Exp Brain Res (1999) 125:281–286

RESEARCH ARTICLE

J.D. Connolly · M.A. Goodale

The role of visual feedback of hand position in the control of manual prehension

Received: 3 July 1998 / Accepted: 18 November 1998

Abstract Although it is obvious that vision plays a primary role in reaching and grasping objects, the sources of the visual information used in programming and controlling various aspects of these movements is still being investigated. One source of visual information is feedback relating to the characteristics of the reach itself – for example, the speed and trajectory of the moving limb and the change in the posture of the hand and fingers. The present study selectively eliminated this source of visual information by blocking the subject's view of the reaching limb with an opaque barrier while still enabling subjects to view the goal object. Thus, a direct comparison was made between standard (closed-loop) and object-only (open-loop) visual-feedback conditions in a situation in which the light levels and contrast between an object and its surroundings were equivalent in both viewing conditions. Reach duration was longer with proportionate increases in both the acceleration and deceleration phases when visual feedback of the reaching limb was prevented. Maximum grip aperture and the proportion of movement time at which it occurred were the same in both conditions. Thus, in contrast to previous studies that did not employ constant light levels across closed- and open-loop reaching conditions, a dissociation was found between the spatial and temporal dimensions of grip formation. It appears that the posture of the hand can be programmed without visual feedback of the hand – presumably via a combination of visual information about the goal object and proprioceptive feedback (and/or efference copy). Nevertheless, maximum grip aperture (like the kinematic markers examined in the transport component) was also delayed when visual feedback of the reaching limb was selectively prevented. In other words, the relative timing of kinematic events was essentially unchanged, reflecting perhaps a tight coupling between the transport and grip components.

Key words Manual prehension · Visual feedback · Grasping · On-line control · Proprioception

J.D. Connolly · M.A. Goodale (✉)
Vision and Motor Control Laboratory,
Graduate Program in Neuroscience, Department of Psychology,
The University of Western Ontario, London, Ontario,
Canada, N6A-5C2
e-mail: mgoodale@julian.uwo.ca,
Tel.: +1-519-661-2070, Fax: +1-519-661-3961

Introduction

It is obvious that visual information plays a significant role in the execution of goal-directed grasping movements. Not only is the limb directed to the correct spatial location, but the posture of the hand reflects the size, shape, and orientation of the object. Moreover, the timing of the finger movements is coordinated with the movement of the limb as the grasp unfolds to ensure that the hand is in the correct configuration as it makes contact with the object (for reviews, see Goodale and Servos 1996; Jeannerod 1988).

Although it is clear that visual information about the target is used to program and control the grasp, there is some debate as to whether or not visual feedback about the moving limb is used in the on-line control of the grasp (for reviews, see Jakobson and Goodale 1991; Jeannerod 1988). Some studies have found that elimination of visual feedback has an effect on the kinematics of manual aiming and grasping, but others have not.

The study of manual aiming movements is a case in point. Carlton (1981) reported that, during trials in which ambient light was eliminated, still being able to see a phosphorescent stylus (or virtual limb) improved movement accuracy over conditions when the stylus was not visible. In contrast, a more recent study by Elliot (1988) reported no difference in accuracy when vision of the stylus was prevented. A study by Prablanc et al. (1979a) found that, when subjects could not see their pointing limb, their movements were hypometric, even though there was no change in movement time. A follow-up study reported that being able to see one's initial hand position greatly improved movement accuracy during visual "open-loop" trials – leading the authors to suggest that a comparison between initial hand position and target position is a critical variable in the effective control of pointing (Prablanc et al. 1979b). This proposal has received support from a more recent study in which the view of the hand and target prior to movement onset increased the accuracy of manual aiming movements (Rossetti et al. 1994).

Work on grasping has also produced contradictory findings. In an early study, for example, Jeannerod (1984) reported that, for two subjects who grasped objects in a situation in which they could not see their reaching limb, movement kinematics were little different from those observed when they had normal visual feedback about limb position. The only reliable difference was a slight decrease in movement time when no visual feedback was available (i.e., when subjects reached towards the virtual image of the object reflected in a mirror). [Tactile feedback was provided at the end of each reach by the subject contacting a real object at the virtual-target location (i.e., situated at a location spatially coincident with the apparent location of the virtual object)].

In contrast to Jeannerod's (1984) findings, a later study by Gentilucci et al. (1994), which also used a mirror apparatus to eliminate vision of the moving limb, found that eliminating this particular source of visual information resulted in longer reach times and larger grip apertures. There were several improvements in the Gentilucci et al. study, however. First, the position of the target was varied randomly over three different positions from trial to trial. Second, the movements of the hand and limb were recorded opto-electronically, giving much more precise information about the kinematics.

Other studies have looked at the role of visual feedback by preventing both vision of the target and vision of the limb during the execution of the movement. In a study by Jakobson and Goodale (1991), for example, visual feedback was prevented as soon as the grasp was initiated by turning off the overhead lights. Removing visual feedback from the moving limb and the position of the target in this way resulted in a significant increase in maximum grip aperture. In addition, maximum aperture and maximum height in the trajectory of the wrist was achieved proportionately sooner in time. Thus, like the study by Gentilucci et al. (1994), this study contradicted the early findings of Jeannerod (1984) and suggested that on-line visual information plays a significant role in the control of the grasp. In the Jakobson and Goodale study, however, visual information about the target as well as the limb was not available. Although it seems intuitive that on-line visual information about limb position and posture is more important than visual information about the target, this study does not separate the effects of these two possible sources of information.

Recently, Berthier et al. (1996) returned to the question of what happens when visual information about the moving limb is prevented during the execution of a grasp. Subjects in this study reached for target objects that were presented in three conditions of progressively reduced visual information: a standard condition (full visual feedback), a condition in which visual feedback was restricted to the target, and finally a condition in which visual feedback was prevented entirely, although, in this condition, the goal object made a sound, thus giving participants an auditory cue as to its location. Subjects' reaches were slower, longer in duration, more asymmetrical, and involved larger peak grasp apertures in the reduced visual-feedback condition than in the full visual-feedback condition (Berthier et al. 1996).

But the Berthier et al. study (1996) was not without problems. In the condition in which vision of the limb was prevented but the target remained visible, Berthier et al. used a "glow-in-the-dark" object. This target was clearly very different visually from the one that was used in the full vision condition. Moreover, the overall light levels in the two conditions were dramatically different. It is likely that the level of ambient light influences pointing kinematics by increasing or decreasing the amount of allocentric information available since the relative availability of this source of visual information is known to affect pointing kinematics (Gentilucci et al. 1997; Toni et al. 1996). Thus, it is not possible to determine whether or not the differences between the two conditions were due to the differences in visual feedback about limb position or to the differences in ambient light and/or the appearance of the target. This same criticism can, of course, be given to the Jakobson and Goodale (1991) study since there were large differences in ambient light levels between the so-called closed-loop condition (in which visual feedback was continuously available) and open-loop condition (in which visual feedback was absent). In fact, even in the original study of Jeannerod (1984), there were differences in the light conditions between open- and closed-loop reaches, although in these cases the differences were probably not as great. In short, in these studies, it is not possible to be sure that the change in performance that occurred when vision of the limb was eliminated was due to the change in the availability of visual information about the position of the target or to changes in the ambient light levels (which would have eliminated or reduced information about the position of the target). Although in the Gentilucci et al. 1994 study, the levels of ambient light in closed- and open-loop trials were more similar, subjects were able to see their initial hand position prior to closed-, but not open-loop trials. It is therefore not clear whether the differences they observed were due to elimination of visual information of the reaching limb or to subjects not being able to compare their initial hand position with the target location. As we saw earlier, information about initial limb position can affect the accuracy of aiming movements (Prablanc et al. 1979b; Rossetti et al. 1994).

In the present study, therefore, we studied the effects of removing visual feedback of the moving limb, while at the same time maintaining a constant level of ambient light, and did not allow subjects to see their initial hand position across both closed- and open-loop trials. To accomplish this, an opaque barrier was used to exclude visual feedback of the hand and limb during open-loop trials in which only information about the target was available. Any differences in performance would have been due to the availability (or not) of visual feedback from the moving limb rather than to changes in the nature of visual information about the target and/or initial hand position.

Materials and methods

The experiment was carried out at the University of Western Ontario in compliance with the Social Sciences and Humanities Research Council (Canada) Guidelines (1981).

Subjects

The subjects were five male and three female students at the University of Western Ontario. They ranged in age from 20 to 29 years, with a mean age of 24.6 years. All subjects were strongly right-handed with normal stereoscopic vision, as determined by a modified version of the Edinburgh Handedness Inventory (Oldfield 1971) and the Randot Stereotest (Stereo Optical, Chicago, Ill., USA), respectively. All subjects had given their informed consent prior to testing and were paid for their participation.

Apparatus

Subjects were seated comfortably on a chair in front of a flat table surface, 100 cm wide and 55 cm deep, with their heads stabilized in a head-and-chin rest. A fluorescent lamp was suspended 80 cm above the table surface and was illuminated by a remote switch, which also triggered the start of data collection. Six wooden oblong blocks with the following surface dimensions were used as targets for reaching and grasping movements: 5.5×4.5 cm, 6.0×4.0 cm, 7.0×3.5 cm, 8.0×3.0 cm, 10.0×2.5 cm, and 12.5×2.0 cm. All blocks were 2.0 cm in height. Subjects began a trial with the index finger and thumb of their right hand resting upon a start key located at the body midline. The target object was placed 27 cm from the start key at one of four positions: 0° (midline); 22.5° to the right of the midline (near ipsilateral side); 72.5° to the right of the midline (far ipsilateral side); 22.5° to the left of the midline (near contralateral side). The approximate viewing angle was 38°, and the level of ambient light was 24 fc across both viewing conditions.

Infrared light-emitting diodes (IREDs) were attached with adhesive tape at three positions on the right (reaching) hand: on the distal left corner of the index finger nail, on the distal right corner of the thumb nail, and on the skin opposite the styloid process of the ulna. The leads corresponding to each IRED were taped to the medial portion of the right forearm to ensure complete freedom of movement. The IREDs were tracked using conventional opto-electronic recording techniques (WATSMART, Northern Digital, Waterloo, Ontario, Canada). For details, see Jakobson and Goodale (1991).

To prevent visual feedback of the hand and limb during object-only visual-feedback trials, subjects wore a pair of safety glasses (Soldono Manufacturing, Toronto, Ontario) with the lenses removed so that occluders could be attached to the frames. Plastic occluders were attached with Velcro to a light wire frame mounted on the bottom of the glasses. These occluders permitted subjects to see only the target; the view of the tabletop from the start key to the near edge of the target was completely blocked. Subjects could not see their initial hand position during both closed- and open-loop trials. Subjects were prevented from seeing their initial hand position by the head-and-chin rest during closed-loop trials, since the start key was located approx. 3 cm perpendicular to the lower rib cage and, thus, initial hand position was always behind the field of view. The position of the occluders were adjusted for each subject at the beginning of the experiment until only the targets, but not the moving limb, were visible. (Consequently, during open-loop trials, the occluders eliminated all other sources of visual information within the lower visual field). In the full visual-feedback condition, the occluders were removed from the glasses.

Procedure

Subjects were instructed to touch the index finger and thumb of the right hand together and to rest the tips of the fingers on the start key. In between reaches, the room lights were extinguished and subjects sat with their eyes closed. During this time, the experimenter quietly placed the target object at one of four locations. Subjects were then given a "ready" command. Approximately 1–2 s after receiving a reply, the experimenter turned on the overhead fluorescent light. Subjects were instructed to open their eyes immediately upon hearing the experimenter's "ready" command and to begin reaching as soon as they could see the target object. Data collection began as soon as the fluorescent light was turned on.

In one block of trials, visual feedback of the hand and limb was prevented by having subjects wear the glasses with the occluders attached (open-loop condition). In another block of trials, participants reached under normal viewing conditions, wearing the glasses without the occluders (closed-loop condition). Each condition was presented twice with the order of testing counterbalanced across subjects.

For each block of trials, subjects reached two times for each of the six blocks at each of the four different positions, for a total of 48 reaches (96 in total for each of the two testing conditions). For each block, the 48 trials were presented in a different random order. If the subject dropped a target object, the trial was discarded and another was collected in its place at the end of that block of trials. Subjects received five practice trials at the beginning of each block of trials.

Dependent measures

The following dependent measures were derived from the wrist IRED: time to movement onset (latency), reach duration, maximum velocity, and the time to maximum velocity. The following measures were derived from the fingertip and thumb IREDs: maximum grip aperture and the time to maximum grip aperture. In some cases, the timing measures were converted to percent of total reach duration.

Results

For each subject, mean values for each dependent measure were calculated from the four replications of each combination of object shape and position across the two blocks of trials for both the open- and the closed-loop conditions. With the exception of two cells (which contained means based on three observations), all means were based on four observations. The mean values were entered into separate 2×4×6 (viewing condition × object position × object dimension) repeated-measures analysis of variance (ANOVA).

The means and standard errors for each dependent measure for the two viewing conditions are presented in Table 1. Figure 1 presents representative velocity profiles for closed- and open-loop reaches for a single subject. As this figure illustrates and as is shown in Table 1, reaches were significantly longer in duration when sub-

Table 1 Effect of blocking visual feedback of hand position on reach kinematics. Values = mean (±standard error of the mean). *MT* Total reach duration

	Visual feedback condition	
	Closed-loop	Open-loop
Time to movement onset (ms)	510 (22.9)	531 (19.4)
Reach duration (ms)***	787 (41.9)	838 (41.6)
Maximum velocity (mm/s)	708 (42.5)	699 (33.1)
Acceleration phase (ms)*	346 (21.0)	366 (25.1)
Deceleration phase (ms)**	440 (22.5)	471 (18.8)
%MT to max. velocity	44 (0.8)	44 (1.1)
Maximum grip aperture (mm)	77.2 (2.8)	78.2 (3.1)
Time to max. grip aperture (ms)***	526 (35.2)	570 (39.1)
%MT to max. grip aperture	67 (2.7)	68 (2.9)

*P<0.05, **P<0.01, ***P<0.001

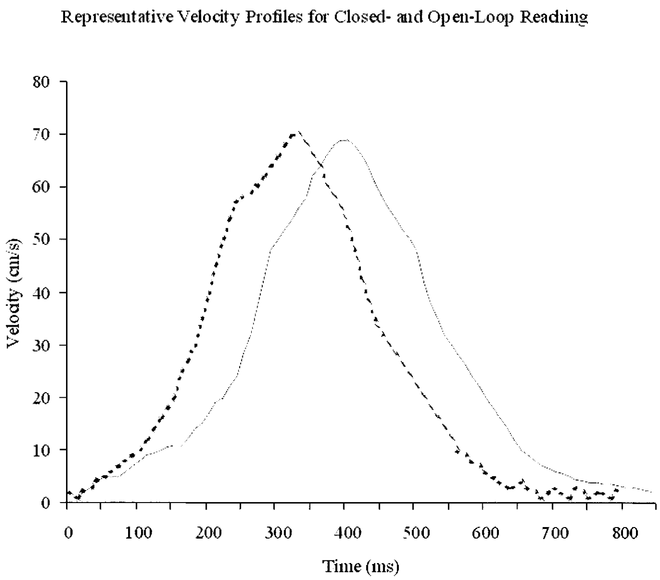

Fig. 1 Representative velocity profiles for a single subject during closed- (standard) and open-loop (object only) visual-feedback conditions

jects could not see their reaching limb than when they could see them [F(1,7)=43.25, P<0.001]. Also, both the time to maximum velocity (i.e., the acceleration phase) and the time from maximum velocity to the end of the reaching movement (i.e., the deceleration phase) were longer for the open-loop than for the closed-loop trials [F(1,7)=12.80, P<0.001 and F(1,7)=11.98, P<0.01, respectively]. However, neither maximum velocity [F(1,7)=0.27, n.s.] nor the percentage of total movement time needed to reach maximum velocity [F(1,7)=.28, n.s.] differed between the two conditions. Finally, there was no difference in the time to movement onset (latency) [F(1,7)=2.57, n.s.].

Although viewing condition affected time to maximum grip aperture [F(1,7)=12.80, P<0.001], eliminating visual feedback of the reaching hand and limb did not affect maximum grip aperture itself [F(1,7)=0.59, n.s.]. It also did not affect the percentage of the total reach duration during which maximum grip aperture occurred [F(1,7)=0.38, n.s.].

As expected, there was a significant effect of object dimension on maximum grip aperture, with the hand opening wider for wider objects [F(5,35)=8.11, P<0.001]. The width of the object also had a significant effect on time to maximum grip aperture [F(5,35)=6.01, P<0.001]. A similar effect was observed on the percentage of the total movement time needed to reach maximum grip aperture [F(5,35)=4.56, P<0.01]. Inspection of the cell means indicated that, as width decreased, maximum grip aperture occurred earlier in the reach. For example, time to maximum grip aperture for reaches to the widest object was 585 ms compared with 495 ms for reaches to the narrowest object. The width of the target object did not affect any of the other dependent measures.

The position of the object also affected various kinematic measures, including total movement time [F(3,21)=19.00, P<0.001]. Reach duration progressively increased from object position on the far right (ipsilateral) to that on the near left (contralateral). Therefore, reaches to the far right (ipsilateral) position were shortest in mean duration (748 ms), and reaches to the near left (contralateral) position were the longest (863 ms). Position also had a significant effect on the length of both the acceleration and deceleration phases of prehension [F(3,21)=12.99, P<0.001 and F(3,21)=7.89, P<0.001, respectively]. Specifically, the amount of time spent in the acceleration and deceleration phases increased as the position of the object was changed from right to left across the experimental workspace, analogous to the effect described above on total movement time. The position of the object also affected maximum velocity [F(3,21)=22.43, P<0.001]. Specifically, maximum velocity increased as the position of the object changed from the far right (ipsilateral side) to the near left (contralateral side) of the workspace (i.e., 668 mm/s, far right; 691 mm/s, near right; 720 mm/s, body midline; 734 mm/s, near left). There was no effect of object position on latency or the percentage time to maximum velocity.

Maximum grip aperture also varied as a function of object position [F(3,21)=4.61, P<0.05], with reaches to the far right showing larger apertures than at the other three positions. The time needed to reach maximum grip aperture increased as the object was moved from right to left [F(3,21)=12.99, P<0.001], although there was no effect on the percent time to maximum grip aperture.

Two significant interactions were found in the nine three-way ANOVAs. The first interaction involved a three-way viewing condition × object position × object dimension effect on total movement time [F(15,105)=1.89, P<0.05]. However, this interaction was not interpretable. The second interaction was a viewing condition × object position effect on maximum velocity [F(3,21)=4.77, P<0.01]. However, the increase in maximum velocity as a function of the position of the object was not as dramatic for open-loop reaches as it was for closed-loop reaches.

Discussion

In contrast to the large difference in maximum grip aperture between open-loop and closed-loop grasping found by Berthier et al. (1996), the present study found no difference in this variable between the two conditions. This suggests that the large difference observed by Berthier and colleagues was probably due to the gross differences in overall illumination between the two viewing conditions rather than the differences in visual feedback about limb position. Nevertheless, there were temporal differences between open- and closed-loop grasping movements in the present study, suggesting that vision of the moving limb makes an important contribution to the control of grasping.

Like Gentilucci et al. (1994), we found that open-loop reaches lasted significantly longer than closed-loop reaches. In our study, the increase in duration was due to an increase in both the acceleration and the deceleration phase. In the Gentilucci et al. (1994) study, the increase in duration was entirely due to a prolonged deceleration phase. There were important methodological differences between the two studies, however. In the Gentilucci et al. study, subjects were able to see their initial arm and hand position during closed-, but not during open-loop trials, whereas in our study subjects could not see their initial hand position during either kind of trial. We will return to this point later. A second difference is that, in the former study, a semi-reflecting mirror was used to eliminate visual feedback of the reaching limb, whereas we used an opaque barrier. Although the presence or absence of the occluders in our experiment could have provided a salient cue to the visuomotor system as to the kind of trial that was about to unfold, in both experiments the open- and closed-loop trials were blocked, so that the visuomotor system would already “know” what kind of trial to expect. Indeed, work by Jakobson and Goodale (1991) has shown that, if open- and closed-loop trials are randomly interleaved rather than blocked, no differences are observed between open- and closed-loop trials. All trials in the interleaved condition are treated as open-loop trials. Blocking the trials allows the visuomotor system to anticipate the reliable presence (or absence) of visual feedback and, thus, to program the reach and grasping movements accordingly.

The prolongation of the deceleration phase in the open-loop condition is not surprising. Paillard (1982), for example, has shown that visual feedback of the hand and limb is used selectively to guide the closing phase of a grasping or aiming movement. This is particularly true as the hand becomes progressively more foveated and its position can be more easily compared to the position of the target. Although this may account for the longer deceleration phase, it does not explain why the acceleration phase was also longer during the open-loop trials in our experiment. Many studies have suggested that the acceleration phase is essentially ballistic (for a review, see Jeannerod 1988); there would be no opportunity to use on-line control at this point in the reach. But, as we have just seen, when open- and closed-loop trials are blocked, the visuomotor system employs different strategies in the programming of the grasp – presumably because the presence (or absence) of visual feedback can be anticipated (Jakobson and Goodale 1991). In other words, the difference in the acceleration phase could reflect a difference in motor planning or programming rather than a difference in the availability of on-line control. However, this explanation is countered by the observation that in the Jakobson and Goodale study, no difference was observed in the acceleration phase of blocked open- and closed loop trials. Moreover, there was also no difference in the acceleration phase of open- and closed-loop reaches in the studies by Gentilucci et al. (1994) and Jeannerod (1984). At present, these differences regarding the early phase of the grasp among the different studies remain a puzzle. Although one might argue that the similar acceleration phases observed in closed- and open-loop reaches in the Gentilucci et al. and Jeannerod studies is due to the fact that the visual array changed only little between the two kinds of trials, this account cannot explain why Jakobson and Goodale also found no difference in the acceleration phase. In their experiment, the two kinds of trials could not have been more different since the open-loop reaches occurred in complete darkness.

As we mentioned earlier, subjects in the Gentilucci et al. (1994) study could not see their initial hand position during open-loop trials. Therefore, it is not clear how much of the difference between the two kinds of trials in their experiment was due to this rather than to the difference in visual feedback. In our experiment, subjects could not see their initial hand position in either closed- or open-loop trials. Thus, the differences in performance that we observed could not be due to the presence or absence of this information. As we reviewed in the Introduction, there is evidence to suggest that visual information about hand position at movement onset can affect movement accuracy and other performance variables (Prablanc et al. 1979b; Rossetti et al. 1994). It should also be emphasized that the same hand posture was required in both the closed- and open-loop trials in our experiment. This is important because others have shown that differences in initial hand posture can produce systematic changes in both the transport and the grasp components of prehension movements (Kritikos et al. 1998). In summary, since there were no differences in initial hand posture or initial vision of the hand in our experiment, the differences we observed must have been due to the presence or absence of visual information about the moving limb during the execution of the movement.

The lack of visual feedback of the hand and limb during open-loop trials did not affect maximum grip aperture or the proportion of time needed to reach maximum grip aperture. The latter finding may have been a simple consequence of the fact that the entire movement was longer in open loop trials and, thus, the time needed to reach maximum grip aperture was scaled accordingly. As Jeannerod (1988) has argued, the grasp and transport components of manual prehension, though functionally and anatomically distinct, are temporally coupled. Thus, even when the duration of the transport component is increased, maximum grip aperture is achieved at the same relative point during the execution of the reaching movement. However, what about maximum grip aperture itself? Why was it not affected? Previous studies have found a dramatic increase in grip aperture when visual feedback is prevented (Berthier et al. 1996; Jakobson and Goodale 1991). But, as noted above, in the Berthier et al. study, light levels were decreased dramatically during open-loop loop trials, and, in the Jakobson and Goodale study, open-loop trials were run in complete darkness, in which neither the hand nor the target were visible. The increase in grip aperture observed in these two studies may have reflected a programming strategy, in which subjects pre-programmed a larger grip aperture to compensate for the fact that, during the closing phase of the reach, information about the target would be sub-optimal (or even missing, in the case of Jakobson and Goodale) in open-loop trials. In our experiment, however, subjects had the same view of the target throughout the entire reach during both open-loop and closed-loop trials. Thus, they could use visual information about the position and size of the target to control their approach in the closing phase of the reach – even when they could not see their hand. In open-loop trials, of course, they would have to rely entirely on proprioceptive feedback (and/or efference copy information) about the position of their limb and the posture of their hand in order to make any adjustments during the execution of the grasp.

In summary, in contrast to previous research in which light levels were not held constant across viewing conditions, the current study found that removal of visual information about the limb had no effect on grasp aperture, but had clear effects on the kinematics of the reach. When vision of the hand was unavailable, subjects showed an increase in movement time, which was evident in both the acceleration and the deceleration phase. But the fact remains that subjects can still reach rather well when they have no visual feedback from their moving limb. This suggests that on-line corrections of the limb trajectory can be accomplished via proprioceptive feedback (and/or efference copy) combined with visual information about the goal object.

Acknowledgements This research was supported by a grant from the Natural Sciences and Engineering Research Council of Canada (NSERC) to M.A. Goodale.

References

Berthier NE, Clifton RK, Gullapalli V, McCall DD, Robin D (1996) Visual information and object size in the control of reaching. J Mot Behav 28:187–197

Carlton LG (1981) Visual information: the control of aiming movements. Q J Exp Psych 33A:87–93

Elliot D (1988) The influence of visual target and limb information on manual aiming. Can J Psychol 42:57–68

Gentilucci M, Toni I, Chieffi S, Pavesi G (1994) The role of proprioception in the control of prehension movements: a kinematic study in a peripherally deafferented patient and in normal subjects. Exp Brain Res 99:483–500

Gentilucci M, Daprati E, Saetti MC, Toni I (1997) On the role of the egocentric and the allocentric frame of reference in the control of arm movements. In: Karnath O, Their P (eds) Parietal lobe contribution to orientation in 3D space. Exp Brain Res 25:339–354

Goodale MA, Servos P (1996) Visual control of prehension. In: Zelaznik HN (ed) Advances in motor learning and control. Human Kinetics, Windsor, pp 87–115

Jakobson LS, Goodale MA (1991) Factors affecting higher-order movement planning: a kinematic analysis of human prehension. Exp Brain Res 86:199–208

Jeannerod M (1984) The timing of natural prehension movements. J Mot Behav 16:235–254

Jeannerod M (1988) The neural and behavioural organization of goal directed movements. Clarendon Press, Oxford

Kritikos A, Jackson GM, Jackson SR (1998) The influence of initial hand posture on the expression of prehension parameters. Exp Brain Res 119:9–16

Oldfield RC (1971) The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychol 9:97–112

Paillard J (1982) The contribution of peripheral and central vision to visually guided reaching. In: Ingle DJ, Goodale MA, Mansfield RJW (eds) Visually oriented behavior. MIT Press, Cambridge, pp 367–385

Prablanc C, Echallier JF, Jeannerod M, Komilis E (1979a) Optimal response of eye and hand motor systems in pointing at a visual target. I. Spatio-temporal characteristics of eye and hand movements and their relationships when varying the amount of visual information. Biol Cybern 35:183–187

Prablanc C, Echallier JF, Komilis E, Jeannerod M (1979b) Optimal response of eye and hand motor systems in pointing at a visual target. II. Static and dynamic visual cues in the control of hand movement. Biol Cybern 35:113–124

Rossetti Y, Stelmach G, Desmurget M, Prablanc C, Jeannerod M (1994) The effect of viewing the static hand prior to movement onset on pointing kinematics and variability. Exp Brain Res 101:323–330

Toni I, Gentilucci M, Jeannerod M, Decety J (1996) Differential influence of the visual framework on end point accuracy and trajectory specification of arm movements. Exp Brain Res 111:447–454