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RESEARCH ARTICLE

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Time to contact and the control of manual prehension

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Abstract In the present study, a kinematic analysis was made of unconstrained, natural prehension movements directed toward an object approaching the observer on a conveyor belt at one of three constant velocities, from one of three different directions (head-on or along the fronto-parallel plane coming either from the subject's left or right). Subjects were required to grasp the object when it reached a target located 20 cm directly in front of the hand's start position. The kinematic analysis revealed that both the transport and grasp components of the movement changed in response to the experimental manipulations, but did so in a manner that guaranteed that, for objects approaching from a given direction, hand closure would begin at a constant time prior to object contact (regardless of the object's approach speed). The kinematic analysis also revealed, however, that the onset of hand closure began earlier with objects approaching from the right than from other directions – an effect which would not be predicted if time to contact was the key variable controlling the onset of hand closure. These results, then, lend only partial support to the theory that temporal coordination between the transport and grasp components of prehension is ensured through their common dependence on time to contact information.

Key words Time to contact · Catching · Prehension · Visuomotor control · Limb movements · Human

Introduction

When we plan to pick up an object in the environment, our first goal is to contact that object at points along its surface that allow us to generate a stable grasp. The accomplishment of this goal involves (1) spatial positioning of the arm (the *transport component* of the movement) and (2) anticipatory shaping of the hand (the *grasp component* of the movement). Jeannerod (1981, 1984) was the first to provide a detailed description of these two components of human prehension movements. On the basis of his early observations, he argued that their planning relies on processing in two independent visuomotor channels, one designed to extract visual information about extrinsic object features (e.g., location relative to the observer) for spatial positioning of the arm, and another designed to extract visual information about intrinsic object features (e.g., size and shape) for the guidance of hand shaping. Numerous studies have been carried out in recent years claiming to test this hypothesis (e.g., Castiello et al. 1993; Chieffi et al. 1992; Jakobson and Goodale 1991; Paulignan et al. 1990, 1991a, b). Although the debate about the degree of independence of the motor components still continues, one point on which the authors of these studies agree is that the two components of prehension are, at least, precisely coordinated in time. Exactly how this temporal coordination is achieved, though, is not entirely clear.

In his original model, Jeannerod (1981, 1984) proposed that coordination between the transport and grasp components could be achieved by generating movements of fixed duration. If this were the case, he argued, temporal coupling could be achieved through a center that synchronized the fast phase of the transport component with the opening of the hand, and the low-velocity phase of the reach with hand closure. Subsequent studies, however, have cast doubt on this proposal by demonstrating that natural prehension movements do not show this type of timing invariance (Jakobson and Goodale 1991; Marteniuk et al. 1990).

Arbib (1981, 1985) also posited the existence of a superordinate control program responsible for regulating the coordination of arm transport and grip formation. In the most recent version of this model (Hoff and Arbib 1993), it is suggested that the transport and grasp components each supply the coordinating schema with an independent estimate of how long it will take that component to achieve its desired final state, given its current state. The model goes on to predict that whichever schema is

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going to take longer will be given the full time it needs, while the others will be slowed down. In this way, it is argued, the model can account for systematic delays that have been observed in the grasping component in response to perturbations of object location which affect the unfolding of the transport component (Paulignan et al. 1991a).

Other researchers (Jakobson and Goodale 1991; Marteniuk et al. 1987) have argued that the two components of manual prehension are not temporally linked in a manner which is strictly invariant, but rather that they are *functionally linked* in such a way that the exact temporal relationship between the components can vary slightly under different experimental conditions. Kelso et al. (1994) have shown that one way in which the temporal synchrony between arm transport and wrist angular rotation (one aspect of anticipatory hand shaping) is roughly maintained in different contexts is through the spontaneous recruitment of new degrees of freedom (e.g., trunk lean, shoulder tilt, etc.), which serve to offset the biomechanical constraints imposed by changing task demands. It has been argued that the rapid, on-line adjustment of motor programs that this sort of spontaneous self-organization entails is a feature of many different, multiarticulator systems (e.g., speech production: Abbs et al. 1984; Tuller and Kelso 1984; typing and handwriting: Vivivani and Terzuolo 1980; two-limb coordination tasks: Schmidt 1987).

What all of these different theories have in common is a program-centered explanation that includes a high-level representation of the overall movement goal. Recently, Bootsma and van Wieringen (1992) have suggested quite a different route through which the transport and grasp components of natural prehension movements might be coordinated in time. Specifically, they have argued that the need for a special, higher-order control structure is obviated by virtue of the fact that both components of prehension movements rely on the same source of visual information, namely information specifying time to contact between the hand and the object to be grasped. According to their theory, reaching to a stationary object might represent a special case of the more general situation in which a subject intercepts a moving object. Here it has been argued that, for objects approaching from any given direction, time to contact can be perceived "directly" using information contained in the combination of the relative rates of (a) dilation of the moving object's optical contour; and (b) constriction of the optical gap separating the object and a designated target (e.g., the reaching limb; Bootsma and Oudejans 1993). [With stationary targets, of course, dilation of the object's optical contour reduces to zero, and so (according to the theory) the primary source of information conveying time to contact comes from dynamic information about the closing gap between the hand and target.] Bootsma and van Wieringen (1992) have suggested that this dynamic information is used to ensure that the hand will begin to close at a constant time prior to object contact.

If this view of the temporal coordination between the components of prehension is correct, of course, then one would expect to see the hand begin to close at a constant time before object contact, regardless of the direction or speed of an object's approach. Although constant grip-closing times have been reported for objects approaching head-on at different speeds (Savelsbergh et al. 1992), no studies to date have manipulated both speed and direction of approach. In the present study, we studied unconstrained, natural prehension movements made toward an object approaching the observer on a conveyor belt at one of three constant velocities, from one of three different directions. In previous research (e.g., Peper et al. 1994), target objects travelling along oblique trajectories were always presented in the right-hand side of space. In the present study, objects could approach head-on (in the subject's sagittal axis), or along the frontoparallel plane, coming either from the subject's left or right. Subjects were required to grasp the object when it reached a target located 20 cm directly in front of the hand's start position. Since on every trial subjects were asked to intercept the same cylindrical object at the same target location, subjects could, theoretically, have employed exactly the same movement to intercept the object under all experimental conditions. We expected, however, to see the kinematics of both the transport and grasp components change in response to the experimental manipulations, but for them to do so in a manner that would guarantee that hand closure always began at a constant time prior to object contact.

Previous studies indicate that individual difference factors (e.g., sports or driving experience, biological sex) can affect skill level in time to collision estimation (Cavallo and Laurent 1988; Schiff and Oldak 1990) and in performance on catching/intercepting tasks (Fischman and Schneider 1985; Watson and Kimura 1991). For this reason, in the present experiment an equal number of male and female subjects were tested, and information was gathered from each subject about their sports experience in an attempt to control for the possible effects of these variables. We also attempted a more fine-grained analysis of grip accuracy than has been used in many studies of one-handed catching performance.

Materials and methods

Subjects

Subjects were 18 Queen's University Psychology students (nine men and nine women), ranging in age from 19 to 37 years. All subjects completed a modified version of the Edinburgh Handedness Inventory (Oldfield 1971) and were classified as right-handed. In addition, all had normal or corrected-to-normal vision, and none had sustained a significant right upper limb injury in the preceding year. Testing procedures met with the standards of the Psychology Department's Ethics Review Committee.

Apparatus

Sports history questionnaire

Each subject completed a brief questionnaire (adapted from Watson 1989) designed to assess catching and/or intercepting experience.

The questionnaire was divided into three parts: (1) self-report measures of experience with baseball, basketball, racquet sports, and ice or field hockey; (2) self-ratings of fitness, coordination, overall sports experience, and overall video-game experience relative to one's peers; and (3) a question about job experiences involving picking objects off a moving conveyor belt (e.g., grocery cashier, assembly line worker, etc.).

Grasping task

Each trial began with a subject sitting with their right index finger and thumb in a pinch formation on a key embedded in a handrest attached to their chair. A conveyor belt (100 cm long×11.5 cm high) placed on a 73-cm-high table carried an experimental object toward the subject. The belt was driven by an adjustable speed motor at one of three different speeds (means 13.9 cm/s, 43.6 cm/s, 70.0 cm/s). The subject's task was to grasp the object, a translucent Plexiglas cylinder (6.7 cm high, 4 cm in diameter), when it reached a target line located 20 cm directly in front of the hand's start position.

In order to block out the sound of the motor changing speeds, subjects wore standard foam earplugs (EAR brand) and protective-type earphones. In addition, white noise was played on a tape recorder in the room. Subjects also wore a pair of liquid crystal spectacles (Milgram 1987), which allowed the experimenter to control viewing times precisely. These shuttered goggles have a turn-on time of 1 ms. The liquid crystals do not become opaque in their closed (off) state but remain translucent and continue to provide substantial illumination to the subject's eyes.

A video camera (Panasonic, wv-BL200) with a 75-mm zoom lens was suspended from the ceiling directly above the conveyor belt. An attached VCR recorded the subjects' finger movements when grasping the object. Black lines drawn on the top surface of the object divided it into four equal quadrants, which served as reference points for subsequent video analysis of the accuracy of the subject's grip.

Hand and object movements were also tracked with an optoelectronic recording system (OPTOTRAK; Northern Digital, Waterloo, Ontario, Canada). This three-camera system sampled the two-dimensional positions of infrared light-emitting diodes (IREDs) attached to: the object, opposing sides of the nails of the subject's right thumb and index finger, and the subject's right forearm (proximal to the wrist). Movements of the IREDS were digitized at a rate of 100 Hz during each experimental trial and passed to the data collection system of the OPTOTRAK computer for off-line reconstruction of three-dimensional movement profiles.

Procedure

During three separate blocks of trials, the object approached the subject from one of three directions: the left, the right, or from directly in front. The order of administration of these blocks was counterbalanced across subjects. Each block consisted of 15 randomly ordered trials, five at each movement speed.

Subjects were instructed to begin each trial with their index finger and thumb touching one another on the start key of the hand rest. The experimenter opened the liquid crystal goggles at the moment the object was placed on the moving conveyor belt, signaling the start of a trial. Subjects were instructed to turn their heads in the direction of the approaching object, to reach for it in one smooth motion, and to pick it up with a pincer grip (using the thumb and the index finger of the right hand) when it reached the target line. Three practice trials were performed, one at each speed, followed by the experimental trials. If an object was dropped, that trial was repeated, and a record was kept of all ″missed″ trials. Data collection for each trial began just before the object was set down on the conveyor belt and stopped 3 s later, shortly after the subject had lifted the target object.

Data analysis

Only data from the trials in which the object was successfully grasped were analyzed. The accuracy of each grasp was determined from the video recordings by noting the positions of the thumb and index finger IREDs in relation to the marks on the top surface of the object. A protractor was used to measure the number of degrees between the thumb and finger IREDs on each trial, using the center of the object as the origin; a 180° grip was considered optimal, as it would provide maximum stability. *Average grip error* was computed by subtracting the actual grip angle from the optimal grip angle.

The two-dimensional OPTOTRAK data files were converted to three-dimensional format off-line and were then filtered with a Butterworth filter using a cut-off frequency of 10 Hz. The following dependent variables were extracted from the filtered files:

1. *Maximum opening velocity* (millimeters per second). The peak resultant velocity of hand opening, measured from the index finger and thumb IREDs.
2. *Maximum grip aperture* (millimeters). The maximum gap between the thumb and index finger IREDs during the prehension movement.
3. *Latency to initiate hand closure* (milliseconds). The time from wrist movement onset (more than 10 mm/s) until maximum grip aperture was achieved.
4. *Maximum closing velocity* (millimeters per second). The peak resultant velocity of hand closure, measured from the index finger and thumb IREDs.
5. *Grip closing time* (milliseconds). The time between the appearance of maximum grip aperture and object contact. The time of object contact was defined as the first interruption – normally a decrease – of object velocity prior to object lift. Time of object lift was defined as the point at which the object finally began to reaccelerate (more than 10 mm/s^2) after this interruption.
6. *Grip stabilization time* (milliseconds). The amount of time that the object was in contact with the subject’s fingers before it was lifted off the conveyor belt.
7. *Maximum wrist velocity* (millimeters per second). The maximum resultant velocity of the wrist IRED occurring prior to object contact.
8. *Wrist deceleration time* (milliseconds). The time between maximum wrist velocity and the time of object contact.
9. *Duration of movement* (milliseconds). The time from wrist movement onset to the time of object contact.
10. *Movement amplitude* (millimeters). The three-dimensional distance between the thumb IRED at the fixed start position, and the position of the object IRED when the object was first contacted. Note that this measure assumes that the arm's trajectory follows a straight line and as such it may frequently underestimate true movement amplitude. Nonetheless, it provides a useful measure of the distance from the start key, and hence from the body, at which the object was intercepted.

Results

Sports history questionnaire

Subjects rated their sports experience by indicating a position on a Likert scale ranging from 1 (no experience) to 5 (a lot of experience) for each of four sports: baseball, basketball, racquet sports, and ice or field hockey. A single-factor, between-subjects analysis of variance (ANOVA) on the mean ratings revealed no sex difference in sports experience ($F_{1,17}$ = 0.067, n.s.); the mean ratings were 1.9 and 1.8 for men and women, respectively, indicating very little sports experience. A sex difference was found, however, in self-ratings of fitness, coordination, overall sports experience, and overall video-game experience ($F_{1,17} = 7.6$, $P<0.05$), with males rating themselves as ″fitter″ and ″more coordinated″ than their peers more often than females.

Grasping task: kinematic analysis

The four variables *maximum wrist velocity*, *wrist deceleration time*, *duration of movement*, and *movement amplitude* apply to the reaching or transport component. The six variables *maximum opening velocity, maximum grip aperture, latency to initiate hand closure, maximum closing velocity, grip closing time,* and, finally, *grip stabilization time* apply to the grasp component.

For every subject, mean values of each dependent measure were calculated for each combination of Direction of approach and Speed of approach, yielding nine values. Since only about 3% of the trials were lost due to technical difficulties (e.g., IRED occlusion), the vast majority of these means were based on five observations (minimum three observations). For blocks with missing data, the means were calculated using only those trials with complete data on all variables. Each dependant variable was then analyzed with a 2 (Sex)×3 (Direction of approach)×3 (Speed of approach) ANOVA, with repeated measures on the last two factors. Finally, simple contrasts between means were performed using post hoc Newman-Keuls analyses. An alpha level of 0.05 was adopted for all tests of significance.

There were no significant differences between male and female participants on any of the dependent variables. Although this was somewhat surprising, given the striking sex differences reported by Watson and Kimura (1991) on a projectile interception task, this result is consistent with the results of the sports history questionnaire, which indicated that the groups were matched for overall sports experience.

Tables 1 and 2 list the overall means, standard errors, F-statistics, and significant contrasts for the main effects that were found for the manipulations of Speed of approach and Direction of object approach. These results are summarized below.

Speed of approach

Reaching movements directed toward quickly moving targets attained higher peak velocities, had shorter periods of deceleration, were of larger amplitude, and were completed in a shorter period of time than reaches to more slowly moving objects. Thus, speed of object approach was found to influence a number of variables describing the transport component.

In addition to the effects on the transport component described above, however, both the maximum opening velocity and the maximum aperture of the grip increased as a function of increasing object approach speed, regardless of which direction the object approached from. (These effects were quite robust, being seen in 13 of 18 and 18 of 18 subjects, respectively.) The net effect of this was that, for objects approaching from a given direction, approach speed had only a small effect on the latency to initiate hand closure ($F_{2,32} = 3.15$, $P = 0.056$, n.s.).

Maximum closing velocity also increased as a function of increasing object approach speed (in 15/18 subjects), which had the effect of keeping total hand closure time remarkably constant (hence the lack of a significant effect or interaction involving Approach speed on this variable). This invariance was evident even when grip closing time was expressed as a proportion of total movement dura-

Table 1 Effects of Speed of Approach on kinematic variables. (*F* Fast approach speed, *M* medium approach speed, *S* slow approach speed)

		Fast	Medium	Slow	Contrasts	F-statistic
Max. wrist velocity (mm/s)	Mean	658.8	618.3	592.1	F>M,S	$F_{2,32}$=8.29**
	SE	15.9	19.8	13.8		
Wrist deceleration time (ms)	Mean	258.2	316.9	375.5	F<M<S	$F_{2,32}$=28.5***
	SE	10.9	11.8	9.6		
Duration (ms)	Mean	685.7	714.0	738.2	F<S	$F_{2,32}$=6.29*
	SE	15.4	15.9	14.4		
Amplitude (mm)	Mean	255.5	241.6	234.9	F>M>S	$F_{2,32}$=85.02***
	SE	4.6	3.1	2.2		
Max. grip aperture (mm)	Mean	88.7	82.2	74.8	F>M>S	$F_{2,32}$=5.72*
	SE	1.3	1.3	1.1		
Max opening velocity (mm/s)	Mean	329.6	278.5	227.6	F>M>S	$F_{2,32}$=34.7***
	SE	15.7	12.3	7.9		
Latency to initiate hand closure (ms)	Mean	558.7	580.9	596.9	n.s.	n.s.
	SE	15.6	16.2	11.6		
Max. closing velocity (mm/s)	Mean	475.1	374.8	252.5	F>M>S	$F_{2,32}$=130.3***
	SE	16.8	15.8	10.4		
Closing time (ms)	Mean	127.0	133.1	141.1	n.s.	n.s.
	SE	1.9	2.8	3.2		
Grip stabilization time (ms)	Mean	135.4	132.2	94.9	F,M>S	$F_{2,32}$=39.9***
	SE	3.5	4.3	3.4		

* $p<0.01$; ** $p<0.005$; *** $p<0.001$

tion: thus, the proportion of total movement time devoted to hand closure was, on average, 18.5%, 18.6%, and 19.1% on fast, medium, and slow trials, respectively. There were costs associated with keeping closing time invariant, however: subjects appeared to achieve a less stable grasp of the object when it approached more quickly, as reflected both in the amount of time spent in contact with the object prior to lift (grip stabilization time), and in the average grip errors measured from the video recordings.

Direction of approach

If a target object was approaching from the right, the reaching movement attained a higher peak velocity, had a shorter period of deceleration, and was completed in a shorter period of time than if it approached from another direction. In contrast, reach kinematics were generally very similar for targets approaching from the left and from directly in front of the subject. There was one exception to this: subjects intercepted quickly moving objects too soon (i.e, before they reached the target line) when they approached in the sagittal plane, as could be seen in the analysis of the movement amplitude data (Direction of approach × Speed of approach, $F_{4,64} = 37.1$, $P<0.001$; see Fig. 1). Despite overshooting the target line in this manner, however, post hoc analysis of the significant Direction of approach × Speed of approach interaction for movement duration ($F_{4,64} = 3.3$, $P<0.05$) revealed that these movements did not take longer to complete than those directed toward more slowly moving targets approaching the subject head-on, or than those directed to objects approaching from the left at any speed (see Fig. 2). It is important to note that a tendency to overshoot in this condition does not interfere with successful prehension, since the hand and the object could, theoretically, meet at any point between their initial positions along the sagittal plane. When objects approach from the left or the right, in contrast, the movement of the hand is orthogonal to the movement of the object, and there is only a single point at which the two trajectories meet, making the target zone for successful interception considerably smaller unless a lateral component is incorporated into the arm movement.

Post hoc analyses revealed that only when objects approached at the slowest speed were maximum opening ve-

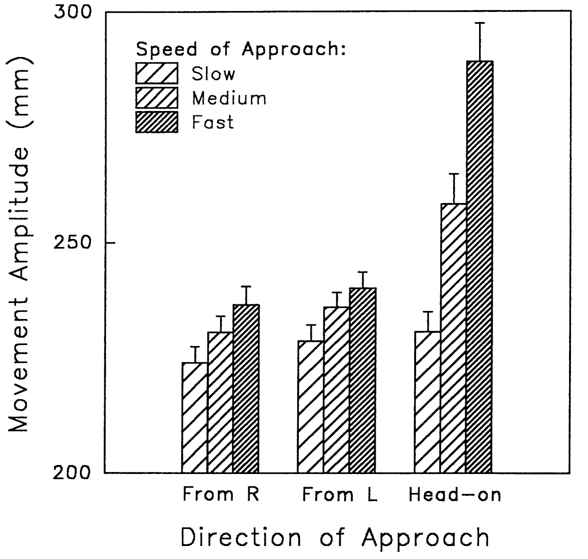

Fig. 1 The effect of speed and direction of object approach on movement amplitude

Table 2 Effects of Direction of Approach on kinematic variables. (*L* Approaching from the left, *R* approaching from the right; *H* approaching the subject head-on, in the sagittal plane)

		Right	Left	Head-on	Contrasts	*F*-statistic
Max. wrist velocity (mm/s)	Mean	681.3	591.3	596.6	R>L,H	$F_{2,32}=8.52$**
	SE	15.9	16.3	16.2		
Wrist deceleration time (ms)	Mean	290.2	344.8	342.9	R<L,H	$F_{2,32}=9.65$**
	SE	11.9	12.5	9.8		
Duration (ms)	Mean	674.5	738.5	724.9	R<L,H	$F_{2,32}=7.86$**
	SE	15.1	11.9	13.3		
Amplitude (mm)	Mean	230.3	234.9	259.3	R,L<H	$F_{2,32}=20.14$***
	SE	2.1	4.6	5.0		
Max. grip aperture (mm)	Mean	84.0	81.3	79.5	R>L,H	$F_{2,32}=134.94$***
	SE	1.6	1.4	1.2		
Max. opening velocity (mm/s)	Mean	330.8	269.0	236.0	R>L,H	$F_{2,32}=20.85$***
	SE	15.1	12.9	8.6		
Latency to initiate hand closure (ms)	Mean	518.9	598.4	619.3	R<L,H	$F_{2,32}=17.84$***
	SE	14.1	13.5	13.0		
Max closing velocity (mm/s)	Mean	388.1	359.6	354.7	n.s.	n.s.
	SE	21.3	18.9	16.9		
Closing time (ms)	Mean	155.7	139.9	105.7	R>L,H	$F_{2,32}=52.3$***
	SE	4.5	3.8	1.9		
Grip stabilization time (ms)	Mean	121.9	123.1	117.5	n.s.	n.s.
	SE	5.2	4.8	3.4		

* $p<0.01$; ** $p<0.005$; *** $p<0.001$

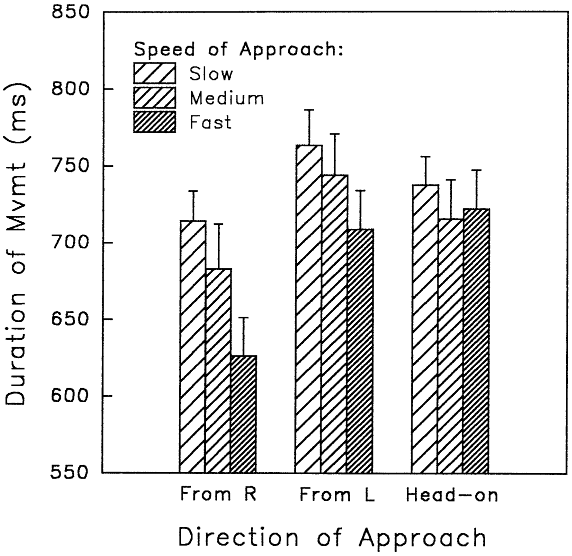

Fig. 2 The effect of speed and direction of object approach on movement duration

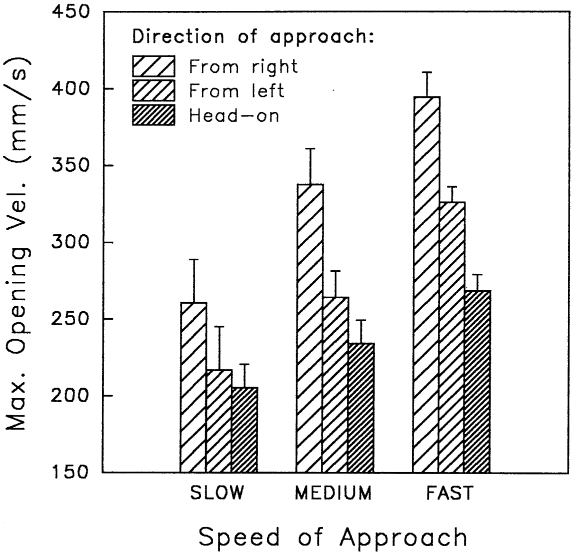

Fig. 3 The effect of speed and direction of object approach on maximum opening velocity

locities and maximum grip apertures unaffected by direction of object approach (Speed × Direction of approach: $F_{4,64} = 3.04$, $P<0.05$, and $F_{4,64} = 4.24$, $P<0.005$, for maximum opening velocity and maximum aperture, respectively; see Figs. 3, 4). At medium and fast speeds, the mean values of both of these variables were greater for objects approaching from the right than for those approaching from other directions (these effects were seen in 15/18 subjects tested). Moreover, latency to initiate hand closure was shorter when subjects reached toward objects approaching from the right than in the other conditions. Closing velocities, however, did not vary as a function of the direction of approach; this meant that, since the hand had opened to a greater extent, closing times were longer for the objects approaching from the right than from other directions. (This was true whether grip closing time was expressed in absolute time, or as a percentage of total movement duration; thus, subjects devoted, on average, 23.1% of total movement time to grip closure when objects approached from the right, but only 18.9% and 14.6%, respectively, when they approached from the left or head-on.) Subjects were, however, able to achieve grasps of comparable stability regardless of the objects' direction of approach. Thus, neither grip stabilization time nor average grip errors as measured in the video analysis were affected by the direction of approach.

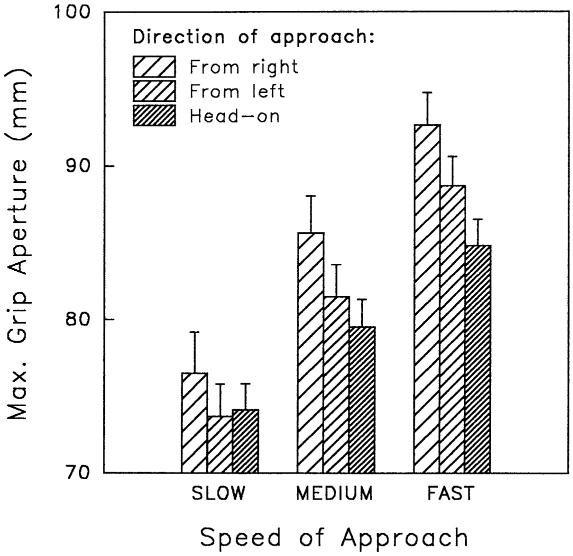

Fig. 4 The effect of speed and direction of object approach on maximum grip aperture

Video analysis of grip accuracy

Grip accuracy scores obtained from the video recordings of the subjects' hands were analyzed using a mixed-design ANOVA as above. The dependent variable in this analysis, *average grip error*, was determined by subtracting the size of the actual grasp angle (defined as the number of degrees between the thumb and finger IREDs on each trial, using the center of the object as the origin) from what would be considered an optimal grasp angle of 180°. A second rater independently rescored 25% of the video trials; grip errors measured by the two raters were highly correlated ($r = 0.744$, $P<0.05$).

Speed of approach was found to have a main effect on average grip error ($F_{32,2} = 26.09$, $P<0.001$), and post hoc analyses revealed that the mean average grip error on fast trials (32.1°) was significantly larger than on medium trials (24.7°), which, in turn, was larger than that seen on slow trials (18.8°). The faster the approach speed of the object, then, the more subjects' grasps differed from an optimal 180° grasp. Thus, it seems likely that subjects required more time to form a stable grasp on objects which approached quickly, because their finger positioning was less than optimal on these trials. The direction from which the objects approached did not impact on average grip error.

Discussion

As predicted, in the present study the kinematics of both the transport and the grasp components of prehension movements directed toward moving objects were found to change in response to manipulations of the speed of an object's approach. This result is consistent with results of earlier studies showing coordinated changes in the transport and grasp components occurring in response to a sudden change in the location of a stationary target (Paulignan et al. 1990, 1991a). It is, however, somewhat at odds with the findings of Chieffi et al. (1992). These researchers studied unconstrained prehension movements executed toward objects approaching in the sagittal plane at different constant velocities. They argued that the acceleration phase of the transport component was only affected by the amplitude of the arm movement that would have to be made to intercept the object at a target line, but that the final, deceleration phase was affected by both the required movement amplitude and by the approach velocity of the object. Specifically, the deceleration phase was shorter for objects approaching at higher velocities. While this effect is largely consistent with the present findings, these authors also reported that maximum grip aperture was not affected by object velocity, even if one considered comparisons between moving and stationary objects. In the present study, in contrast, there was a difference of almost 1.4 cm between the mean maximum grip apertures seen in the fast approach and slow approach conditions.

One factor that may have contributed to producing this discrepancy is that subjects in the Chieffi et al. (1992) study were instructed to reach *as quickly and accurately as possible*. The effect of an instruction to reach and grasp a stationary object quickly was explored in a study by Wing et al. (1986). These authors found that ″fast″ reaches were executed nearly twice as quickly as reaches for which no instructions were given. Wing et al. also found, however, that the increase in wrist velocity on ″fast″ trials was associated with a corresponding increase in maximum grip aperture, and that hand positions prior to object contact were less accurate on these trials. If one compares mean peak velocites and maximum grip apertures in the report by Chieffi et al. (in which instructions were given to reach quickly) and in the present study (in which no such instruction was given) one sees this same relationship. Peak wrist velocities in the study by Chieffi et al. were approximately twice as fast as those seen in the present report, and grip apertures were correspondingly larger. Moreover, recall that in the present study there was a speed-accuracy trade-off in that less-accurate grasps accompanied movements of higher velocity. Subjects appeared to achieve a less stable grasp on the object when it approached more quickly, as reflected both in the video analysis and in the amount of time spent in contact with the object prior to lift. Thus, the lack of an effect of approach velocity on maximum grip aperture in the study by Chieffi et al. may have reflected a biomechanical constraint imposed by the adoption of a large safety margin to compensate for the increased likelihood of error during rapid movements. In the present study, in which subjects reached at a self-regulated speed, an extrinsic characteristic of the object (its speed of approach) dictated several coordinated changes in movement kinematics, including changes to the maximum opening of the hand.

One of the key questions posed in the Introduction was how the onset of hand closure is regulated during interceptive acts. One possibility is that subjects begin to close their hands when a fixed *proportion of total movement time* has elapsed. Although this pattern appeared to hold in the case of objects moving at different speeds (i.e., subjects initiated hand closure when roughly one-fifth of the total movement time remained), it did not appear to hold for different directions of approach. Here, the proportion of movement time devoted to hand closure was quite variable, ranging from a mean of 14.6% for objects approaching head-on to a mean of 23.1% for objects approaching from the right. Moreover, the physiological mechanisms that would support such control are unclear, and the computational demands seem unwieldy.

Another possibility is that subjects use time to contact information. Although Chieffi et al. (1992) did not directly address the question of whether time to contact might have been used to regulate the onset of hand closure, their data are not inconsistent with this notion. Moreover, these researchers were able to demonstrate that distance to contact was *not* employed by their subjects to control this important phase of the grasping action. In the present study, it was demonstrated that, when an object approached *from a given direction,* the speed at which it moved did not affect the time taken to close the hand. Instead, this phase of the movement consistently began during the final 100–150 ms prior to object contact. Thus, the coordinated adjustments that were made to the transport and grasp components in response to the manipulation of approach speed guaranteed that hand closure would always begin at a constant time prior to object contact. The present findings, then, replicate and extend those of other researchers who have shown, in the case of head-on object trajectories, that the timing of hand closure is not affected by object approach speed (Savelsbergh et al. 1992).

Although grip closure time was equivalent for objects approaching from a given direction, subjects spent slightly longer closing their hands on the object when it approached from the right than when it approached from one of the other directions. This result would not be predicted if, as Bootsma and Oudejans (1993) have argued, the same source of visual information is used to specify the future time of arrival of a moving object at any designated position in the field of view, regardless of the object's approach trajectory (viz. information contained in the combination of the relative rates of dilation of the moving object's optical contour and constriction of the optical gap separating the object and a designated target). This suggests either that time to contact (or, more specifically, the tau margin) is *not* the critical variable controlling the onset of hand closure (cf. Smeets et al. 1996; Wann 1996), or that this variable is not used in particular circumstances (e.g., when the final approach of an object is likely to be temporarily blocked from view by the moving limb or some other object – as would be the case when the right hand reaches out to grasp an object approaching from the right).

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