Developmental Neuropsychology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/hdvn20

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Available online: 08 Jun 2010

DEVELOPMENTAL NEUROPSYCHOLOGY, *30*(2), 719–738

A Comparison of the Reach-To-Grasp Movement Between Children and Adults: A Kinematic Study

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In this study, the reach-to-grasp movement of 5-year-old children was compared to that of adults. Participants were required to reach out and grasp objects, with and without on-line visual feedback. Object size and distance were covaried in a within-subjects design and it was found that for both groups, grip formation and reach kinematics were affected by the manipulation of either variable. Although there are a large number of similarities, a few differences between the two groups emerge. For the reaching component, the children revealed a longer movement duration and deceleration time and a lower maximum height of wrist trajectory than in adults. For the grasp component, the children, in both the vision and no-vision condition, show a maximal finger aperture larger than the adults. Further, the children of this study were able to scale their grip aperture according to object size when visual feedback during the movement was lacking. These findings suggest that children adopt different strategies than adults when planning a reach-to-grasp movement on the basis of object size, distance, and the predictability of visual feedback. The results are discussed in terms of the neural mechanisms underlying hand action and how these mechanisms may not be fully developed by the age of 5.

The everyday action of reaching to grasp an object is commonly described in terms of a proximal-distal distinction. The reaching and positioning actions, affected by

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upper arm and forearm musculature, are subserved by central nervous system visual motor mechanisms that are largely independent from mechanisms underling the hand and digit opening and closing on the object for its grasp. With this description, the two neural channels, reaching and grasping, are said to be activated simultaneously and in parallel (the "channel" hypothesis of Jeannerod, 1981, 1984), being coupled functionally for the goal-directed action by a higher order coordinative structure (Hoff & Arbib, 1993; Jeannerod, 1994; Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991a, 1991b). The "reaching" channel extracts information about the spatial location of the object for transformation into motor patterns that bring the hand appropriately toward the object. The "grasping" channel extracts information about the intrinsic properties of the object (such as size and shape) for the determination of a suitable grasping pattern. However, although the two components can be considered as distinct, they seem to be coupled functionally, hence although arm reaching serves the function of bringing the hand to the immediate vicinity of the target object, and because it may be postulated that its neural channel will be primarily affected by changing the object's spatial location, the object's size also modifies this component (Gentilucci, Castiello, Corradini, Scarpa, Umiltà, & Rizzolatti, 1991; Jakobson & Goodale, 1991). Similarly, although hand posture serves the function of grasping the target object, and because it may therefore be postulated that its neural channel will be primarily affected by changing the object's size, the object's spatial location would also modify this component (Gentilucci et al., 1991; Jakobson & Goodale, 1991).

In humans, reaching and grasping movements are not present at birth. Their development occurs as a series of steps during ontogeny. Reaching serves to bring the hand to a desired location in space. Thus grasping objects requires appropriate goal-directed reaching. Grasping involves digit coordination according to the intrinsic properties of the object (e.g., size and shape). Newborn infants do not grasp the objects they reach for. As observed in some of the newborn's reflexes, as the arm extends forward, the hand has a tendency to open, and conversely, as the arm is flexed toward the body, the hand has a tendency to close (von Hofsten, 1984). It is at around 2 months of age that the synergy described earlier begins to break up. von Hofsten (1984) found that, instead of opening the hand during the extension of the arm, 2-month-old infants typically fisted the hand in the extended phase of the arm movement. At around 3 months of age, the infants started to open the hand again when extending the arm, but this time only when fixating on a target. The significance of this change lies in the fact that the opening of the hand can no longer be described simply as a part of an extension synergy, but as a preparation for grasping the object. At approximately 4 to 5 months of age, both the distance and the direction of the reach improve, but the hand orientation and finger closure are still rather limited. It is by 9 months of age that the hand begins to be shaped according to object size (von Hofsten & Rönnqvist, 1988). von Hofsten and Rönnqvist (1988) monitored the distance between the thumb and index finger in reaches performed by 5- to 6-month-old, 9-month-old, and 13-month-old infants. They found that the infants in the two older age groups did adjust the opening of the hand to the size of the target, but this was not evident for the youngest age group. The reason for this difference is that infants of 5 to 6 months of age do not predominantly use the thumb and the index finger when grasping objects, but the medial part of the hand and the palm. Further, although the older infants would adjust the opening of the hand to the size of the object, their pattern is still very different from the adult pattern, where the hand fully opened during the approach to targets of different sizes (von Hofsten & Rönnqvist, 1988). A possible interpretation of this behavior is that a fully opened hand optimizes the possibility of grasping the object if the movement is not spatially precise.

The natural question is therefore, when do children start to exhibit correct hand preshaping (as a function of time and amplitude) with respect to object size and distance? Unfortunately, although the kinematics of the reach-to-grasp movement have been widely investigated in adults, and to some extent in infants, there are not much data available for the intermediate age level. Some evidence, however, is provided by Kuhtz-Buschbeck, Stolze, Boczek-Funcke, Jöhnk, Heinrichs, and Illert (1998) and Kuhtz-Buschbeck, Stolze, Jöhnk, Boczek-Funcke, and Illert (1998). These authors studied the kinematics of the reach-to-grasp action in children of 6 to 7 years of age, in different experimental conditions. In particular, they asked children to reach toward and grasp objects of different sizes, positioned at different distances in a vision and no-vision condition. It was found that the temporal coupling between the transport and grasp components of prehension was very similar in children and adults. Peak transport velocity increased by the same factor in both age groups when the object distance was doubled. However, the decelerating approach phase was shorter in the children, who opened their hands relatively wider than adults. Unlike the adults, children failed to scale their grip aperture according to object size when visual feedback during movement was lacking. The grip aperture increased with object distance in adults, but not in the children. The intrasubject variability of kinematic parameters was distinctly higher in the children. The results suggest that grip formation is not yet mature at an age of 6 to 7 years, depending more on visual feedback than in adult prehension.

In a subsequent study (Kuhtz-Buschbeck, Stolze, Jöhnk, et al., 1998), the same authors evaluated the normal development of prehension movements in children from 4 to 12 years of age. Within the investigated age span, neither the movement duration nor the normalized 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 children 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 continues to the end of the first decade of life.

Differences between younger and older children have also been revealed by a recent study by Smyth, Katamba, and Peacock (2004). They investigated the reach-to-grasp movement toward targets of different size, positioned at different distances, with and without vision of the reaching hand, in children from 5 to 10 years as compared to adults. It was found that all children scaled velocity appropriately for movement distance, both with and without sight of the hand. However, 5- to 6-year-old children did not increase grip aperture with increased distance, whereas older children and adults did. The older children and adults showed a longer deceleration phase and a larger maximum finger aperture when vision of the hand was prevented. More important, they revealed that younger children did not integrate reach and grasp over different distances and did not use visual information about hand position to optimize accuracy.

Although these three studies provide a detailed kinematic characterization of the reach-to-grasp movement in children, it is clear that further experimentation is needed to investigate the childhood population. In particular, two issues need attention. The first is concerned with the relation between the choice of grasping pattern with respect to object size. To date, previous studies have imposed constraints on children about how to grasp objects of different size, namely the use of a precision grasp independent of object size. This may have determined a mismatch, which in turn could prevent the unfolding of a natural pattern. To this end, in this study we have not imposed the adoption of a specific grasping pattern upon the children.

The second issue relates to the range of ages characterizing the childhood population. It may well be that grouping children of different ages adds to the variability of the results. Further, it may well be that each specific age group shows a specific kinematical pattern of prehension. To this end, our experiment was undertaken to provide a thorough, normative study of the reach-to-grasp for the specific age sector of 5 years.

Our results suggest that these two factors may be responsible for the differences found in the kinematic patterning between this and previous studies.

MATERIALS AND METHODS

Participants

Ten healthy children aged 5 years (4 boys and 6 girls) participated in this study. As an adult group, five men and five women (aged 24–36 years) were examined. All participants were right-handed and were naive as to the purpose of the experiment. The children's handedness was determined by the age-appropriate manual dexterity subtest of the Movement Assessment Battery for Children (MABC; Henderson & Sudgen, 1999) and confirmed by the specific items included in the Revised Neurological Examination for Subtle Signs (Denckla, 1985). The adults' handedness was determined on the basis of their writing hand.

The motor coordination level of children was screened using the MABC Scale (Henderson & Sudgen, 1999). Only two children scored respectively below and equal to the 15th percentile, so their motor development should be considered at a norm limit; all the others scored above the 15th percentile on the MABC test (Table 1). Children attended two sessions that lasted 2 hr. The MACB test was administered in the first session, whereas the kinematical test was proposed in the second session.

Prior to participation, the adults and the children's parents gave their informed consent.

Procedure

Figure 1 represents the experimental setup and the stimuli used for collecting the data presented here. The participant was seated in a height-adjustable chair such that their feet and back were supported and their forearms rested on the table surface (50 x 60 cm; see Figure 1, panel a). The starting position of the arm and hand to be observed was with the shoulder slightly flexed and internally rotated (< 45°), the elbow flexed (< 90°), the forearm in mid pronation, and the ulnar border of the hand resting on the desk 6 cm anterior to the thorax. The thumb and index finger were held in a relaxed position of opposition as if to gently grip two pins (8 mm diameter) positioned 3 cm apart, which marked the starting point on the table surface. The objects to be grasped were red wooden cylinders (see Figure 1; panel b)

TABLE 1
Details of the Two Groups of Children and Adults

Children					*Adults*		
Age	*Sex*	*MABC Score*	*%*	*Humerus Length (mm)*	*Age*	*Sex*	*Humerus Length (mm)*
5 years, 1 month	M	7.0	26°	162	24 years, 10 months	F	273
5 years, 1 month	F	4.5	42°	165	25 years, 3 months	F	253
5 years, 2 months	F	4.0	46°	151	27 years, 6 months	M	232
5 years, 3 months	F	1.0	80°	185	28 years, 0 months	F	281
5 years, 3 months	F	2.0	67°	160	28 years, 2 months	M	261
5 years, 4 months	F	11.0	14°	181	28 years, 8 months	F	291
5 years, 4 months	M	8.0	22°	167	29 years, 9 months	F	310
5 years, 5 months	M	5.5	34°	152	33 years, 9 months	M	236
5 years, 6 months	M	5.5	34°	170	34 years, 5 months	M	282
5 years, 6 months	F	10.5	15°	152	36 years, 4 months	M	269

Note. MABC = Movement Assessment Battery for Children.

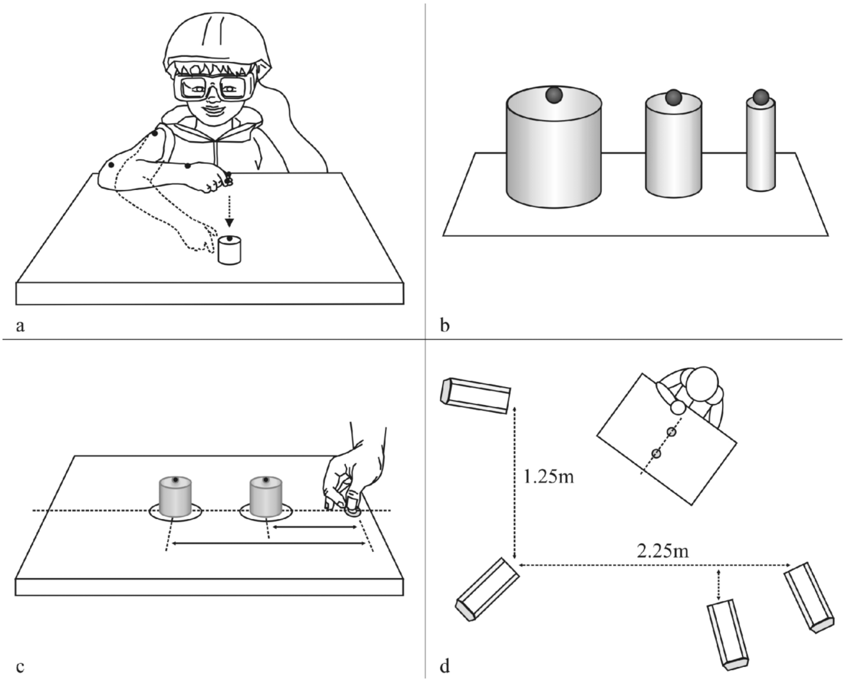


FIGURE 1 Experimental setup. Panel A represents how the participants were seated at the table, the positioning of the markers on the anatomical landmarks of interest, and the helmet on which the shutter glasses were attached. Panel B represents objects' diameter. Panel C represents a detailed description of the hand's starting position with respect to the two target locations. Panel D represents a top view of the experimental setup and the positioning of the four infrared cameras.

that were either small (1.5 cm diameter), medium (3 cm diameter), or large (5 cm diameter) in size (independent variable = Object Size), and positioned vertically on the midline at either 15 or 30 cm (independent variable = Object Distance) from the starting position (see Figure 1, panel c). Participants were requested to perform the grasping action in a vision and in a no-vision condition (independent variable = Vision). To control for visual availability, we used liquid crystal shutter glasses (Plato Visual Occlusion Spectacles, Translucent Technologies Company; see Figure 1, panel a). For the vision condition, upon the clearing of the shutter glasses, the participant was required to start reaching toward the object and then grasp to lift it. For the no-vision condition, the sequence of events was the following: at the beginning of the trials the lenses of the shutter glasses were opaque, then they were very briefly opened (400 msec), and then they were made opaque again. Participants were instructed to start the action at the time when the lenses were made opaque for the second time. A specific movement speed was not stipulated, but each participant was instructed to perform the movement as they would normally do when reaching to grasp an object at home. The experiment lasted approximately 60 min (divided in two sessions) and consisted of about 72 reaches divided into 4 blocks. Pauses were allowed between the blocks to avoid fatigue, attention difficulties, and loss of motivation to pursue the task. For each target size/distance/vision combination, the participants performed 2 practice trials and then a block of 18 test trials. To distribute practice effects across conditions (size, distance, and vision), the block order was counterbalanced across participants.

Movement Recordings and Data Analysis

Movements were recorded, at a sampling rate of 200 Hz, by a 3D infrared motion analysis system (ProReflex MCU 240 Version 6.42 constructed by Qualisys Medical Company , Gothenburg, Sweden) that consisted of four infrared cameras, inclined at an angle of < 45° to 50° to the vertical, placed at 2 m from the floor and –1.30 m beside the table and –1.30 m apart (see Figure 1, panel D for details). The cameras recorded the reflections of passive markers (.5 cm diameter) attached to the following points of the right upper limb: (a) the wrist–radial aspect of the distal styloid process of the radius, (b) the index finger–radial side of the nail, and (c) the thumb–ulnar side of the nail (see Figure 1, panel A). The spatial error from a stationary target was .1 mm within the calibrated cubic workspace (depth 1 m × breadth 1 m × height .60 m). To reconstruct the movements, the recordings were filtered (digital low pass filtering, cutoff frequency 30 Hz) and the three-dimensional coordinates of the marker's center were transferred to a PC for the calculation of kinematic parameters. The release of the two pins at the starting position activated an infrared light-emitting diode indicating the start signal. The end of the movement was registered when the fingers kept a constant distance after the timing of maximum opening.

The dependent variables were chosen on the basis of having demonstrated size, distance, and vision functions in previous research (Gentilucci et al., 1991; Jakobson & Goodale, 1991). Movement duration was calculated as the time between movement onset (defined as the time at which the wrist first began to move) and the end of the action (defined as the time at which the fingers kept a constant distance after the timing of maximum opening). The period during which the target was lifted was not assessed.

The reaching component was assessed by analyzing the trajectory and velocity profiles of the wrist marker. In particular, for the velocity profile the amplitude of peak velocity and the time from peak velocity to the end of the movement (deceleration time) were considered. Analyses of spatial trajectories included the time and amplitude of the maximum height of the wrist trajectory from the working surface and the time and amplitude of the maximum curvature of the trajectory path from an ideal line linking the starting position and the object location.

The grasping component was assessed by analyzing the distance between the thumb and index finger markers as a function of time.

Temporal data were analyzed in both absolute and relative values as a percentage of movement duration. Given the differences in arm length between the children and the adult participants, we adopted a normalization procedure in which amplitude data were normalized to humerus length as measured by computing the distance between elbow (epicondilus lateralis) and shoulder (acromion) markers. Because of the existing anatomical relation between long bone length and age and stature of the participants, the humerus length is useful for scaling amplitude parameters to adults and children of different ages (Cheng et al., 1998; Holliday & Ruff, 2001; Pritchett, 1988).

For each participant in the two groups, mean values for each of the dependent measures were calculated for each size/distance/visual combination. An analysis of variance (ANOVA) was conducted with group as the between-subjects factor (adults and children) and object size (small, medium, large), object distance (near, far), and visual modality (vision, no-vision) as within-subject factors. Prior to the ANOVA, normal distribution of the data was verified. Post hoc comparisons were performed with the *T* test procedure (alpha level = .05). To establish possible differences in variability between the two groups, the same analyses were conducted on standard deviations.

RESULTS

Consistent results within the reach-to-grasp literature are a longer movement duration, a prolonged arm deceleration time, a lower arm peak velocity amplitude, and an anticipated and lowered amplitude of maximum grip aperture for smaller stimuli than for larger stimuli (Castiello, 1996; Gentilucci et al., 1991; Jakobson & Goodale, 1991; Smeets & Brenner, 1999). Similar kinematical alterations are evident when participants are prevented from using vision (Castiello, Bennett, & Stelmach, 1993; Jakobson & Goodale, 1991; Wing, Turton, & Fraser, 1986). Changes in kinematics have also been reported with respect to object distance. A longer movement duration, a prolonged arm deceleration time, and a lower arm peak velocity amplitude, as well as a delayed amplitude of maximum grip aperture for far than for near objects, have been reported (Gentilucci et al., 1991; Jakobson & Goodale, 1991; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990).

With this in mind, later we describe the results in terms of object size, distance, and visual availability, which are common for the two age groups. In the Effects of Age section, we discuss differences between the kinematic patterning of the two groups.

Effects of Manipulating Object Size

For the three object sizes, means are summarized in Table 2 with respect to the two groups. The manipulation of object size had predictable effects on the reaching and the grasp component, respectively. In particular, movements of the wrist to smaller objects (1,069 msec) had a longer latency than movement of the wrist to medium (1,000 msec) and large (1,006 msec) objects, $F(2, 17) = 7.42$, $p < .005$. The maximum height above the table to which the wrist was raised was also greater for the large than for the medium and small cylinders, $F(2, 17) = 3.94$, $p < .046$; 73, 72, 71 mm, respectively.

For the grasp component, there was a direct relation between the size of the object and the maximum opening of the hand en route to the target, and between the size of the object and the time taken to open the hand maximally. The normalized grip aperture was greater for the large than for the medium and the small objects, $F(2, 17) = 69.642$, $p < .001$; 51, 46, and 43, respectively, $p < .001$. The time of maximum grip aperture, expressed as a percentage of total movement time, was reached earlier for the small than for the medium and the large object, $F(2, 17) = 56.55$, $p < .001$; 57%, 59%, and 63%, respectively.

Effects of Manipulating Object Distance

For the two distances, means are summarized in Table 3. The manipulation of object distance determined a longer latency for the object positioned at the far distance rather than at the near, $F(1, 18) = 156.59$, $p < .001$, 1117 versus 934 msec. The deceleration phase of the reach was proportionally longer for the far than for the near distance, $F(1, 18) = 35.154$, $p < .001$; 68% versus 63%. Analyses of hand path revealed that the time of maximum trajectory curvature was reached later, $F(1, 18) = 10.67$, $p < .006$; 41% versus 37%, and its amplitude was greater, $F(1, 18) = 9.344$, $p < .01$; .26 versus .21, for the shorter than for the longer distance. Furthermore, at the shorter distance the time of maximum trajectory height was reached later for the near than the far distance, $F(1, 18) = 13.97$, $p < .002$; 48% versus 41%. The distance manipulation also affected the normalized grip aperture, such that maximum grip aperture was wider for the longer than for the shorter distance, $F(1, 18) = 19.027$, $p < .001$; 47 versus 46.

Effects of Vision

Means for the two visual conditions are summarized in Table 4. Removing visual feedback determined an overall increase of movement duration (1,136 msec) with respect to the vision condition, 914 msec, $F(1, 18) = 26.60$, $p < .001$, and also affected the relative timing of deceleration and maximum grip aperture. The percentage of time spent decelerating was greater for the no-vision than for the vision condition,

TABLE 2
Mean (± Standard Deviation) of Kinematic Parameters With Respect to Object Size in the Two Groups

	Children			*Adults*		
Variable	*Small*	*Medium*	*Large*	*Small*	*Medium*	*Large*
Movement duration (msec)	1,147 ± 162	1,102 ± 244	1,105 ± 179	992 ± 190	898 ± 159	908 ± 172
Reaching component						
Peak wrist velocity (mm/sec)	518 ± 54	373 ± 42	518 ± 70	480 ± 49	495 ± 48	487 ± 47
Peak wrist velocity (%)	34 ± 6	34 ± 7	33 ± 7	34 ± 4	36 ± 2	38 ± 4
Deceleration time (msec)	777 ± 152	835 ± 204	752 ± 214	688 ± 152	608 ± 123	605 ± 114
Deceleration time (%)	66 ± 5	66 ± 8	67 ± 7	66 ± 4	64 ± 2	64 ± 2
Time maximum trajectory curvature (msec)	424 ± 87	419 ± 61	428 ± 66	383 ± 65	374 ± 56	385 ± 63
Time maximum trajectory curvature (%)	37 ± 4	38 ± 5	39 ± 5	39 ± 3	41 ± 4	41 ± 4
Amplitude maximum trajectory curvature	0.22 ± 5.4	0.26 ± 0.1	0.27 ± 0.19	0.23 ± 7.6	0.23 ± 6.1	0.24 ± 6.9
Time maximum trajectory height (msec)	517 ± 191	478 ± 138	542 ± 160	408 ± 62	397 ± 58	418 ± 64
Time maximum trajectory height (%)	47 ± 14	43 ± 10	50 ± 11	42 ± 7	44 ± 6	46 ± 8
Maximum trajectory height (mm)	58 ± 8	63 ± 7	61 ± 10	82 ± 11	82 ± 9	85 ± 10
Grasp component						
Time of maximum grip aperture (msec)	527 ± 72	517 ± 83	597 ± 148	452 ± 99	443 ± 107	473 ± 103
Time of maximum grip aperture (%)	58 ± 5	60 ± 6	66 ± 5	55 ± 5	58 ± 4	61 ± 4
Grip aperture (mm)	85 ± 10	90 ± 8	99 ± 7	91 ± 5	100 ± 6	111 ± 6
Normalized grip aperture	52 ± 6	55 ± 4	60 ± 4	34 ± 4	37 ± 3	41 ± 3

TABLE 3
Mean (± Standard Deviation) of Kinematic Parameters With Respect to Object Distance in the Two Groups

	Children		*Adults*	
Variable	*15 cm*	*30 cm*	*15 cm*	*30 cm*
Movement duration (msec)	1,003 ± 183	1,233 ± 206	865 ± 180	1,000 ± 165
Reaching component				
Peak wrist velocity (mm/sec)	392 ± 44	666 ± 105	318 ± 32	656 ± 68
Peak wrist velocity (%)	37 ± 8	30 ± 5	38 ± 4	34 ± 3
Deceleration time (msec)	655 ± 187	949 ± 146	577 ± 127	690 ± 135
Deceleration time (%)	63 ± 8	70 ± 5	63 ± 4	66 ± 3
Time maximum trajectory curvature (msec)	405 ± 80	437 ± 75	372 ± 76	389 ± 50
Time maximum trajectory curvature (%)	40 ± 6	35 ± 3	42 ± 4	39 ± 3
Amplitude maximum trajectory curvature	0.26 ± 5.6	0.22 ± 0.2	0.26 ± 8	0.20 ± 7.1
Time maximum trajectory height (msec)	489 ± 150	549 ± 166	415 ± 69	400 ± 61
Time maximum trajectory height (%)	50 ± 12	43 ± 12	47 ± 9	40 ± 6
Maximum trajectory height (mm)	54 ± 6	68 ± 9	76 ± 9	90 ± 11
Grasp component				
Time of maximum grip aperture (msec)	497 ± 97	593 ± 104	409 ± 87	503 ± 117
Time of maximum grip aperture (%)	63 ± 4	59 ± 6	58 ± 4	59 ± 5
Grip aperture (mm)	89 ± 9	94 ± 6	100 ± 5	101 ± 6
Normalized grip aperture	54 ± 5	57 ± 4	37 ± 3	38 ± 3

$F(1, 18) = 27.08$, $p < .001$; 68% versus 63%. The time of maximum grip aperture was reached earlier in the no-vision than in the vision condition, $F(1, 18) = 64.49$, $p < .001$, 55% versus 64%. Finally, there was an overall increase in the normalized grip aperture during reaching movements when participants could not see their moving limb, relative to when they could, 50 versus 43; $F(1, 18) = 32.69$, $p < .001$.

Effects of Age

Significant effects of age on several kinematic parameters were found. For the 5-year-old children, movement duration was longer, $F(1, 18) = 5.23$, $p < .035$; 1118 versus 933 msec, the time of maximum trajectory curvature occurred earlier, $F(1, 18) = 5.03$, $p < .043$; 37% versus 40%, and the normalized grip aperture was wider, $F(1, 18) = 100.96$, $p < .001$; 56 versus 37, than in adults. The main factor group interacted significantly with the distance, size, and visual factors for a few parameters. In relative terms, the deceleration phase was longer for the children than for the adults (70% vs. 66%) when the target was positioned at a 30-cm distance (Group × Distance interaction; $F(1, 18) = 7.503$, $p < .013$; see Figure 2; panel a). The children reached maximum grip aperture later than the adults at a 15-cm distance (Group × Distance interaction; $F(1, 18) = 13.23$, $p < .002$; 63% versus 58%; see Figure 2; panel b).

TABLE 4
Mean (± Standard Deviation) of Kinematic Parameters With Respect to Vision and No-Vision in the Two Groups

	Children		*Adults*	
Variable	*Vision*	*No-Vision*	*Vision*	*No-Vision*
Movement duration (msec)	999 ± 189	1,237 ± 242	830 ± 147	1,035 ± 229
Reaching component				
Peak wrist velocity (mm/sec)	563 ± 112	495 ± 63	492 ± 44	482 ± 65
Peak wrist velocity (%)	36 ± 6	31 ± 7	40 ± 4	32 ± 5
Deceleration time (msec)	729 ± 117	904 ± 242	522 ± 100	745 ± 191
Deceleration time (%)	64 ± 6	69 ± 7	61 ± 2	68 ± 5
Time maximum trajectory curvature (msec)	420 ± 63	439 ± 86	350 ± 51	411 ± 78
Time maximum trajectory curvature (%)	39 ± 5	36 ± 6	41 ± 4	39 ± 5
Amplitude maximum trajectory curvature	0.21 ± 8.3	0.29 ± 0.12	0.23 ± 6.8	0.24 ± 7.7
Time maximum trajectory height (msec)	482 ± 161	567 ± 184	381 ± 50	435 ± 85
Time maximum trajectory height (%)	44 ± 11	45 ± 11	45 ± 5	42 ± 10
Maximum trajectory height (mm)	66 ± 7	58 ± 12	87 ± 10	79 ± 10
Grasp component				
Time of maximum grip aperture (msec)	559 ± 105	556 ± 108	462 ± 123	450 ± 92
Time of maximum grip aperture (%)	65 ± 4	57 ± 6	63 ± 5	53 ± 5
Grip aperture (mm)	88 ± 7	95 ± 10	89 ± 7	112 ± 8
Normalized grip aperture	54 ± 5	58 ± 6	33 ± 2	42 ± 5

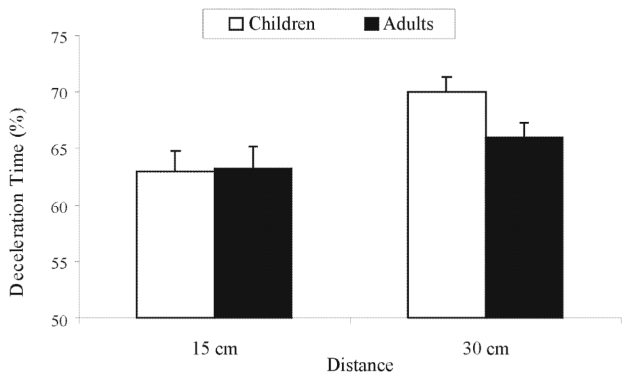
As indicated by the significant Group × Distance interaction, $F(2, 17) = 24.20$, $p < .001$, the "classic" lower arm peak velocity amplitude for smaller than for larger stimuli was found only for the adult group (see Figure 3). For this group, this peak was lower for the small (480 mm/sec) than for the medium (495 mm/sec) and the large objects (487 mm/sec). For the children, higher amplitudes were found for the small and the large object (both 518 mm/sec) than for the medium sized object (373 mm/sec).

The Group × Vision interaction, $F(1, 18) = 4.018$, $p < .05$, indicates that both adults and children have a wider hand opening for the no-vision (42 vs. 58) than for the vision condition (33 vs. 54; see Figure 4). However, in both vision and no-vision conditions the children show a wider hand opening than the adult group (see Figure 4).

Analysis of the maximum height of the trajectory revealed an interaction between Group, Size, and Vision, $F(1, 18) = 8.20$, $p < .005$; see Figure 5. Irrespective of object size and visual conditions, the adults showed a higher trajectory than the children. The three-way interaction between Group, Distance, and Vision was significant for movement duration, $F(1, 18) = 5.748$, $p < .028$; see Figure 6. When the target was positioned at the far distance in both the vision and no-vision conditions, movement duration was longer for the children than for the adult group.

Variability was higher for the children than for the adult group for two parameters: the amplitude of maximum peak velocity and the time of maximum trajec-

Panel A



Panel B

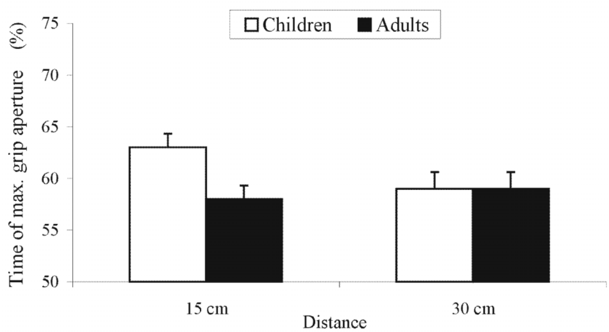


FIGURE 2 Diagrammatic representation of the Group × Distance interaction for the parameters Deceleration Time (panel A) and the Time of Maximum Grip Aperture (panel B).

tory curvature. In the former, variability was higher for the children than for the adult group, 115 versus 51 mm/sec; $F(1, 18) = 32.19$, $p < .001$. Furthermore, as revealed by the significant Group × Distance interaction, $F(1, 18) = 15.25$, $p < .001$, the variability for the amplitude of peak velocity was higher for the children when reaching an object at the far (146 mm/sec) than at the near distance (85 mm/sec), whereas variability remained constant for the adult group for the far and the near distance (61 and 41 mm/sec, respectively). In the latter, the Group × Size interaction, $F(2, 17) = 4.98$, $p < .022$, revealed that in children, variability for the maximum reach trajectory deviation was higher when reaching toward the large rather than the medium or the small object (145, 98, 79

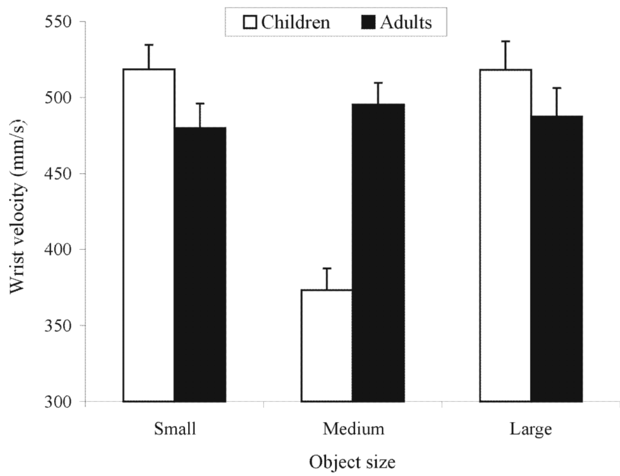


FIGURE 3 Diagrammatic representation of the Group × Size interaction for the parameter Amplitude of Maximum Peak Velocity. *Note.* mm/s = millimeters/seconds

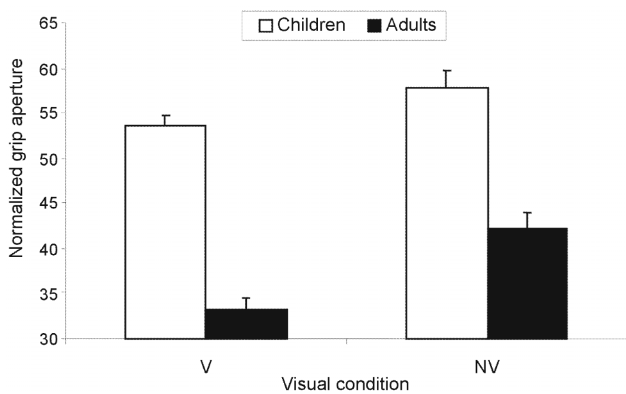


FIGURE 4 Diagrammatic representation of the Group × Vision interaction for the parameter Normalized Grip Aperture.

msec, respectively). For the adult group no differences in variability for this parameter with respect to object size were noticed (86, 76, 76 msec, respectively).

DISCUSSION

The aim of this study was to compare the planning of the reach-to-grasp movement in 5-year-old children with the mature pattern of an adult group. For this purpose,

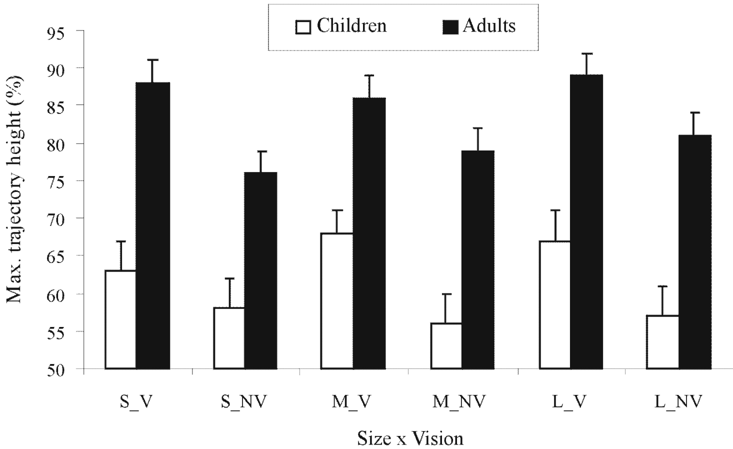


FIGURE 5 Diagrammatic representation for the Group × Size × Vision interaction for the Maximum Height of Spatial Trajectory. *Note.* S = small sized object; M = medium sized object; L = large sized object; V = vision; NV = no vision.

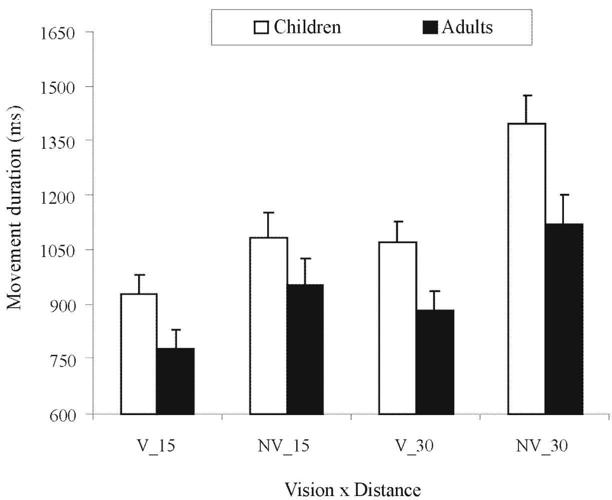


FIGURE 6 Diagrammatic representation of the Group × Vision × Distance interaction for the parameter Movement Duration. *Note.* V = vision; NV = no vision; 15 = 15 cm; 30 = 30 cm; ms = milliseconds.

three "functions," tested with previous research, were investigated: object size, object distance, and visual availability.

A global view of the results suggests that they are largely in agreement with earlier reports in the literature describing reach-to-grasp movements in adults and children (Gentilucci et al., 1991; Kuhtz-Buschbeck, Stolze, Boczek-Funcke, et al., 1998; Kuhtz-Buschbeck, Stolze, Jöhnk, et al., 1998; Smyth et al., 2004). Increasing the amplitude of the required movement in this study led to corresponding increases in the duration of the transporting movement and affected the timing and formation of the grasp (Gentilucci et al., 1991; Jakobson & Goodale, 1991). Our size manipulation produced changes both in the reaching and the grasping components. Thus, the aforementioned results confirm that object characteristics such as size and distance do not have independent effects on the reach and grasp (Gentilucci et al., 1991; Jakobson & Goodale, 1991). Moreover, it appears that, when visual feedback is not available during the unfolding of action, participants build a larger margin of error in their grasp by opening their hand more widely. In this condition, the reach is programmed in such a way that the maximum opening of the hand occurs proportionately sooner in time and the deceleration phase of the movement is proportionally longer.

Although there were a large number of similarities with previous findings, this study shows a few important differences. For example, in contrast to the previously reported shorter movement duration and deceleration time and higher curvature of the trajectory for children with respect to adults, we found that for the children, movement duration and deceleration time were longer and the maximum height of wrist trajectory was lower than in adults. These results suggest an age-related lengthening, which may signify the need for greater accuracy on behalf of the children to complete the action, thus compensating for an erroneous scaling of hand velocity. This statement is corroborated by the evidence that in children the kinematics of hand velocity was influenced by variations in target size. The “classic” lower arm peak velocity amplitude for smaller than for larger targets was found only for the adult group. For the children, higher amplitudes were found for the small and the large object than for the medium sized object. The significant differences found relative to the reach component for the size function indicate that the ability to change movement patterning according to the intrinsic characteristics of a target may not be fully mature in 5-year-old children. In other words, their action may not be fully fine-tuned and they may not be able to maximize activation in the most appropriate neural channel. This is further confirmed by looking at the grasp component of the action, which shows that the children, in both the vision and the no-vision condition, show a maximal finger aperture larger than the adults. To counterbalance possible errors in the planning of reaching, they adopt a compensatory strategy of grasping objects with a larger safety margin. Similar strategies seem to be confirmed by the results obtained for the spatial trajectory. The children’s lower curvature of the trajectory with a careful approach toward the target may be a strategy to facilitate finger positioning and thus a correct target acquisition. Similarly, such a cautious strategy may explain how the children of this study were able to scale their grip aperture according to object size when visual feedback during the movement was lacking. This would suggest that, in contrast to what has previously been reported, in children appropriate preshaping of the grip does not entirely depend on vision. This is an important point because it suggests that when such a "cautious" strategy is adopted, factors such as memory decay related to object size do not seem to play a relevant role in determining a source of uncertainty. Conversely, distance to the target seems to be less efficiently retained than object size. For instance, in relative terms the deceleration phase was longer for the children than for the adults when the target was positioned at 30 cm. This may point to developmental issues concerned with limited spatial memory capacity in children (von Hofsten & Rösblad, 1988).

At this stage, the natural question is what are the factors that may have determined the differences between the kinematic organization of the 5-year-old children of this study and the children of a similar (Kuhtz-Buschbeck, Stolze, Jöhnk, et al., 1998; Smyth et al., 2004) or older age in the previous studies (Kuhtz-Buschbeck, Stolze, Boczek-Funcke, et al., 1998).

We suspect that these differences may lie in two specific aspects. The first is concerned with the type of grasping action the participants were requested to perform. The second is in regard to the homogeneity of the samples in terms of age. In neural terms, control mechanisms for a precision grip are separate from those for a whole hand prehension. Rizzolatti, Camarda, Fogassi, Gentilucci, Luppino, and Matelli (1988) found periarcuate neurons (area 6) that discharge specifically for one of these grasp types, suggesting the idea of neural matching between appropriate grasp and object size. That control mechanisms for whole hand prehension and precision grip are distinct is also supported by the work of a small number of corticomotor neuronal cells (Muir, 1985; Muir & Lemon, 1983). Motor cortex neurons that establish monosynaptic synapses within the motor neuronal pools projecting to forearm and hand muscles were active only during the precision grip task. With performance of a power grip these neurons showed little or no discharge, despite electromyographic evidence of activity within the same target muscles. Of interest for this study is that the formation of a precision grip corresponds to a mature corticospinal tract, which appears to be almost fully mature not before the sixth year of life (Muller & Homberg, 1992). It could thus be advanced that the 5-year-old children tested in this study have not fully acquired the mechanisms that allow skilled coordination of the pinch during a precision grip. This may imply that the selection of appropriate grasping actions with respect to an object's intrinsic properties is still under formation or uncertain. Here, the children were free to choose the grasping pattern to adopt and from observation, it clearly emerged that they very rarely used a precision grip pattern for the smaller objects, suggesting that age and experience may be factors in the selection of the most efficient grasp patterns (Wong & Wishaw, 2004). For all objects they used a hybrid grasping pattern involving all fingers. Nevertheless, this appears to be the most natural pattern they can unfold. This conclusion is supported by the fact that we were able to replicate most of the classic reach-to-grasp kinematic results with respect to the distance, size, and visual manipulations.

However, our experiment did not replicate all of the results found in prior studies. The imposition in previous research of one grasp type for both small and large objects in older children, who may have a wider and more mature range of grasp patterns, inevitably results in a mismatching of appropriate grasp to object. Using an index finger and thumb opposition for an object with a large diameter not only infers inhibition of neural processes for a whole hand grasp, but activation of patterning for both a large aperture and appropriate placement of two digits on a greater surface area. For example, in those studies the classic and highly replicable prolongation of movement duration and deceleration time when reaching for objects of a smaller size was not found in both children and adults (Kuhtz-Buschbeck, Stolze, Jöhnk, et al., 1998). Furthermore, children were not able to scale the grip aperture with respect to object size when visual feedback was not allowed.

The second reason for the reported discrepancies may lay in the age of the participants used in this study. Here we considered children within a specific age range of 5 years, whereas, at least in one of the previous studies, children of 6 to 7 years were included in the same group. Thus, possible differences in terms of neural maturation and structural changes between age groups may be responsible for the reported differences. In this connection, the fact of having children of different ages within the same group rather than a specific age group may be relevant in terms of intra-individual variability. In this respect, previous investigations ascribe to the children higher intra-individual variability for the differences found in kinematic patterning between children and adults. In this study, variability of the repetitive trials was significantly higher in children only on a few occasions, confirming that a more circumscribed age group may minimize the variability factor.

In conclusion, this study provides the kinematical description of the reach-to-grasp movement in 5-year-old children. It is nested within previous observations of children of different ages. It demonstrates that this age group shows specific kinematic patterning that differs from those previously reported for older children. These age-dependent differences may prove to be critical in unraveling the different phases characterizing the development of an action normally and routinely performed within the familiar context of living activities.

ACKNOWLEDGMENTS

This research is part of the project, “Development of the Reach to Grasp (RTG) Movement During Childhood: A Longitudinal Approach” (RC No. 60/2003), supported by the Institute of Child Health IRCCS Burlo Garofolo and the Italian Ministry of Health.

A heart-felt thanks to the children (and parents) who took part in this project for their generous collaboration, without which this study would not have taken place.

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