 0.5 mm was indicated by an IRED which was triggered by a switch concealed beneath the target. Another IRED lit up with the start signal. All prehension trials were videotaped. Only those trials were analyzed in which the object was grasped correctly, and all markers were adequately visible throughout the movement. About 5% of the trials had to be excluded, mainly because markers were obscured or accidentally lost. There were no systematic differences in the number of usable trials between visual conditions and/or age groups.

Hand transport was described with the kinematic data obtained from the marker attached to the wrist. Movement initiation time lasted from the acoustic start signal until movement onset, when the displacement of the wrist exceeded 0.7 mm and hand velocity increased for at least five successive samples thereafter. Movement duration was defined as the interval between movement onset and lifting of the object. Retraction of the hand back to the starting position, after grasping, was not evaluated quantitatively. Peak tangential velocity of the reaching hand, and the absolute and relative (as a percentage of movement duration) timing of peak velocity and peak deceleration were calculated. According to the criteria devised by von Hofsten (1991), the velocity profile of hand transport was broken down into movement units. Each unit consists of one acceleration and one deceleration phase, and velocity curves with multiple peaks thus comprise several movement units. At the beginning of a movement unit the cumulative increase in velocity had to exceed 2 cm/s and acceleration 5 mm/s^2 to filter out slow changes. To compute the straightness of the reaching path, the length of the wrist trajectory (measured three-dimensionally) was divided by the distance between starting point and target. A more circuitous approach would render a higher ratio. Grip formation was analyzed by measuring the distance between the markers attached to the thumb and index finger. The maximum grip aperture was also expressed as a percentage of the FS to obtain normalized values. Furthermore, the absolute and relative timing of this event was calculated. For both the visual and the no-vision condition, intraindividual means of the kinematic parameters and age group averages were calculated. To detect significant age-dependent changes the intraindividual means (average of nine or ten trials per child) were entered into analyses of variance, with age as a between-subjects factor. Separate such analyses were carried out for the different kinematic parameters and for the visual and the nonvisual conditions.

Results

Prehension in the visual condition

Hand transport and timing: The children reached for the objects with a coupled shoulder/elbow extension and grasped and retrieved the cylinders with a precision grip of the thumb and index finger. In the vast majority of trials most of the distance to the target was covered by the first acceleration-deceleration sequence of the reach. Table 2 presents the mean age group results of kinematic parameters for the standardized prehension task (target distance 60% AL, object diameter 10% FS). The older children reacted quicker than the younger ones, and the time elapsed between the start signal and movement onset decreased from 670 ms at the age of 4 years to 400 ms at the age of 12 years (Fig. 1). This effect of age was significant ($F_{3,50}$=6.92, P<0.01). However, the movement duration changed less with age. The decline from 840 ms

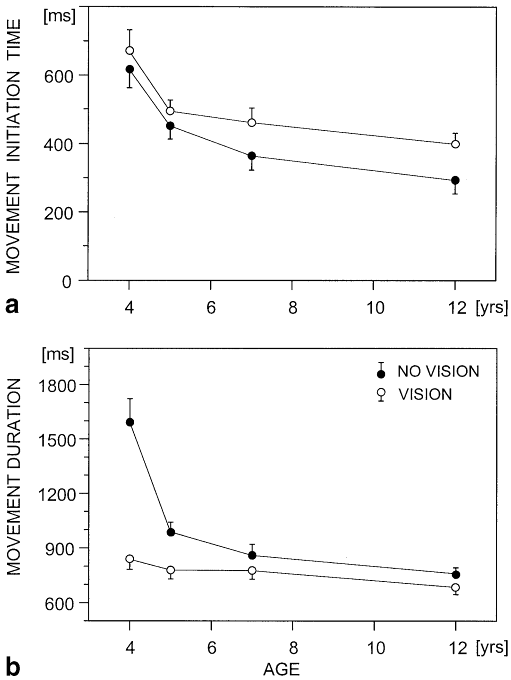

Fig. 1a, b Movement initiation time and movement duration of a standardized prehension task at different ages; mean±SEM of the different age groups (12–14 subjects per group). *Open circles* Prehension with visual control; *filled circles* prehension without visual control of the movement

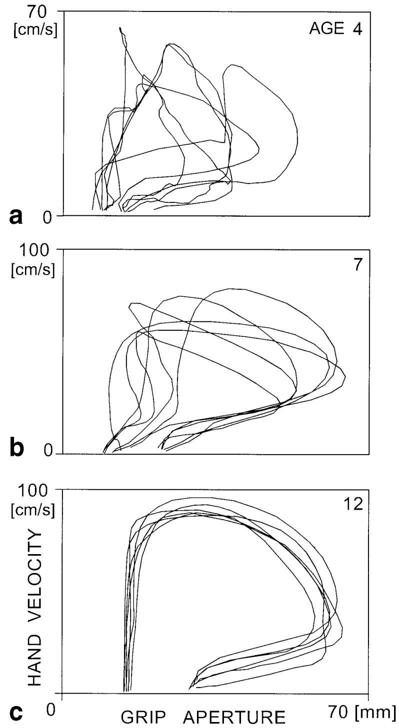

Fig. 2a–c Kinematic profiles of prehension at the age of 4, 7, and 12 years. The hand velocity is plotted against the grip aperture in three children of different ages. Six trials are superimposed for each subject (visual condition)

(4 years) to 685 ms (12 years) failed to reach statistical significance.

The time of acceleration to peak velocity was remarkably constant in the different age groups, the mean values ranging between 290 and 300 ms (Table 2). On average, peak velocity was reached after 36%–42%, and peak deceleration after 59%–67% of movement time, without significant age-dependent changes. Maximum velocity of hand transport increased significantly with age ($F_{3,50}$=17.6, P<0.001) from about 65 cm/s (4 years) to 100 cm/s (12 years). However, since endpoint velocity is proportional to the length of the moving segments, these data were normalized. When hand velocity was divided by AL, the age-related differences vanished. The increase in speed therefore seems to reflect the childrens' growth (AL) and not a faster execution of the movement (faster joint angular excursions) in the older subjects. This is consistent with the fairly constant movement duration that was recorded in the different age groups.

Grip formation: The peak grip aperture attained during reaching increased significantly with age ($F_{3,50}$=9.2, P<0.01), as was expected from the growing size of the hand. However, when grip aperture was normalized as a percentage of the *maximum possible* grip size (i.e., the FS of the fully open hand), it became evident that the young children opened their grip *relatively* wider than the older ones ($F_{3,50}$=2.9, P<0.05), thus grasping with a larger safety margin (Table 2). In all age groups the maximum grip aperture was attained during the decelerating phase of hand transport, but the mean time interval between this event and *peak* deceleration of the hand decreased from 40 ms at the age of 4 years to 9 ms at the age of 12 years. This indicates a tighter temporal coupling of grip formation and hand transport in the older children.

Smoothness of the movement: The uniformity and regularity of the movements improved during motor development. This can be seen in by Fig. 2, which displays velocity/grip size profiles of repetitive prehension trials at three different age levels. The variability decreased and fluctuations of kinematic profiles disappeared with age, indicating a more automatized performance. The number of movement units per reach declined with age ($F_{3,50}$ =6.7, P<0.01), and at the age of 12 years hand transport generally consisted of only one acceleration-deceleration sequence (Table 2). Furthermore, the approach towards the target became more linear, as indicated by the decreasing straightness ratio (significant effect of age; $F_{3,50}$=3.7, P<0.05). In addition, the profiles of the grip aperture, which frequently displayed multiple peaks in the young children, developed towards a single stereotyped opening-closing sequence (see Fig. 3). The higher uniformity of repetitive trials was reflected by an age-dependent decrease in the intraindividual scatter of most kinematic parameters. Thus the mean intraindividual standard deviation of movement duration decreased steadily and significantly ($F_{3,50}$=8.8, P<0.01) with age from 164 ms at the age of 4 years to 70 ms at the age of 12 years (Table 2).

Table 3 Prehension in the no-vision condition: interindividual means (±SD) of kinematic parameters in the different age groups

Age	4 years	5 years	7 years	12 years
Movement initiation time (ms)	617±185	452±138	364±148	293±144
Movement duration (ms)	1594±441	988±200	860±225	760±123
SD of movement duration (ms)	223±71	188±54	168±83	125±62
Transport parameters				
Peak transport velocity (cm/s)	55.3±10.7	73.7±11.9	82.4±13.1	100.9±11.4
Time to peak velocity (ms)	334±76	267±46	251±50	262±31
Relative time (% of movement duration)	22.6±6.5	28.1±5.1	29.9±4.9	36.1±4.7
Time to peak deceleration (ms)	734±246	488±136	424±103	396±88
Relative time (% of movement duration)	50.1±17	48.4±11.1	51.0±11.4	54.2±7.3
Straightness ratio	1.45±0.17	1.42±0.13	1.25±0.09	1.13±0.08
Number of transport subunits	3.3±0.8	2.9±0.7	1.9±0.7	1.3±0.5
Grasp parameters				
Maximum grip aperture (cm)	6.75±1.12	7.01±0.87	7.61±1.01	8.33±0.93
Normalized grip aperture (% of the maximum finger span)	68.6±12.4	66.1±8.2	65.7±8.6	58.5±6.5
Time to max. grip aperture (ms)	702±281	501±138	454±91	406±70
Relative time (% of movement duration)	41.2±12.6	50.1±9.9	51.9±12.1	54.6±6.5

Prehension in the no-vision condition: In the no-vision condition the hand must be geared to the memorized location of the target object, without concurrent visual feedback. For this condition, original data (Fig. 3) and mean age group results of kinematic parameters (Table 3) are presented. In particular, the 4- and 5-year-old children had some difficulty fulfilling the task requirements promptly. Although they directed their reach towards the approximate location of the target, several corrective submovements at the end of the reach were needed to pick up the object. These corrections resulted in a distinct prolongation (significant age effect: $F_{3,50}$=16.9, P<0.001) of movement time (see also Fig. 1). The decelerating phase elapsing between peak hand velocity and successful grasping was lenghtened particularly in young children. Within the temporal frame of movement duration, the relative setting of peak velocity was shifted more towards the beginning of the reach in the young children than in to the older ones (significant age effect: $F_{3,50}$=8.2, P<0.01). The kinematic profiles of a 4-year-old child (Fig. 3) illustrate the prolonged deceleration phase and the additional acceleration-deceleration sequences (movement units) of hand velocity with concomitant grasping movements at the end of the reach in the no-vision condition. There was no conspicuous systematic improvement in performance in the course of the experiments, i.e., no clear-cut learning effect. At the age of 12 years irregularities were far less frequent, and prehension was commonly accomplished within one or two movement units. Nevertheless the basic reach-to-grasp synergy was preserved in the no-vision condition even in the young children. Most of the distance to the target was covered by the first acceleration-deceleration sequence of hand velocity, and maximum grip size was attained later than peak velocity during deceleration. Regardless of age, the children opened their hands wider in the no-vision situation than in the visual condition, thus adapting their grip to counterbalance errors of hand transport.

Experiment 2

In the first experiment the kinematics of a quasinatural prehension task were analyzed. By scaling object size and distance according to the anthropometric data of each subject the experimental conditions were standardized and comparable for the different age groups. The results indicate a smoother, more consistent performance and a more accurate grip formation with increasing age, whereas the movement duration remains fairly constant. Moreover, young children are more dependent on visual guidance than older ones. However, it remains open how children adapt their individual motor strategy to variations in target distance and size, since in the first experiment these parameters were kept constant for each subject. In the second experiment, distance and size were now varied for each subject, both in the visual and in the nonvisual condition. The amount of variation was kept proportionate for the different age levels.

Materials and methods

Fifty-two of the children who had participated in experiment 1 took part in the second experiment. Two boys (5 and 7 years old) had to be excluded because of disruptive behavior. Pauses were allowed between the experiments to avoid fatigue, and in some cases sessions were spread out over 2 days. The apparatus and procedure, placement of the markers, and the calculation of kinematic parameters were the same as in experiment 1. However, distance (near, far) and size (small, large) of the target objects were now varied in random order for each subject. The target distance was 30% of AL for near reaches and twice as long for far reaches (60% AL). The cylinder diameter was 25% of FS for the large target objects, and 10% for the small objects. One block of 20 trials was carried out under normal viewing conditions, and another was performed in the no-vision condition. The order of viewing conditions was counterbalanced across subjects. For each combination of factors five trials were recorded and averaged in each child. Separate analyses of variance were carried out on the kinematic parameters, with age as a between-subject factor, and distance, size, and viewing condition as within-subject factors.

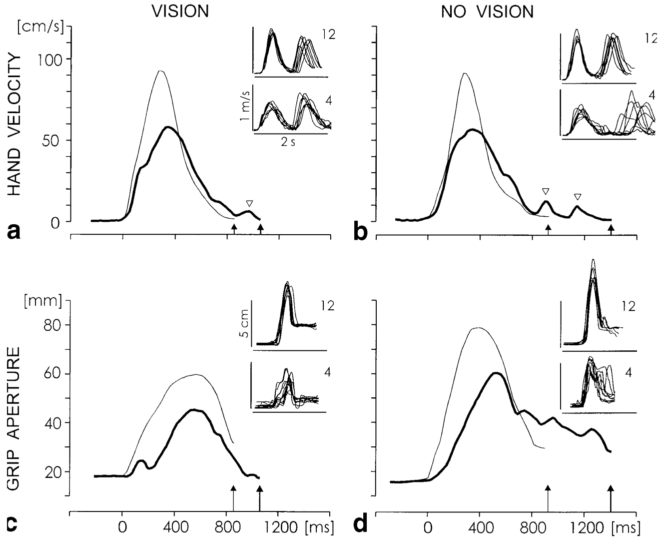

Fig. 3a–d Original hand velocity and grip aperture profiles at the age of 4 (*bold lines*) and 12 years (*thin lines*). Prehension trials were performed with (**a**,**c**) and without (**b**,**d**) visual control. Movement onset is at 0 ms. *Vertical arrows* End of the movement (lifting of the target objects); *triangles* additional acceleration-deceleration sequences (movement units) of hand velocity at the end of the reach. *Insets*, 8–10 superimposed trials for each subject to illustrate the intraindividual variability

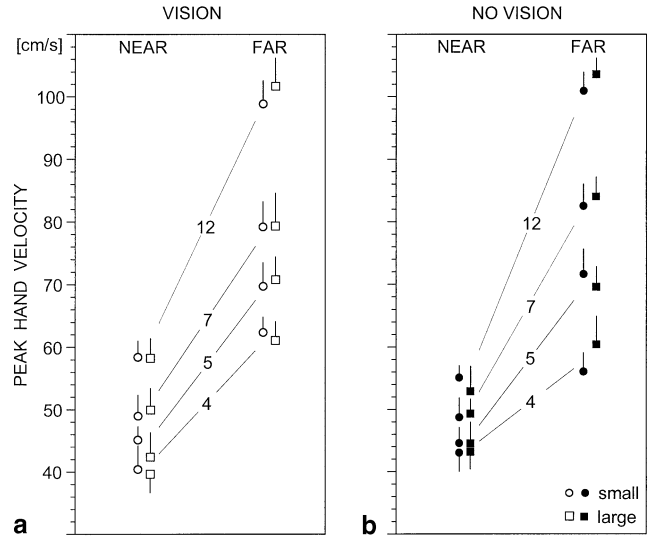

Fig. 4a, b Peak transport velocity as a function of movement amplitude and target size in the different age groups (4, 5, 7, 12 years). *Symbols*, *error bars* Age group means±SEM (12–14 children per group). Target distance was 30% of the AL for the near, 60% for the far reaches. *Circles* Small target objects; *squares* large objects. Trials were performed with (**a**) and without (**b**) visual control

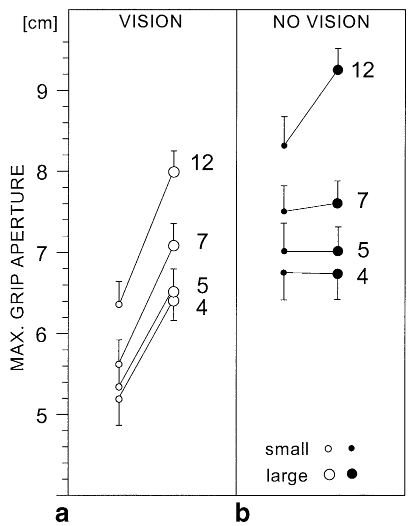

Fig. 5a, b Maximum grip aperture as a function of the object size in the different age groups (4, 5, 7, 12 years). The diameter of cylindrical objects was 10% of the FS for the small target object (*small symbols*), and 25% for the large targets (*large symbols*). Trials were performed with (**a**) and without (**b**) visual guidance. Otherwise as in Fig. 4

Results

Hand transport: The twofold increase in target distance (30%→60% AL) led to a highly significant ($F_{1,48}$=417.8, P<0.001) increase in the peak transport velocity. This effect was present in all age groups regardless of the viewing condition (Fig. 4). Therefore the children adapted their velocity of hand transport according to the movement amplitude even when visual control of the reach was lacking. The scaling factor describing this increment in velocity was rather constant in the visual condition, ranging between 1.5 and 1.7 for the different age groups, and slightly more variable in the nonvisual condition (increasing from 1.3 at the age of 4 years to 1.8 at 12 years). Furthermore, in all age groups the increase in target distance led to a proportionately earlier temporal setting of the maximum velocity (significant effect of distance; $F_{1,48}$=33.7, P<0.01). On average, the peak velocity was timed at 35±9% of the movement duration for the far reaches (mean±S.D. of all subjects), and at 40±11% for the short distance. Since the movement duration lengthened significantly with increasing distance (from 691 ms to 887 ms; $F_{1,48}$=59.5, P<0.01), the increase in hand velocity was not sufficient to keep movement time constant. Altogether the distance-dependent increases in movement time and peak transport velocity were consistently present at all age levels; neither the movement duration nor the velocity were substantially influenced by variations in the object size. Furthermore, peak velocity was not significantly affected by the viewing condition, but its timing changed. Maximum velocity was attained significantly earlier in the nonvisual (at 33±9% of the movement time) than in the visual situation (42±10%; $F_{1,48}$=37.6, P<0.01) in all age groups.

Grip formation: An increase in the object size (cylinder diameter 10%→25% FS) led to a highly significant enlargement of the grip aperture ($F_{1,48}$=11.1, P<0.01). However, a significant interaction between viewing condition and age was found ($F_{3,48}$=13.6, P<0.01). In the visual condition, children of all age groups adapted their finger aperture according to object size en route to the target (Fig. 5a). The situation was different in the no-vision situation. Only the 12-year-old children clearly scaled their grip size according to the object size when reaching in the dark (Fig. 5b). In this condition, adequate adjustments in the grip size develop later than the distance-dependent scaling of the hand transport velocity. In the no-vision condition, the maximum grip size was reached on average around 49±11% of the movement time, earlier than in the visual condition (65±9%). Lack of visual control led to a substantial enlargement of the hand aperture (significant effect of modality; $F_{1,48}$=16.6, P<0.01) at all age levels, whereas variations of target distance had no significant effect upon grip size. Adjustments in grip size according to the object size were present at all age levels during visually guided prehension movements, but these adjustments were lacking in the no-vision condition except in the oldest children.

Discussion

Mature prehension involves the smooth integration of reaching and grasping in a unified and stereotyped action. While the hand approaches the target, the fingers are postured according to the shape and size of the object. Well synchronized with hand transport, the grip starts to close in anticipation of the encounter with the target, so that the finger pads contact the object at the end of the reach (Jeannerod 1984; Chieffi and Gentilucci 1993). The present cross-sectional study yields developmental data of reaching and grasping in 4- to 12-year-old children. Within this age range, the quality and coordination of the movement components improved. Three developmental aspects can be discerned: first, the refinement of hand transport, which requires correct perception of distances and involves predominantly proximal joint movements (shoulder, elbow); second, the development of grip formation and its coordination with hand transport; third, the evolving ability to reach and grasp without visual guidance, which requires the object's intrinsic and extrinsic properties to be memorized.

Hand transport: Goal-directed reaches emerge around the fourth month of life, developing earlier than differentiated finger movements (Jeannerod 1986; von Hofsten 1991). Whereas the first reaches are awkward and circuitous, the endpoint kinematics of the hand improve rapidly until the seventh month, and more gradually thereafter (Fetters and Todd 1987; Konczak et al. 1995, 1997). Even in the age range covered by the present study (4–12 years) the kinematics of hand transport still improved. This was evident from the emanation of smooth and reproducible, bell-shaped velocity profiles with a decreasing number of movement units per reach and more linear trajectories. Analysis of the intersegmental dynamics in infants has revealed that the development of a stereotyped hand trajectory is mirrored by concurrent changes in the temporal organization of the torques acting on proximal limb segments and by an appropriate integration of gravitational and reactive torques into movement execution (Konczak et al. 1995). Immature motor control is characterized by oscillations in the torque output, which results in a segmentation of the velocity profile and in a more circuitous approach path. The timing of muscular and motion-dependent torque peaks shows a systematic development towards an adult timing profile with increasing age (Konczak et al. 1997; Konczak and Dichgans 1997). Although the improvements of reaching kinematics found in the present study were far less dramatic than those occurring during the first 3 years of life, they may nevertheless represent the final stage of this development.

Other kinematic features were more stable, showing no further development between 4 and 12 years of age. Movement time was rather constant in the visual condition, and the values of the normalized hand velocity (maximum velocity divided by AL) did not change significantly with age. Therefore, when reaching at their normal speed, the older children did not move faster than the young ones. Note that unlike other tests of manual skill that require maximum rapidity (e.g., tapping rate; Müller and Hömberg 1992), the present paradigm was meant to represent natural behavior and not the limits of motor performance. The remarkably constant time to peak velocity of the different age groups suggests a uniform temporal frame of the initial ballistic phase of the reach. In support of this, a development towards early and constant timing of the torque burst of shoulder flexion during forward reaching has been found even in infants (Konczak et al. 1995).

In the present study all children showed an appropriate scaling of movement velocity to movement amplitude, which may be interpreted as a time-distance calibration of the workspace. Similar behavior has been observed in younger children (von Hofsten 1991). The finding agrees with the neural network model of Bullock and Grossberg (1988), which simulates behavioral data of planned arm movements. The model predicts that movement rate depends on the force difference, which in turn depends on the distance between the starting position and the final position of the hand (the difference vector). The distance-dependent increment in velocity does not merely result from a lengthening of the acceleration time but is mirrored by electromyographic changes (increase in the first agonist burst) of arm muscle activity early after movement onset (Brown and Cooke 1981) and an enhanced acceleration. However, in contrast to the model (Bullock and Grossberg 1988), the velocity profiles of hand transport showed neither duration invariance nor shape invariance in the present study. The profiles became more asymmetric when distance increased, since the relative timing of peak velocity shifted toward movement onset. Furthermore, the movement time lengthened, which corresponds to previous investigations of reaching and grasping in adults (Jakobson and Goodale 1991). The differences may be task-specific, since invariant duration and invariant shape of velocity profiles were found in a kinematic analysis of a pointing task (Atkeson and Hollerbach 1985), but not in prehension paradigms.

Grip formation: Anticipatory preshaping of the grip aperture according to target size, a well-known feature of adult prehension (Jeannerod 1988), was present even in the 4-year-old children during visually guided reaching. The younger children opened their hands relatively wider than the older ones, possibly to compensate for inaccuracies of hand transport. Corresponding results have been found in infants (Hofsten and Rönnqvist 1988; Siddiqui 1995). Between 4 and 12 years of age, grip formation improved, developing towards a uniform opening-closing sequence with a single peak that was well synchronized with the deceleration in hand transport. Grip formation and hand transport formed a reproducibly coupled synergy in the oldest subjects, as if defined by a stable central coordinative organization (Bernstein 1967). This maturation is similar to the observations of Forssberg et al. (1991), who recorded grip and load forces during repetitive lifts of a small object, which was grasped with the thumb and index finger (precision grip). Multipeaked profiles with poorly coordinated, incremental force increases were found in children younger than 4 years. A mature synergy with parallel output of the grip force and load force generators and bell-shaped grip force rate curves emerged around the age of 8 years. There was a transition from a feedback control to an anticipatory strategy. Forssberg's paradigm involves anticipation of weight and proprioceptive feedback, whereas the present visuomotor task of prehension requires spatial coding to achieve preshaping of the grip, involving both visual and proprioceptive control. It is noteworthy that similarities in the maturational process are evident, despite task-specific differences. For a more comprehensive developmental timetable, it would be interesting to study grip formation in younger children. However, reliable measurements of grasp parameters require that the initial posture of the hand be kept constant throughout trials (Kritikos et al. 1998). This is difficult to achieve in younger children.

Dependence on visual control: When visual control is lacking, an internal representation of the object's extrinsic (distance, location) and intrinsic (size, shape) properties must be present to reach and grasp efficiently. The hand must be directed to the memorized location of the target. Even in this situation, all children scaled their hand transport velocity according to the distance. Preshaping of the grip was less consistent, i.e., the internal representation of the object's size and shape was weak. Adequate adjustments of the finger aperture to the object diameter, as known from adult grasping (Jakobson and Goodale 1991), were present only in the 12-year-old subjects (Fig. 5b). In the no-vision condition, the grip aperture was wider than in the visual condition, in order to counterbalance inaccuracies of hand transport. Despite this, the young children (4–5 years) often missed the target initially, which indicates their strong dependence upon visual guidance. In investigating ballistic aiming movements, Whiting and Cockerill (1972) came to comparable results and concluded that 5-year-old children succeed only in sensorimotor tasks which provide many visual cues. A much greater accuracy was found in children in an open-loop pointing task (Hay 1979), where the target was visible, but vision of the hand was precluded. Therefore the errors of the young children in the no-vision condition may be explained by their inability to maintain a mental image of the target location rather than by erroneous proprioceptive sensing of hand position in space. To resolve this issue, it would be worthwhile to study prehension in children in a no-visual-feedback condition (Jeannerod 1984), where the target is visible but the hand is not.

It is tempting to presume a correlation between behavioral data and the growth of neuronal pathways. The maturation of corticospinal connections is a prerequisite for smooth visuomanual coordination (Müller and Hömberg 1992; Porter and Lemon 1993; Armand et al. 1996). The emergence of the precision grip in children at an age of approx. 12 months has been related to the myelination of corticospinal fibers, which continues until the third year, according to anatomical data (Jeannerod 1986; Brody et al. 1987). However, the refinement of skillful manipulative forces proceeds up to an age of about 8 years (Forssberg et al. 1991). Even longer lasting structural changes have been deduced from the gradual increase in central conduction velocity of fast corticospinal efferents (studied by transcranial magnetic stimulation), which lasts until an age of 10–15 years (Eyre et al. 1991; Armand et al. 1996). This maturational profile has been shown to be correlated with development of the fastest repetitive voluntary motor activities (Müller and Hömberg 1992), which, however, do not represent natural and functional motor behavior.

It has yet to be determined which behavioral test results show the closest correlation with structural changes. Concerning the present, functionally pertinent prehension task, it must further be considered that, in addition to the primary motor cortex, various other areas of the parietal and premotor cortex seem to be engaged in the planning of hand transport and grip formation. In monkeys the premotor area F4, linked to parietal areas VIP and PF, stores motor schemata for bringing the arm towards specific spatial locations (Rizzolatti et al. 1997). The transformation of an object's size and shape into specific grips takes place in a circuit which is formed by the premotor area F5 and the inferior (area AIP) parietal lobule (Jeannerod et al. 1995). A specific anatomical location of the control program regulating the coordination of arm transport and grip formation (Hoff and Arbib 1993) is not yet known. This makes it difficult to establish a simple relationship between kinematic improvements and structural maturation. Moreover, skilled behavior is not only a structure-bound phenomenon but must be accomplished by repetitive practice. Optimum performance is achieved by successive approximation, using knowledge of errors to fine-tune the functional connectivity of the motor system to improve future accuracy (Kalaska and Crammond 1992). Concerning prehension, this learning process may encompass the first decade of life.

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