Journal of Motor Behavior, 2005, Vol. 37, No. 2, 103–110

Developmental Changes in the Response to Obstacles During Prehension

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ABSTRACT. Adults are proficient at reaching to grasp objects of interest in a cluttered workspace. The issue of concern, obstacle avoidance, was studied in 3 groups of young children aged 11–12, 9–10, and 7–8 years (n = 6 in each) and in 6 adults aged 18–24 years. Adults slowed their movements and decreased their maximum grip aperture when an obstacle was positioned close to a target object (the effect declined as the distance between target and obstacle increased). The children showed the same pattern, but the magnitude of the effect was quite different. In contrast to the adults, the obstacle continued to have a large effect when it was some distance from the target (and provided no physical obstruction to movement).

Key words: movement, obstacle avoidance, planning, prehension, preparation

In reaching out to pick up a target object with a pincer grip, the hand must be transported forward while the fingers and thumb form an aperture. The formation of the aperture between the fingers and thumb is coupled to the transport of the hand toward the object (Jeannerod, 1988), such that perturbations to transport result in changes in aperture formation, and vice versa (Haggard & Wing, 1995; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991). Objects within the reaching space can act as obstacles to different limb segments as the hand is transported to the target and the grasp aperture is formed. Under those conditions, the movement may be made without any part of the limb coming into contact with any of the obstacles—an achievement that may require modifications of either or both the reach and the grasp aperture formation movements that normally occur in the absence of the obstacles.

In relatively few studies have obstacle avoidance strategies been explicitly explored—although in a number of studies, hand trajectories have been found to be altered in the presence of nontarget objects (Howard & Tipper 1997; Jackson, Jackson, & Rosicky, 1995; Saling, Alberts, Stelmach & Bloedel, 1998; Tipper, Howard, & Jackson, 1997). Dean and Brüwer (1994) studied aiming movements in the presence of an obstacle and found that adult participants maintained a minimum distance from the obstacle (see also Sabes & Jordan 1997). Tresilian (1998) reported a similar result in a study of prehension, although the minimum proximity of body parts to an obstacle was found to depend upon movement speed (faster movements were associated with greater minimum distances from obstacles).

In prehension, an object flanking the target presents a potential obstruction to the fingers or thumb that together form the grasp aperture (depending on whether the flanker is to the right or left of the target). Participants in the study of Tresilian (1998) responded to flankers by decreasing the size of their grasp aperture and by increasing movement time (MT). Mon-Williams and McIntosh (2000) showed that MT in a prehension task decreases systematically as the distance between the target and flankers is increased (see also Jackson et al., 1995). Increasing MT allows for more use of visual feedback so that the movement can be modified as necessary.

Results from adults suggest that they preplan reaching movements so that they take into account potential collisions with obstacles and that their adaptations are subtle and flexible (Sabes & Jordan 1999; Tresilian, 1998). The nontarget objects must be identified as potential obstacles and appropriate trajectory modifications made that maintain reasonable speed as well as accuracy—the observed modifications are often small but systematic and replicable (Tresilian; see

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also Howard & Tipper, 1997; Tipper et al., 19987). In addition, the slower movements produced in the presence of potential obstacles allow for more effective use of visual feedback if the person observes a body part heading for a collision. Thus, adults appear to use a movement control strategy that takes into account nontarget objects and adjusts the progression of movement to avoid collision.

In the current study, we were concerned with obstacle avoidance during prehension in children—a behavior that has not been investigated previously in that group. There is a body of literature concerned with prehension in infants (see, e.g., Hohlstein, 1982; McCarty & Ashmead, 1999), but there have been few detailed studies of the development of prehension during childhood, and those have appeared only recently (Kuhtz-Buschbeck et al., 1998; Kuhtz-Buschbeck, Stolze, Jöhnk, Boczek-Funcke, & Illert, 1999; Pryde, Roy, & Campbell, 1998). Although children in the age groups studied did show an overall pattern similar to that of adults, the results of those studies have not provided a completely clear picture. Kuhtz-Buschbeck et al. (1998) found that the deceleration phase of the transport component of the movement was shorter in children aged 6–7 years than in young adults, whereas Pryde et al. found the opposite in a comparison between adults and a group of 9- to 10-year-olds. Nevertheless, conclusions common to both studies were that the children were more reliant on visual feedback than the adults were, had longer MTs, and displayed a prehension pattern similar to that of adults. Those findings are in accord with the results of studies of other types of aimed movements in children between 6 and 11 years and suggest that the younger the child, the greater his or her reliance on feedback, both visual (Bard & Hay, 1983; Brown, Sepehr, Etlinger, & Skreczek, 1986; Rösblad, 1997) and kinesthetic (Hay & Redon, 1997).

In the cross-sectional study reported in this article, we examined how three groups of children 7–12 years old and a group of young adults performed a prehension task in the presence of nontarget objects that flanked the target (Figure 1). Flanking objects pose a potential obstruction to the reach (dependent on their proximity) and have been found to affect performance of prehension in adults (Jackson et al., 1995; Tresilian, 1998). Our purpose in the study was primarily descriptive, but it is possible to test certain predictions made on the basis of the research reviewed in this introduction. First, it seems reasonable to predict that the pattern of prehension behavior should be similar in children and adults. Second, the fact that children appear to have a greater reliance on visual information leads to the hypothesis that flanking objects should have a greater effect on children than on adults. Thus, we sought to determine whether children's prehension movements would be affected by flanking objects in the same way as adults' are and whether there would be any systematic age-related changes. Only when the pattern of age-related variation of prehension in response to obstacles has been described will it be possible to formulate more specific hypotheses concerning the mechanisms underlying the pattern. Reliance on visual feedback is one mechanism that might affect obstacle-avoidance behavior during development. We consider later whether the results we report can be explained by that mechanism.

Method

The target and obstructing objects were arranged on a smooth, flat, table surface (Figure 1). The target object was a square section block of wood (3 × 3 cm) 10 cm tall. Two opposite long sides were painted yellow and the remainder black; the yellow sides were defined as the grasping surfaces. The obstacle was an unpainted wooden cylinder 10 cm tall and 3 cm diameter. Four infrared-emitting diodes (IREDs) were placed on the participant's reaching limb (styloid process of radius, lateral surface of the metacarpophalangeal joint of the index finger, distal phalanx of the index finger and thumb). Positions of the IREDs were recorded by an Optotrak (Northern Digital, Inc., Waterloo, Ontario, Canada) movement recording system factory precalibrated to a static positional resolution of better than 0.2 mm at 100 Hz (dynamic resolution did not differ from that value significantly).

Six unpaid adults (3 women and 3 men, aged between 18 and 24 years, mean age = 21 years) volunteered to participate in the experiment. None of the participants had any history of neurological or ophthalmological abnormality. The children were recruited from a vacation care program. The study received ethical clearance from the University of Queensland, and all of the children participated willingly with their parents' consent. We screened all of the children by using a standard movement assessment battery for children (the Movement ABC; Henderson & Sugden, 1992) and placed them in groups (n = 6 per group) according to the age bands specified in the test. That resulted in three groups of school children: (a) 3 girls and 3 boys aged between 7–8 years (mean age = 7.9 years); (b) 3 boys and 3 girls aged 9–10 years (mean age = 9.7 years); and (c) 4 girls and 2 boys aged 11–12 years (mean age = 11.3 years).

Participants reached for the target object, which had a fixed position 25 cm from the start position along the center line that was approximately 12 cm to the right of the participants' midline (Figure 1). The hand was initially positioned with the wrist in a relaxed neutral posture (neither flexed nor extended) and with the fingers flexed and the thumb and index finger touching. The point at which the thumb and index fingerpads met was at the start point defined as the junction of the T in Figure 1. Participants made reaches under five conditions: (a) no obstacle (N), (b) obstacle 3 cm to the left of the target (L3), (c) obstacle 3 cm to the right of the target (R3), (d) 6 cm to the right of the target (R6), and (e) 9 cm to the right of the target (R9). We recorded 10 reach trials in each of the five obstacle conditions (50 trials in total). The experimenter instructed participants to reach out and grasp the target, pick it up, and place it on the T. At the beginning of the experiment, participants were told explicitly to avoid touching the obstacle. The experimenter instructed them to grasp the target on the yellow surfaces and cued them to start with the verbal signal "Go."

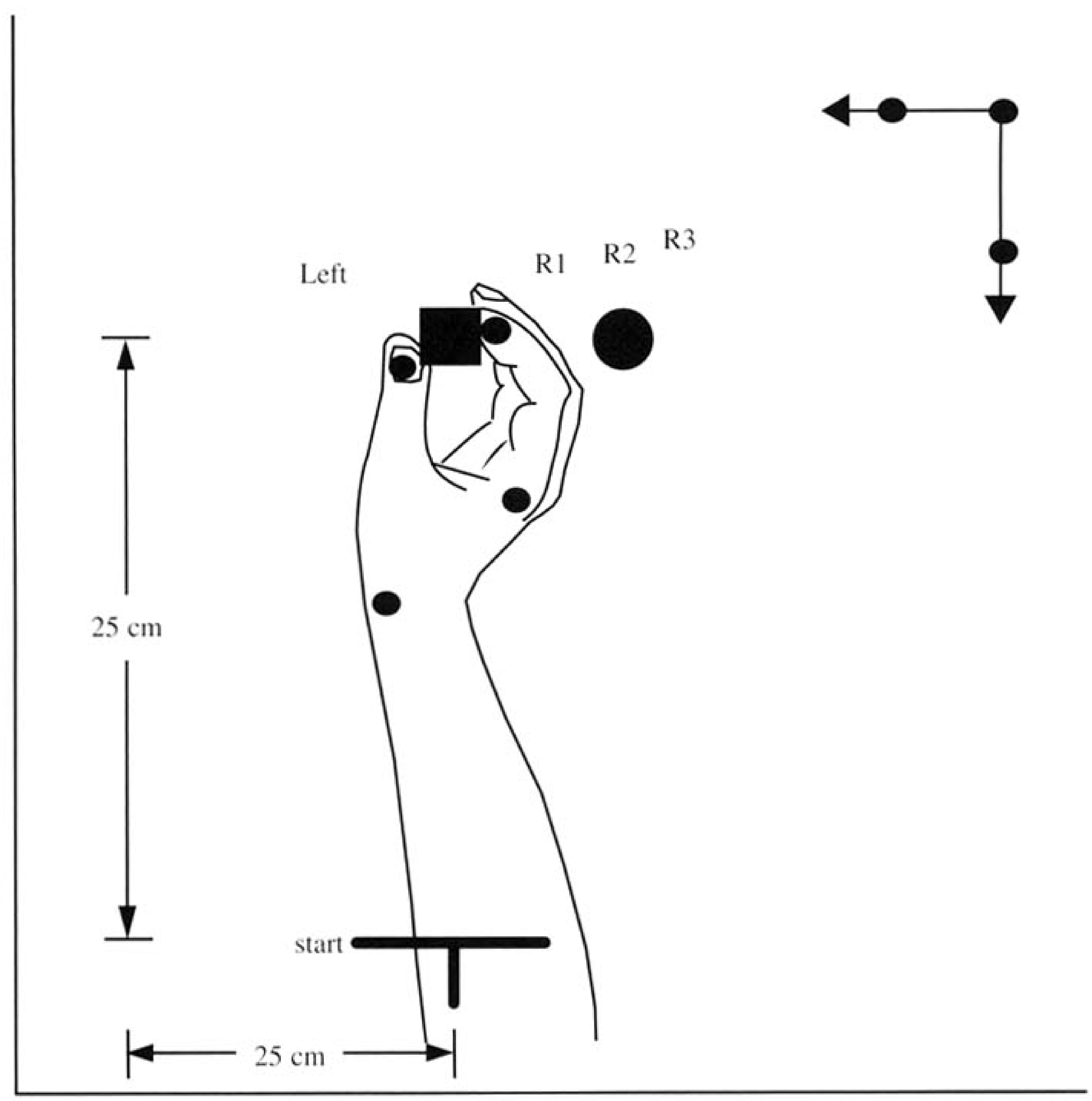

FIGURE 1. Schematic of the experimental layout from above. Four infrared-emitting diodes (IREDs) were placed on the participants' reaching limb (styloid process of radius, lateral surface of the metacarpophalangeal joint of the index finger, distal phalanx of the index finger and thumb). Participants were asked to reach and grasp the target object (solid square) when an obstacle (shaded circle) was placed either 3 cm to the left (approximate position labeled *left*), 3 cm to the right (R1), 6 cm to the right (R2), 9 cm to the right (R3), or with no obstacle in position. The target object had a fixed position 25 cm from the start position along the center line, which was approximately 12 cm to the right of the participants' midline. The hand was positioned initially with the thumb and index finger touching at the start point, defined as the junction of the T.

Data acquisition was initiated approximately 1 s before the experimenter's verbal start command. We digitally filtered the raw x, y, and z coordinates of each IRED by a dual-pass through a second-order Butterworth filter with a cutoff frequency of 20 Hz (equivalent to a fourth-order filter with no phase lag and a cutoff of ≈ 16.5 Hz). Following that operation, we computed the tangential speed of the wrist IRED and estimated the onset of the reaching movement by using a standard algorithm. We used custom analysis routines to compute the dependent variables of interest in this study: MT, maximum speed of transport (max. speed), and maximum grip aperture (max. aperture). Median values for each dependent measure were derived from the 10 experimental trials performed in each condition by each individual participant. Those medians formed the basis for further statistical analysis with analysis of variance (ANOVA).

Results

Group Effects

The group mean values of the three dependent measures (MT, max. aperture, max. speed, and relative max. speed) are plotted for each experimental condition in Figure 2 (panels b, c, and d). As can be seen from the figure, the pattern shown by the children was similar to that of the adult group (closed circles [•]) for each dependent measure. However, there were obvious differences in overall magnitude (e.g., children always reached considerably lower max. speeds; see Figure 2c). Whereas adults tended to show little or no response to the flanking object when it was 9 cm to the right (R9), the children did. (Note that the IREDs were positioned on the outside of the digits, and thus the maximum grip apertures reported are

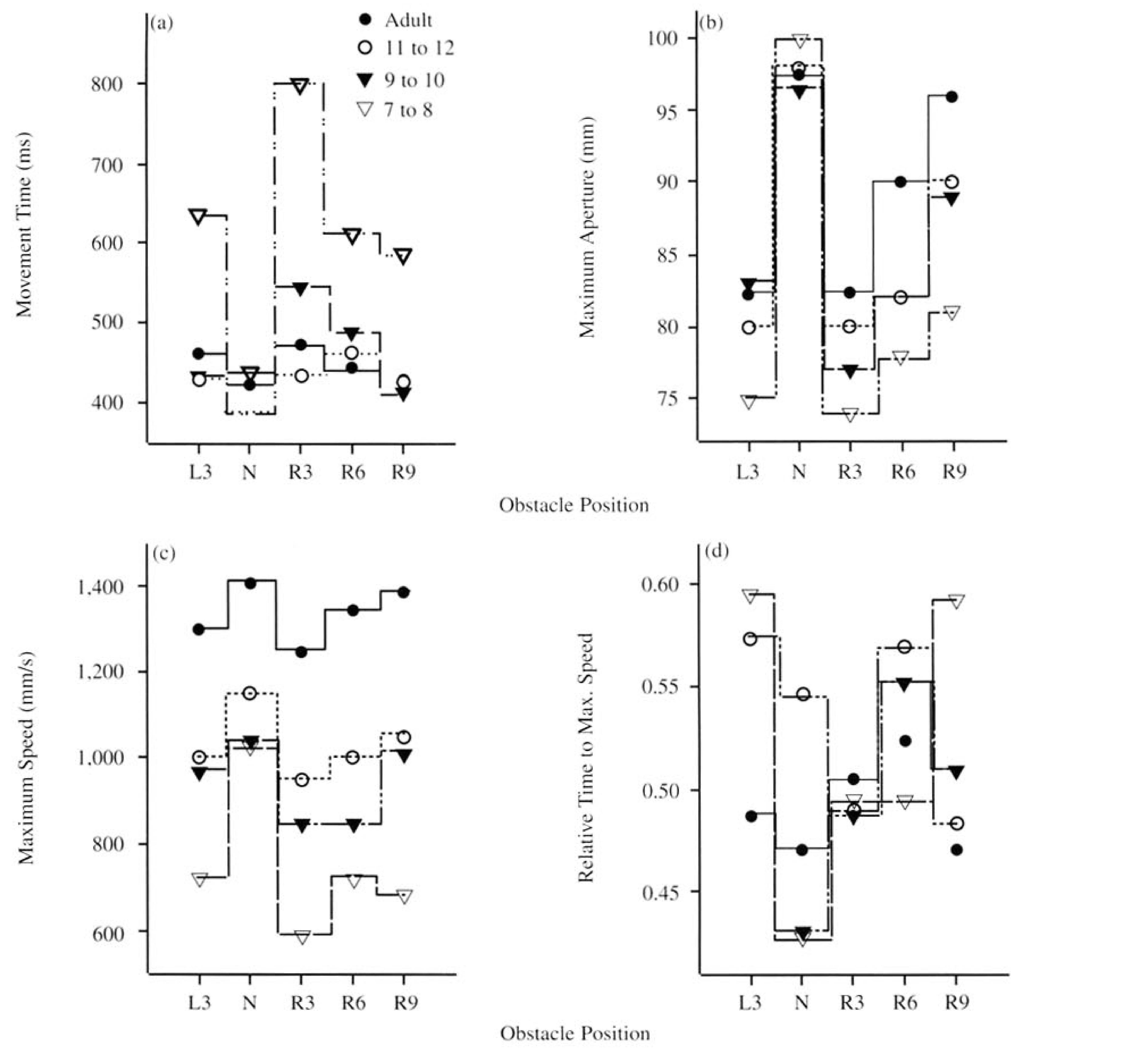

FIGURE 2. Group mean data plotted against experimental condition: N, L3, R3, R6, and R9 = no flanking object; flanker 3 cm to left of target; and flanker 3, 6, and 9 cm to right, respectively. (**a**) Mean movement time for the four participant groups. (**b**) Mean maximum aperture for the four groups. (**c**) Mean maximum speed. (**d**) Mean relative time to maximum speed.

approximately 2 cm larger than the distance between the inside of the fingertip pads.)

To analyze the effects shown in Figure 2, we separately performed planned comparisons (one-tailed) for each experimental group, using repeated measures ANOVA. To assist in the interpretation of the tests of significance, we calculated measures of effect size, following Cohen (1988). The effect size for ANOVA (f) is a dimensionless index that describes the degree of departure from no effect—in other words, the degree to which the phenomenon is manifested. A small effect size is considered by convention to be indicated by an f of 0.10, a medium effect size by an f of 0.25, and a large effect size by an f of 0.40 or greater (Cohen). Table 1 provides the effect size of the flanking object (relative to the no-flanker condition) for the three dependent measures (MT, max. aperture, and max. speed) for the different age groups.

A reliable effect of obstacle position on MT was found for all of the groups, apart from the 11- to 12-year-old children: adults, 9- to 10-year-olds, and 7- to 8-year-olds, $Fs(3, 21) = 7.97$, 8.54, and 6.14, respectively, $ps < .05$; 11- to 12-year-olds, $F(3, 21) = 0.91$, $p > .05$. A reliable effect of obstacle position on max. aperture was found for all of the groups: adults, 11- to 12-year-olds, 9- to 10-year-olds, and 7- to 8-year-olds, $Fs(3, 21) = 2.12$, 9.27, 8.50, and 2.47, respectively, $ps < .05$.

TABLE 1. Effect Sizes (fs) for the Comparison Between the Effects of the Flanking-Object and No-Obstacle Conditions for All Groups of Participants

Dependent variable	Obstacle location			
	Left 3 cm	Right 3 cm	Right 6 cm	Right 9 cm
		Adults		
MT	1.04	1.35	0.56	0.14
Max. ap.	1.98	1.96	1.01	0.18
Max. speed	0.77	1.13	0.45	0.15
		11- to 12-year olds		
MT	0.31	0.35	0.54	0.27
Max. ap.	1.43	1.44	1.23	0.65
Max. speed	0.81	1.09	0.82	0.54
		9- to 10-year olds		
MT	0.42	1.38	0.90	0.24
Max. ap.	1.01	1.44	1.06	0.57
Max. speed	0.29	0.8	0.78	0.12
		7- to 8-year olds		
MT	0.77	1.42	0.68	0.58
Max. ap.	2.4	2.46	2.1	1.81
Max. speed	1.58	2.26	1.58	1.77

Note. Effect size f is dimensionless. MT = movement time (in ms); Max. ap. = maximum aperture (in mm); Max. speed = maximum speed (in mm/s).

Inspection of Figure 2 and Table 1 shows that the presence of an obstacle 3 cm from the object on either the left or right side had a large effect on MT for all of the groups. It can also be seen that the impact of the obstacle declined to almost nothing for the adult group as the obstacle was positioned farther from the target object. Inspection of the effect size for the farthest obstacle (R9) shows that clearly—the effect was small for adults but medium or large for the groups of children. Comparison of panels (a) and (c) in Figure 2 shows that the differences between age groups were more marked for the max. speed dependent variable than for the MT dependent variable. The adults reached much higher max. speeds than the children (Figure 2c), but in some conditions the MTs of the adult group were similar or sometimes larger than those of the children (Figure 2a). That finding may have resulted from the relatively longer period of deceleration for the adults than for the children (extended deceleration phase), in which case the adults would have produced speed profiles with max. speed relatively earlier in the movement than the children's. The time at which max. speed was reached, expressed as a proportion of the total MT, is plotted in Figure 2d for each group in all conditions. Although in the L3 and R9 conditions there was an indication that adults reached max. speed relatively earlier than the children did, there is no indication that they did so in the other conditions.

Age-Related Trends

The MT and maximum grasp aperture data for the conditions in which flanking objects were present were also expressed, respectively, as a proportion of the mean MT and as a proportion of the mean maximum grasp aperture for the conditions in which no flanking object was present. Those computations provided a simple measure of the effect of the flanking object relative to the no-flanker condition. Figure 3 shows the proportional effect of the flanking objects on MT (panel a) and maximum grasp aperture (panel c), plotted against age group for the flanking object positioned 3, 6, and 9 cm to the right. We evaluated the statistical reliability of the age-related trends by using a linear trend analysis conducted on the arcsine transformed proportions. A trend for an increasing proportional effect on MT with decreasing age was statistically significant for all flanking positions ($p < .025$). A trend for a proportionally smaller max. aperture size with decreasing age was statistically significant for the 6-cm-right position, $F(1, 21) = 11.8$, $p < .01$, and the 9-cm-right position, $F(1, 21) = 22.4$, $p < .001$. An anonymous reviewer suggested that we should illustrate the differences in group variability (the adults' behavior was far more stereotypical than the children's), and those data are shown in Figure 4.

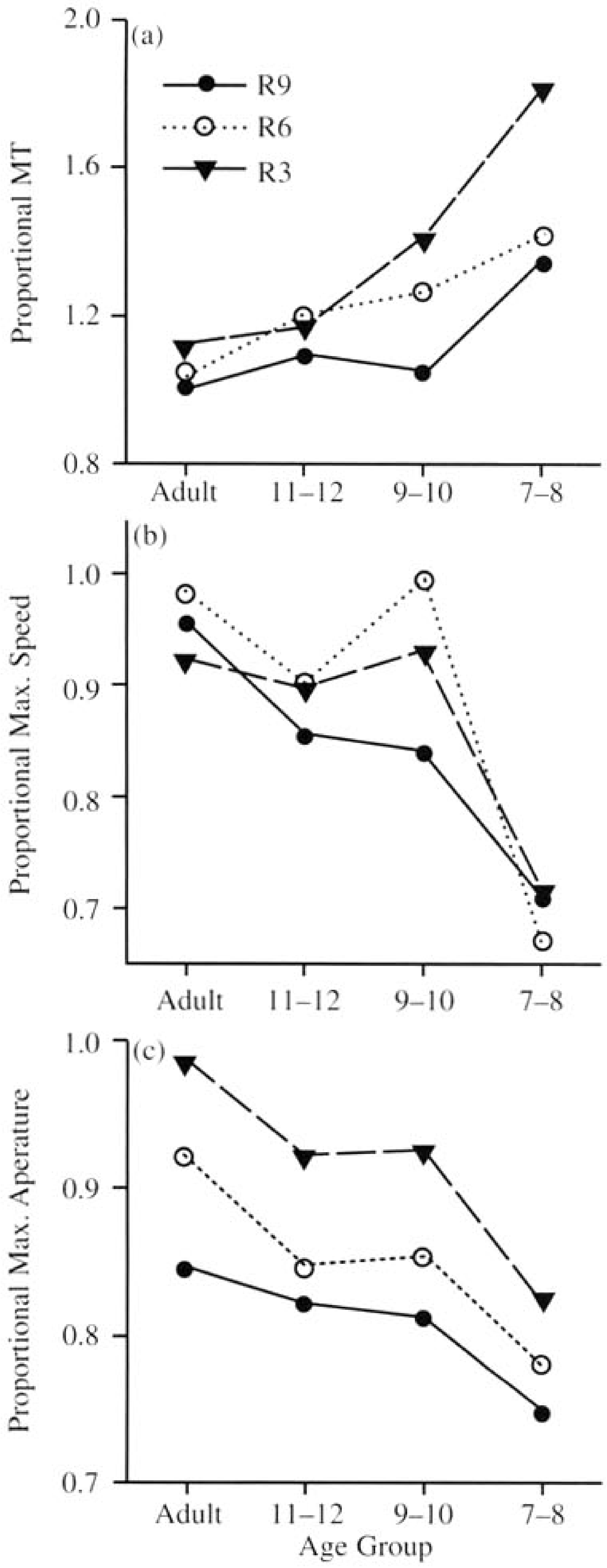

FIGURE 3. Movement time (MT), maximum speed, and maximum aperture data expressed as a proportion of the mean in the no-flanking-object condition. The data are plotted against age group for the flankers positioned 3, 6, and 9 cm to the right (R3, R6, and R9, respectively). The plot provides a simple measure of the effect of the flanking object relative to the no-flanker condition. (**a**) The proportional effect of the flanking objects on MT, plotted against age group. (**b**) The proportional effect on maximum speed, plotted as in (a). (**c**) The proportional effect maximum aperture plotted as in (a).

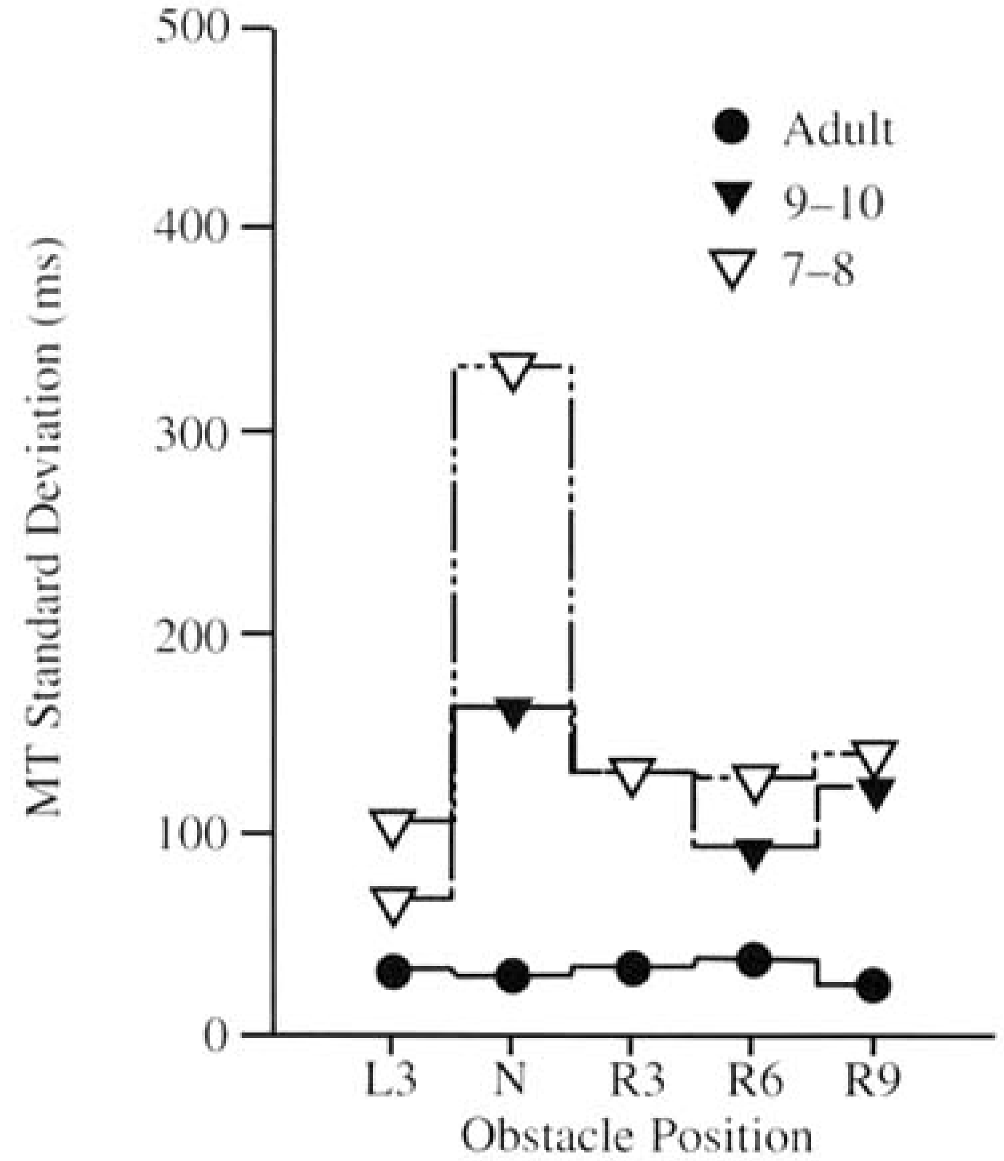

FIGURE 4. Group variability (standard deviation) plotted against experimental condition. MT = movement time. N, L3, R3, R6, and R9 = no flanking object, flanker 3 cm to left of target, and flanker 3, 6, and 9 cm to right, respectively.

Discussion

Consistent with previous work (Jackson et al., 1995; Tresilian, 1998), the presence of flanking objects affected both the speed with which participants reached for the target and the maximum grip aperture: The effects were qualitatively the same in all age groups studied. The max. speed of the reach was reduced in the presence of flanking objects, and that reduction was associated with increased MT (Figure 2, a and c). The maximum grip aperture was reduced when a flanking object was present. Thus, the flanking objects appear to have been treated as obstacles to the movement.

Although all groups showed the same type of response to the presence of flanking objects, the responses were largest in the youngest group, and there was a trend for the effect to decrease in size with increasing age. The effect on MT and max. aperture was largest for the youngest age group (7–8 years) both in absolute terms (Figure 2) and when expressed as a proportion of the unobstructed MT (Figure 3). The differences between the adults and the 9–10 and 11–12 year age groups were not as clear-cut in terms of effect sizes (Table 1). That was in part attributable to the greater variability observed in those groups (see Figure 4) than in the adults. Nonetheless, there were clear age-related trends. The effect of the flanking objects was progressively greater with decreasing age for both MT and max. aperture (Figure 3).

Thus, the children demonstrated the same responses to flanking objects as the adults did. The children tended to exhibit those effects more prominently than the adults did. As an illustration, consider the condition in which the flanking object was 9 cm from the target. In the adult group, the object had very little effect on the reach-to-grasp movement. The absence of an effect is consistent with the fact that the object presented no physical obstruction to the movement path exhibited during unobstructed reaching. The same flanking object had a large impact on the children. The size of the effect increased as the age of the children decreased.

Those results indicate that children as young as 7 years have developed a movement strategy similar to that used by adults, a scheme that enables them to take into account the presence of potential obstacles in the reaching space. Increasing MT and decreasing the distance the fingers extend during aperture formation (smaller max. aperture) are most reasonably interpreted as strategies for avoiding potential collisions with a flanking object. Increasing MT gives one more time to make feedback-based corrections to the movement trajectory if some part of the reaching limb is seen to be moving too close to the flanker. Alternatively, an increased MT could be the result of the feedback corrections themselves (e.g., Meyer, Kornblum, Abrams, Wright, & Smith, 1988), although both mechanisms seem to work together (Elliott, Helsen, & Chua, 2001). Decreased aperture size also reduces the chances of a digit contacting the flanking objects, although again the mechanism could involve either or both preplanning a smaller aperture and feedback adjustment of aperture size.

Research studies of aimed arm movements in children in the age range studied here have provided evidence that children tend to rely more on visual feedback for accurate performance than adults do (e.g., Bard & Hay, 1983; Brown et al., 1986; Rösblad, 1997). It seems likely, however, that longer MTs in the presence of obstacles are, at least in part, preplanned. Grasping an object with a flanker present involves placing the grasping digits into the gap between the target and the flanker. In aiming tasks analogous to that, movements divide into two phases—an acceleration phase before and a deceleration phase after max. speed. The execution of the acceleration phase is typically thought to be visually open loop—feedback corrections being made during the deceleration phase, which tends to be of longer duration than the acceleration phase (Elliott et al., 2001). When the target of an aiming movement is small, the max. speed is lower and the deceleration phase more extended than it is when the target is larger (for a review, see Plamondon & Alimi, 1997). Thus, max. speed can provide an index of changes in the open-loop component of an aimed movement—changes that reflect the anticipated difficulty (in Fitts's, 1954, sense) of being sufficiently accurate. Thus, the tendency to reach smaller peak speeds in the presence of flanking objects both in the experiment reported here and in other studies (Tresilian, 1998) indicates that a person treats the task as more difficult in the presence than in the absence of a flanker. The flanking objects had a greater proportional influence on max. speed in children than in adults, indicating that the children treated the task as more difficult when the flanker was present. The condition in which the flanker was 9 cm to the right of the target (R9) had hardly had any effect on the adults but influenced the children quite strongly, particularly the youngest children, despite the smaller dimensions of their hands. The other two flanker positions had an effect on proportional max. speed only for the youngest group (Figure 3b).

It should be acknowledged that there may have been systematic differences between the age groups with respect to the psychological significance that they attached to a collision with a flanking object. That is, the younger children may have attached more importance to avoiding a collision than the older children and adults did. It is a persistent challenge to determine whether disparities between age groups result from differences in the mechanisms underlying performance or simply from differences in the ways the groups interpret the task. Nevertheless, whatever the balance of those factors, it is clear that children adopt the same avoidance strategy as adults do. The observation that the impact of a flanking object varied systematically with its distance from the target indicates that children are sensitive to the possibility of collision. The precise origin of that anticipation remains to be determined.

ACKNOWLEDGMENT

Preparation of this article was supported in part by a grant from the National Health and Medical Research Council, Australia.

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Submitted November 27, 2000
Revised September 29, 2003