Max–Planck–Institut
für biologische Kybernetik
Arbeitsgruppe Bülthoff

Technical Report No. 12 February 1995

Eye-Hand Coordination for 3-D Oriented Objects

Pascal Mamassian, Heinrich H. Bülthoff, and Daniel Kersten

Abstract

When reaching for an object in space, the distance of the object, its orientation and shape should all be correctly estimated well before the hand arrives in contact with the object. We investigate here how the visual information about the object's orientation is incorporated into the motor program which guides the hand to the vicinity of the object. This motor program governs in particular the transportation of the hand, the opening of the hand, and the rotations of the forearm and wrist. These variables are analyzed in the light of the "visuo-motor channels" framework proposed by Jeannerod (1981), in which the information about the object's distance and shape is processed independently, from perception to action. Our results seem to favor an alternative framework, in which an interpretation of the three-dimensional world should be built before a motor command can be generated. Due to time constraints, this mechanism appears to be mainly feedforward.

This work was supported by the Max-Planck Gesellschaft. The authors would like to thank Melvyn Goodale for enjoyable discussions, Dietrich Opitz for computer assistance, the workshop of the Max-Planck-Institut für biologische Kybernetik for its mechanical skills, and Roland Hengstenberg for letting the authors use his patent-pending magnetic spherical joint. The authors can be reached via electronic mail: P. M. at pascal@cns.nyu.edu (New York University), H. H. B. at hhb@mpik-tueb.mpg.de (Max-Planck-Institut), and D. K. at kersten@eye.psych.umn.edu (University of Minnesota).

This document is available as /pub/mpi-memos/TR-12.ps.Z via anonymous ftp from ftp.mpik-tueb.mpg.de or by writing to the Max–Planck–Institut für biologische Kybernetik, Spemannstr. 38, 72076 Tübingen, Germany.

1 Introduction

The rich coordination between the eye and the hand is exemplified by a large number of everyday activities, such as pointing, reaching, grasping, catching, hand-writing, drawing, and various tools manipulation. Two possible classifications on these different actions can be envisaged, depending on the standpoint adopted.

From the standpoint of the viewer, different actions require to attend to different attributes of the environment. Indeed, while pointing only requires the location of the object in the visual field, a proper reaching movement needs the knowledge of the remoteness of the object (at the very least, whether the object is within reach). Catching and tracking obviously requires one to infer the trajectory of the object. As a final example, grasping requires an analysis of the object's shape in order to locate stable grasp points, in anticipation of the final purpose of the movement (whether and how the object should be transported or manipulated).

From the standpoint of the actor, different actions are related to different motor programs. For instance, both pointing and reaching can be executed through the motion of the proximal joint segments, that is the rotation of the shoulder and elbow. In comparison, grasping and drawing are more specifically concerned with the motion of the distal segments, that is the wrist and the hand fingers.

Since the viewer and the actor are one and same person, these two standpoints need to be unified in some way. Jeannerod suggested an influential framework to achieve such a unification (for a comprehensive review, see Jeannerod, 1988). The framework rests on the dichotomy between intrinsic properties of an object –those which form the object identity, such as its shape, size, weight, and center of gravity– and its extrinsic properties – those which correspond to the particular arrangement of the object relative to the actor. From the actor's standpoint, intrinsic object properties are the attributes on which a stable grasp shall be decided and executed by the distal segments motion; on the other hand, extrinsic properties are critical characteristics for accurate transportation of the arm by proximal segments motion. From the viewer's standpoint, it has been argued that intrinsic and extrinsic object properties are processed through two separate visual pathways, both at the sub-cortical level (Schneider, 1969), and cortical level (e.g. Ungerleider and Mishkin, 1982). The key aspect of Jeannerod's framework is the postulate that there exists "visuo-motor channels", that is parallel mechanisms which are specialized in the processing of either intrinsic or extrinsic information, from sensation to action (Jeannerod, 1981; Jeannerod and Biguer, 1982).

One key issue which has received very little attention, is the effect of object orientation on manual grasping. This aspect is important, for it lies at the boundary of the intrinsic/extrinsic dichotomy. From the viewer's standpoint, it is possible to define several surface orientation representations (i.e. local, apparent and intrinsic), depending on the frame of reference chosen (Mamassian, 1995). From the actor's standpoint, the joint which will be affected by the object orientation is the wrist, which appears difficult to arbitrarily classify as distal or proximal.

The structure of the paper is as follows. We first state the problem faced by the central nervous system to coordinate an action of the hand with some knowledge acquired visually. We then review some relevant behavioral research, both in adults and in infants. The neural substrates which participate in the eye-hand coordination, and in particular the posterior parietal lobe, are the subject of the next section. In the final section, we describe the experiment we have performed to investigate the prehension of 3-D oriented objects.

2 Statement of the Problem

2.1 Levels of Representation

A successful goal-directed action involves a transfer of information between a number of coordinate systems (Paillard, 1991; Soechting and Flanders, 1989a, 1989b, 1992). As far as grasping is concerned, these coordinate systems can be grouped under two separate frames of reference, depending on the use of the information to be represented. Firstly, an extrapersonal frame of reference is necessary to plan the trajectory of the hand, according to the object to be grasped, the potential obstacles to avoid, and the direction of the gravitational field. Secondly, an intrapersonal frame of reference appears necessary to register the instantaneous limb position through proprioception.

Each of these two frames of reference – extrapersonal and intrapersonal– involves its own set of coordinate systems. Firstly, the extrapersonal frame of reference represents the environment in a world-centered coordinate system. However, the information about the viewer location and orientation relative to the world is first sensed in retinal and vestibular coordinate systems. Secondly, the intrapersonal frame of reference can be segmented into as many coordinate systems as there are joints in motion. For instance, a rotation of the elbow can be most easily characterized in a coordinate system centered on the elbow joint and tied to the upper-arm (the decision of which one between the fore-arm and the upper-arm the coordinate system should be tied to is guided by choosing the more proximal body-part).

The central nervous system then faces the problem to transform the information from the extrapersonal to the intrapersonal frame of reference. This transformation is ill-posed, because each frame involves a different number of degrees of freedom. On one hand, an object in the world has six degrees of freedom (3 for location, and 3 for orientation); on the other hand, the arm has eleven degrees of freedom to position the hand (3 at the pectoral girdle, 3 at the shoulder, 2 at the elbow, 1 at the radioulnar joint, and 2 at the wrist joint). Mapping world coordinates to joint coordinates for a grasping task therefore leaves five free degrees of freedom. While one additional degree of freedom appears necessary to avoid the singularities of this mapping (Hollerbach, 1985), the advantage of disposing of five supplementary degrees of freedom is not clear (cf., however, Bernstein, 1967).

2.2 Levels of Processing

There is evidence that motor planning by the central nervous system is elaborated in the extrapersonal frame of reference, and then transformed in joint and muscle coordinates (Bernstein, 1967; Morasso, 1981; Georgopoulos et al., 1982). This transformation is classically decomposed into two stages (cf. Hildreth and Hollerbach, 1987). *Inverse kinematics* is concerned in mapping world coordinates into joint angles, while *inverse dynamics* is concerned in mapping joint angles into joint torques.

From a neural perspective, Georgopoulos and co-workers (Georgopoulos, 1986; Georgopoulos et al., 1988; Schwartz et al., 1988) found that the direction of movement was represented in the motor cortex and in area 5. This finding suggests that the motor cortex is not concerned with the forces to apply to the muscles. This is in agreement with the hypothesis that the inverse dynamics problem is solved at the cerebellar level (Albus, 1975a, b). It is important to keep in mind though, that inverse dynamics for multi-joint movement is a non-trivial problem, since every joint movement is affected by some complex interaction with the other joints (Hollerbach and Flash, 1982). Nevertheless, several methods have been suggested to solve the inverse dynamics problem (Albus, 1975a, b; Hollerbach, 1980), and we shall here focus on the inverse kinematics.

3 Behavioral Background

In this section, we review the behavioral literature on reaching and grasping, in both infants and adults. We focus on the grasping parameters which will be analyzed in our own study.

3.1 Adults

Woodworth (1899) noted the stereotyped pattern of prehension movements, consisting of a fast-rise acceleration, followed by a slower deceleration. In spite of the deceleration phase, the hand does not arrive with a null velocity at the object. Although a full-opened hand would maximize the chances to grasp the object, this would definitely not be a very efficient strategy. As a matter of fact, the hand opens appropriately to the size of the object, as can be inferred from the maximum aperture realized by the hand (Jeannerod, 1981). In addition, the maximum aperture of the hand occurs at about 80% of the total reach duration, that is well before seizure of the object (Jeannerod, 1984; Hofsten and Rönnqvist, 1988).

Since the end-point of the hand trajectory and the size of the hand aperture are properly programmed with respect to the object location and size, the question arises whether the hand programming is visually triggered or visually guided. This question has been addressed by hiding the arm during the reach (Jeannerod, 1981). Because only the hand end-point was affected, the hand aperture staying the same, it appears that intrinsic properties are used only to trigger the opening of the hand, while extrinsic properties are continuously used to guide the hand transportation. A further experiment in which the object size was changed at the start of the reach showed a late hand adjustment, but did not affect the transportation component (Jeannerod, 1981). It therefore appears that visual information is used to guide the final part of the movement, the first part being better described as ballistic (Jeannerod and Biguer, 1982).

3.2 Newborns

Given the extended body of knowledge concerning adult reaching, it is reasonable to study the development of prehension in infants. It seems now well established that newborns can extend their arms in the direction of an object (Hofsten, 1982; Rader and Stern, 1982). In addition, it appears that this hand transport is already visually-guided, since, as noted by Hofsten (1982), fixating the target improved the aiming accuracy of the newborns.

Whether or not neonates are opening their hands appropriately to the object to be grasped is still controversial. While Halverson (1931) noted that proper finger posturing during reaching is lacking until the age of approximately 20 weeks, Bower (1972) has claimed that newborns were adjusting their hand opening to the target size. Unfortunately, later studies in neonate reaching did not confirm Bower's results (DiFranco, Muir and Dodwell, 1978; Ruff and Halton, 1978).

3.3 Young Infants

Bruner and Koslowski (1972) observed the activity of infants between 2 and 5 months of age in front of both small graspable objects and larger objects which exceeded the grasping capability of the hand; they found that older infants were differentially more active for the graspable objects. Similarly, Gordon and Yonas (1976) showed that the duration and number of reaches of 5 month old infants are smaller if the object is beyond reach than if it is within reach, and when confronted with two objects at different distances, the infant will consistently reach for the closer one. This corroborates quite well the belief that by 5 months of age, infants appear to be able to use binocular disparity information to estimate the three-dimensional location of an object (cf. Yonas and Granrud, 1985). Hofsten and Rönnqvist (1988) studied older infants, between 5 and 13 months of age. While all infants started to close their hands before touching the object, only infants older than 9 months started to close their hand as early as adults did.

Of particular importance for the present paper is the reaching performance for oriented objects. Lockman, Ashmead, and Bushnell (1984) investigated the reaching of vertically or horizontally oriented dowels, in 5 and 9 months old infants. While the older infants oriented their arm before actually touching the object, 5 month-olds appeared to wait tactual contact to correctly orient their hand. These results have been confirmed by Hofsten and Fazel-Zandy (1984). The differentiation between younger and older infants could not be explained by arguing that the younger did not see correctly the target, since two month olds can discriminate horizontal from vertical orientations (Aslin and Salapatek, 1975; Essock and Siqueland, 1981). It could not be argued either that an immaturity of the motor system was the underlying reason for the age differentiation, since 2 month old infants have been observed to rotate their hand while reaching (Halverson, 1931). It therefore seems that a deficit in the visuomotor coordination is responsible for the age differences.

4 The Neural Substrates

In this section, we shall discuss anatomical substrates which participate in the coordination between vision and action (for more exhaustive reviews, see Hyvärinen, 1982a; Andersen, 1987; and Johnson, 1992). Although several cortical and sub-cortical areas participate in either the perceptual or the motor part, it is likely that the coordination itself (that is, the transformation between extrapersonal and intrapersonal frames of reference) is well localized. The posterior parietal cortex immediately appears to be a good candidate brain structure. Once described as an association area, this part of the primate brain is both polysensorial (sensitive to visual and somatic stimulation) and involved in motor control. It is located at the pinnacle of the dorsal stream, which is known to process visual spatial information.

4.1 Anatomy of the Posterior Parietal Lobe

The homologies between monkey and man of the posterior parietal cortex, although once debated, now seem well established (von Bonin and Bailey, 1947).

The parietal lobe contains the primary somatosensory cortex at its anterior aspect. The posterior parietal lobe regroup the superior and inferior parietal lobules, which are separated by the intraparietal sulcus. The superior parietal lobule (SPL) corresponds to area 5 of Brodmann (1905, 1907) or to area PE in von Bonin and Bailey's nomenclature (1947). The inferior parietal lobule (IPL) is the most posterior area of the parietal lobe, therefore adjacent to the occipital lobe, and was originally named area 7 by Brodmann.

Based on cytoarchitechtural distinctions, the inferior parietal lobule was further subdivided into a caudomedial area designated 7a by Vogt and Vogt (1919) or area PG by von Bonin and Bailey, and a more laterorostral area 7b or PF. Electrical stimulation of the area 7a produced eye movements whereas stimulation of area 7b produced hand movements (Vogt and Vogt, 1919). More recent recording studies have confirmed this general distribution between visual (7a) and somatic (7b) functions (Hyvärinen, 1981).

Hyvärinen (1982b) identified more than 60 connections between the posterior parietal cortex and ipsilateral cortical areas or subcortical nuclei; with almost as many connections to the contralateral hemisphere, one understands the complexity of this region, and its denomination as the "associative cortex". The posterior parietal cortex connects with sensory cortical regions (both somatosensory and visual), the frontal lobe, the superior temporal sulcus, the cingulum, the basal ganglia, the thalamic pulvinar, lateral posterior and ventral lateral nuclei, the superior colliculus, and with the pontine nuclei. Most of these connections are reciprocal.

Based on corticocortical connection criteria, area PG has been even further segmented into at least three sub-areas: the lateral intraparietal area (LIP), the medial superior temporal area (MST), and a relabeled (much smaller) area 7a (Andersen, 1987).

4.2 Physiology

Both the superior and the inferior lobules of the posterior parietal cortex respond to somatic stimulations (Hyvärinen, 1982a). Single cell recordings made clear the fact that the posterior parietal cortex had also a visual functional role (Hyvärinen and Poranen, 1974; Mountcastle et al., 1975).

In their pioneering work, Mountcastle et al. (1975) described the properties of neurons in area 7 according to the position of the eyes, namely whether the cell was mostly active during fixation of a target, during smooth pursuit of an object within reach, or when an object was presented out of reach. Sakata et al. (1980) later showed that the population of neurons mostly active during fixation was sensitive to the gaze direction (that is, where the animal was looking), not only within the visual field of the animal but also in depth. This finding was confirmed by Andersen et al. (1985) who interpreted this property of cells in area 7a as an implicit code for spatial location. Some cells in area PG other than 7a also show a specificity. The activity of area LIP has been correlated with eye movements (Shibutani et al., 1984), while cells in area MST are motion sensitive, some being selective to expansion/compression, rotation or motion shearing (Sakata et al., 1985).

Interestingly, some cells of the inferior parietal lobule respond to both somatic and visual stimuli. Hyvärinen and Poranen (1974) give the example of a cell which was activated when the hand moved downwards but not upwards, and less so if the hand was displaced while the eyes were covered. More recently, Taira et al. (1990) described a population of cells in the same location (IPL) which were sensitive to the orientation in the frontal plane of a target to be reached for. Again, some of these cells were maximally active when the animal was fixating and reaching, and less active if only the visual of the somatic stimulation was present. Such results are consistent with the view that the inferior parietal lobule plays a major role in the coordination of the information between extrapersonal and intrapersonal frames of reference (Andersen, 1987).

4.3 Lesion of the Posterior Parietal Areas in Monkey

Haaxma and Kuypers (1975) showed that a lesion of the posterior parietal cortex in monkeys induced an inability to pick up little pieces of food placed on a board requiring precise orientation of the finger grip. The effect was limited to the hand contralateral to the lesion.

Monkeys with posterior parietal lesions consistently avoid using the limb contralateral to the lesion in visually directed movements, even though it is devoid of any paralysis and may be used for other purposes such as walking or climbing (Faugier-Grimaud et al., 1978; Lamotte and Acuna, 1978). Larger lesions in the posterior parietal lobe produced a misshaping of the hand in addition to the impairment in reaching the target.

Stein (1978) compared the functional role of the inferior and superior parietal lobule by selectively cooling down one or the other region. While cooling of the superior lobule caused clumsiness of the contralateral arm that misreached in all directions, cooling of the inferior lobule produced a reaching impairment of both arms but only in the contralateral visual hemifield (and this independently of gaze direction).

4.4 Clinical Studies of the Parietal Lobe Syndrome

Shortly after Critchley (1953) reviewed the clinical cases of patients with a parietal lobe lesion, Hécaen et al. (1956) reported the behavioral deficits of 17 patients who were treated for parietal lobe epilepsy by careful neurosurgery. From these and later analyses (e.g. Newcombe and Ratcliff, 1989), it appears that the parietal lobe syndrome (*Optic Ataxia*) include a spatial neglect, a spatial disorientation, and some visually guided reaching deficits.

Lesions of the right hemisphere produce a neglect –and, in the extreme cases, denial of the existence– of the left side of the body and of the left half-field of extracorporeal space. There may be a neglect of the toilet and dressing of the contralateral side of the lesion (apraxia for dressing). When somesthetic or visual stimuli are presented to both left and right sides of the patient, the contralateral stimulus is often not perceived (extinction). Haptic examination of the shape and size of objects is also impoverished (astereognosia). When the severity of the lesion induces a left-sided hemiplegia, the patient insistently denies the existence of the paralysis.

Patients with parietal lobe lesions have difficulties in apprehending the spatial layout of a scene, while still being able to identify individual objects. This is shown in their inabilities to reproduce a scene or a complex object by modeling or drawing it (constructional apraxia). Individuals with a right hemisphere lesion usually fail to draw the left side of objects. More often than with left hemisphere lesions, patients with injuries in the right parietal lobe have difficulties to orient themselves and to interact with their environments.

Patients suffering from parietal lobe injury are unable to reach accurately towards visual targets that they can otherwise recognize (Perenin and Vighetto, 1988). In addition, these patients are impaired in positioning their fingers and orienting their hand when reaching to an oriented target. These deficits are not due to a purely motor impairment.

The spatial deficits appear to be more than just an attentional or a memory problem. In the experiment designed by Bisiach and Luzzati (1978), parietal patients were asked to describe from memory the landmarks bordering the Piazza del Duomo in Milan. By imaging that they were either standing on the Piazza facing the cathedral, or looking at the Piazza while standing on the steps of the cathedral, these patients reported only half of the landmarks, namely those located in their ipsilateral "imaged" visual field.

Finally, there appears to be an asymmetry between left and right hemispheres. Unilateral left-sided lesions induce usually only contralateral deficits, while unilateral right-sided lesions can induce either contralateral or bilateral deficits. Right hemisphere lesions in right-handed individuals produce the most severe deficits. On the other hand, left hemisphere lesions are usually more complex to interpret, presumably because of an accompanying affectation of the neural bases for language (*aphasia*).

5 Experiment

5.1 Motivations

The problem we are addressing in this paper is the integration of visual information into the motor program which directs the hand towards an object in extrapersonal space. The interdisciplinary review of the previous section suggests two theoretical frameworks in which this eye-hand coordination might be realized. In a first framework, Jeannerod (1981, 1988) has argued that visual information was separated between extrinsic and intrinsic object properties, and that this separation was conserved within the central nervous system up to the motor output. This framework has received good support, principally from behavioral studies which showed a dichotomy between the transportation of the hand towards the target (extrinsic channel) and the shaping of the hand according to the shape of the object (intrinsic channel). As opposed to this first framework, a second framework can be proposed in which a model of the extrapersonal space is first built from visual information, and a motor program is then formed upon this model. Support for this alternative framework comes from the interpretation of neural data, in which the posterior parietal cortex has the role of integrator of visual and motor information (Andersen, 1987).

In the present section, we describe an experiment in which these two frameworks are confronted. As pointed out in the introductory section, it is difficult to a priori classify the orientation of an object as being part of either the extrinsic or intrinsic channel. With regard to the first framework, this ambiguity can be resolved, that is the outcome of the experiment should tell us whether object orientation is more an intrinsic or extrinsic property. With regard to the second framework, object orientation is just another surface attribute which should be taken into account in order to build an accurate model of the world.

5.2 Methods

Subjects

Three subjects participated in this experiment, between 25 and 32 years old. All subjects were right-handed, and naive to the purposes of the experiment.

Apparatus

The recording device was an OPTOTRAK/3020 (Northern Digital Inc., Waterloo, Canada), which consists of three lens systems mounted within a

1.1 m long bar. This device can compute the three-dimensional positions of up to 24 markers, which consist of small (4mm radius) InfraRed Emitting Diodes (IREDs). The field of view of the OPTOTRAK is about 34 deg. by 24 deg., with a range of about 6 m. One important constraint of this apparatus is that a marker should be in view of the three cameras to be informative. The error for each marker's position was estimated to be about 1 mm over a 50 cm trajectory (standard deviation less than 0.5 mm). Seven markers were placed on the arm of the subjects in the following arrangement: two markers on the forearm, two on the dorsal part of the hand, and the remaining three at the tips of the thumb, index, and middle fingers. Except for the two markers on the forearm, the markers were fixed on a light-weight cotton glove. The marker positions were updated at 200 Hz.

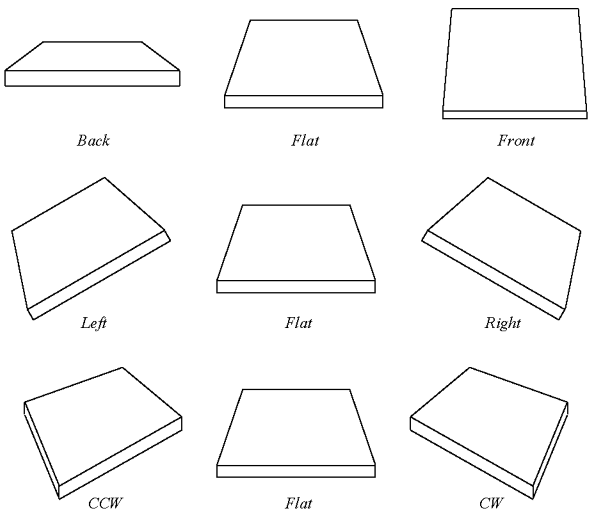


Figure 1: The seven conditions used to orient the object. The baseline condition (*Flat*) was reproduced twice in the middle column to show more clearly the effect of slanting the object away and toward the subject (*Back* and *Front*), tilting the object on the *Left* or *Right*, and rotating the object *Counterclockwise* or *Clockwise*.

Stimulus

The stimulus consisted of a rectangular polyhedron, of size $70 \times 50 \times 8mm$. This object was made of black PVC (polyvinyl chloride), and uniformly textured with small white dots. The object rested on a small spherical joint enabling any orientation within a cone of semi-angle 45 deg. The object and spherical joint were placed on a table of size 1 by 0.8 m. Changing the orientation of the object did not change the position of its center of gravity. Seven orientations were selected, as shown schematically in Figure 1. First a baseline condition, called *flat*, where the object laid parallel to the table-top, its long edge parallel to the line passing through the shoulders of the subject. The six other orientations were rotations by plus or minus 20 deg of the object from the baseline condition: the *front* and *back* conditions were slant orientations moving the object toward or away the subject; the *left* and *right* conditions were tilt orientations; finally, the *clockwise* and *counterclockwise* conditions were self-rotations of the object in the plane parallel to the table-top.

Design

Subjects were asked to grasp the object placed in front of them, and to lift it up by about 20 cm in a direction orthogonal to the orientation of the object. The object was located in the mid-sagittal plane of the subjects, 60 cm in front and 50 cm below their eyes. Subjects started each trial with their hand resting on a half sphere, whose radius was about 10 cm. This half sphere was itself fixed on the table, 35 cm in front and 35 cm on the right of the object to be grasped. The actual distance to be traveled by the hand to reach the object was therefore about 50 cm.

Subjects were instructed to pick up the object always with the same precision grip (Napier, 1956). This grip consisted in the thumb placed on the left edge of the object, the index and middle fingers on the far long edge, and the remaining two fingers on the close right corner in order to stabilize the grip. This positioning of the fingers was quickly learned by the subjects. There were 10 practice trials before the actual experiment started, so that, together with the time during the calibration of the system, the subjects were feeling comfortable with the overall apparatus.

The subject was instructed to close his/her eyes before each trial to allow the experimenter to adjust the orientation of the object. Three computer-generated sound signals were then generated sequentially. The first signal indicated that the subject could open his/her eyes, and the second signal (2 seconds later) that he/she could start the reach. In order to obtain comparable grasping strategies between subjects and between trials, the duration of the reach was chosen to be 1 second. The purpose of the third signal (produced 1 second after the second one) was to inform the subjects of this temporal constraint.

There were four repeated trials per object orientation. The total twenty-eight trials were randomized and run in a single session which lasted about 45 minutes.

It is important to note that the motor program underlying the reaching and grasping of the object is identical for all the object orientations. In other words, the joint angles and torques vary in degree but not in nature between experimental conditions. In this respect, our study differs from the one by Stelmach et al. (1994) who explored two basic configurations of the forearm.

5.3 Results and Discussion

To analyze the results of this experiment, one has to be aware of the dimensionality of our task. Since for each trial (about 1 second long), we recorded the 3-D positions of 7 markers at 200 Hz, each trial generates by itself $200 \times 7 \times 3 = 4200$ data points. With 7 experimental conditions, 4 repeated trials per condition, and 3 subjects, the whole experiment consisted of more than a third of a million data points. In the following, we suggest a set of characteristic variables to summarize the experiment. This set consists of the reach duration and length, the times of occurrence of the hand peak velocity and of the hand maximum aperture, this hand maximum aperture, the orientation of the tips of the finger just before contact with the object, the angles of the joints participating in the orientation of the hand just before contact with the object, and finally, a piece-wise approximation of the kinematics of these joints.

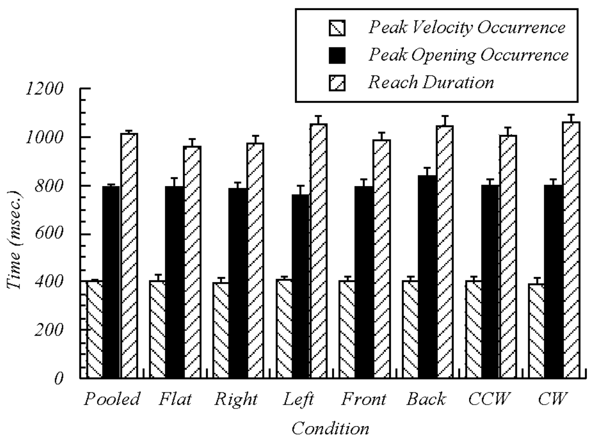


Figure 2: Mean reach durations for the seven different conditions, and pooled over these seven conditions, and mean time occurrences for the peak of the wrist translation velocity and for the peak aperture of the hand.

Reach Duration

The transportation of the hand to the vicinity of the object can be examined by recording the instantaneous positions of the wrist. The center of rotation of the wrist can in turn be computed from the four markers placed on the forearm and on the back of the hand. The start and end times of the reach can be obtained from the trough of the velocity of the wrist transportation (cf. infra Figure 4a). The reach duration (difference between end and start times) was then computed from the three subjects across the four repeated trials (6 trials were removed from this analysis, because of occlusion of at least one marker at the end of the trajectory). The mean reach duration was found to be 1011 milliseconds (standard error of the mean 14 msec.), which is close to the one second constraint imposed on the subjects (Figure 2). There was no significant differences of reach duration across orientation conditions ($F(6,71) = 1.278$, $p = 0.278$).

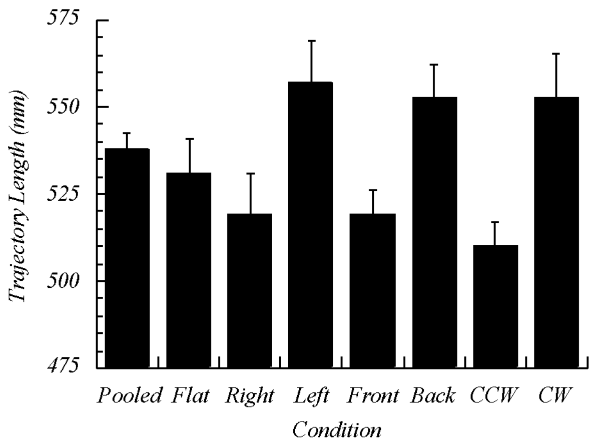


Figure 3: Trajectory lengths for the seven conditions, and pooled over these conditions.

Trajectory Length

It is here important to note that the positioning of the wrist for grasping the object was dependent on the object orientation (Figure 3). For instance, the distance traveled by the hand to approach the object when it was tilted to the right was smaller than when the object was tilted to the left. This effect of object orientation over trajectory length was significant: $F(6,50) = 3.212$, $p = 0.010$ (27 trajectories had to be rejected from the analysis, because at least one marker was momentarily occluded). Therefore, although the object was rotated about its center of gravity, so that the object can be said to be always at the same location, the length of the hand trajectory was necessarily different from one object's orientation to the other.

When we compare this finding with the result that reach duration was independent of object orientation (previous sub-section), we can conclude that the motor programming of the hand incorporated the fact that the hand had to travel a longer distance depending on the orientation of the object. Within the framework of Jeannerod (1981), this finding suggests that *object orientation is part of the extrinsic system*, for the orientation information was used in the timing of the transportation component of the reach.

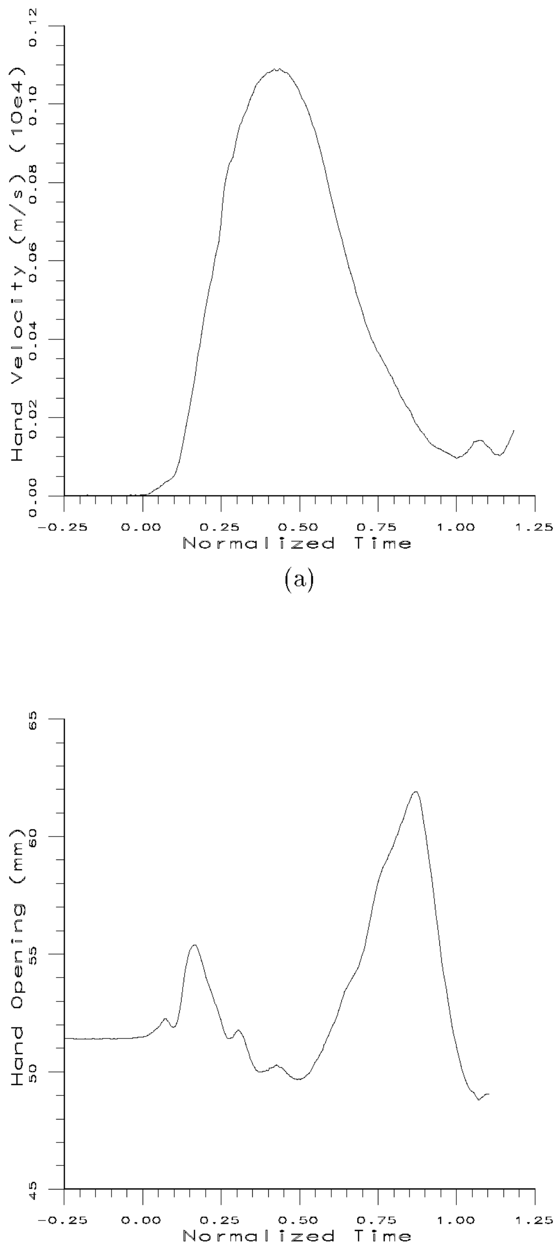
Hand Velocity

Figure 4a shows the velocity of the hand transportation, computed from the variation of successive wrist positions. The hand velocity has a characteristic bell shape, with a deceleration phase longer than the acceleration phase, as found in previous measurements (Jeannerod, 1984). It has been argued that the acceleration phase is ballistic in nature, while, in contrast, visual and proprioceptive information are used to correct the reach trajectory only during the deceleration phase (Jeannerod, 1981; Jeannerod & Biguer, 1982).

Figure 2 shows the time occurrence of the peak of the hand velocity across conditions, which occurred at about 40% of the reach duration. The object orientation did not have any effect on the time occurrence of this peak transportation velocity: $F(6, 71) = 0.776$, $p = 0.591$ (statistics based on data normalized to the reach duration). We shall therefore conclude that object orientation did not produce any measurable change on the velocity profile of the hand transportation.

Hand Opening

The hand opening can be evaluated either from the distance between the thumb and index tips, or by the area of the triangle formed by the thumb, index and middle finger tips. These two measures gave similar results, so we report here only the finger distance for easier comparison with earlier studies. Intuitively, the closure of the hand should be tightly synchronized with the final approach of the object, for an early closure will miss the object while a late closure might dangerously displace the object before seizing it. The analysis of the fingers motion reveals that the hand "pre-shapes" in anticipation of the actual grasp (Jeannerod, 1984). We shall take the temporal occurrence of the maximum aperture of the hand to indicate the end of



(a)

(b)

Figure 4: (a) Instantaneous velocity of the hand for a single trial. The temporal axis has been normalized to the duration of the reach (0 for the start, 1 for the end). (b) Instantaneous hand opening for a single trial as a function of normalized time.

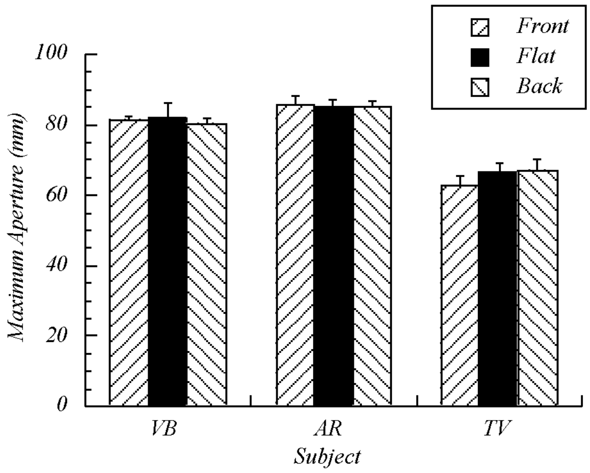


Figure 5: The maximum aperture of the hand during the reach for three subjects, under three of the seven experimental conditions.

the preshaping stage (cf. Figure 4b).

Figure 2 shows the time occurrence of the peak opening of the hand, which occurred at about 80% of the reach duration. The object orientation had an effect on the time occurrence of this peak hand opening: $F(6,71) = 2.761$, $p = 0.018$ (statistics based on data normalized to the reach duration). We shall therefore conclude that object orientation influences the delay of closure of the hand on the object.

It is of interest to look at the peak aperture of the hand itself (i.e. the distance between the markers on the thumb and index fingers). Indeed, Jeannerod (1981) showed that this peak aperture was correlated with the size of the object. It is important to note that, although the object had always the same physical size, the orientation of the object affected its apparent size as projected on the retina. This foreshortening effect is mostly noticeable between the *Flat*, *Back* and *Front* conditions (cf. Figure 1).

Figure 5 shows the peak aperture of the hand for these three conditions. The peak aperture was constant within subject and across conditions (the differences between subjects can be due to different hand sizes and different location of the markers on the fingers). Together with the result on the time occurrence of the peak aperture, and within the framework of Jeannerod (1981), this finding suggests that *object orientation is part of the intrinsic system*, for the orientation information was used in the grasping component of the reach. This result is exactly the opposite to the one reached from the trajectory length analysis.

Orientation of the Finger-Tip-Plane

In a precision grip such as the one used in this experiment, the grip forces are applied perpendicularly to the axes of the finger bones (Westling and Johansson, 1984). In order to achieve a stable grasp of our planar object, the fingers should therefore be oriented perpendicularly to the plane of the object. We can thus consider the position of the finger tips as an index of the accuracy with which the subjects perceived the object's orientation. It is important to note that there is still some freedom in the exact positioning of the object inside the hand. Indeed, while the very tips of the fingers are usually used to pick up a fragile object, a more powerful grip can be achieved with the fingers englobing the object (Napier, 1956). Nevertheless, the orientation constraint will not be affected by where along the fingers the object is being grasped.

We have therefore computed the orientation of the plane passing through the three markers placed at the finger tips, which we will call the *finger-tip-plane*. Only the slant and tilt of the finger-tip-plane can be accurately computed in this way (the self-rotation of the plane was left unknown). Since the markers were arbitrarily positioned along the fingers, the absolute orientation of the finger-tip-plane is only an approximation of the object orientation. We can avoid this problem by computing the orientation of the finger-tip-plane relative to the baseline provided by the flat experimental condition.

Figure 6a shows the orientation of the finger-tip-plane pooled over the three subjects. As expected, the right and left conditions are negatively and positively tilted relative to the flat condition. Similarly, the front and back conditions are negatively and positively slanted relative to the flat condition. An interesting result is obtained when we compare the amount of tilt and slant of the finger plane with the 20 deg variations from the flat conditions. A significant underestimate of the slant for the front and back conditions is found. In contrast, the tilt is correctly apprehended for the right and left conditions.

It is of interest to compare these results obtained for grasping with a less active task. For this purpose, we ran a supplementary experiment with the same subjects, in a subsequent session. In this experiment, the task of the subject was not to grasp the target object, but instead to match its orientation with the help of another hand-held object. The target object could be oriented either in the

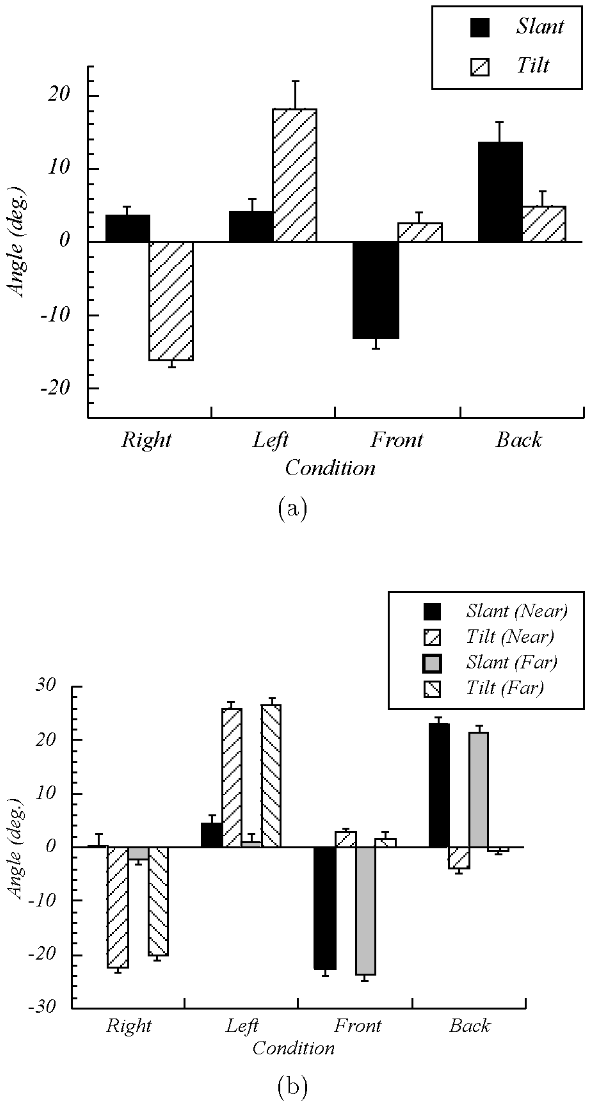


Figure 6: Slant and tilt of the finger-tip-plane, for four conditions (*Right*, *Left*, *Front*, and *Back*) relative to the mean slant and tilt of the *Flat* condition. (a) Orientation of the finger-tip-plane in the reaching experiment just before the hand touches the object. (b) Orientation of the finger-tip-plane in the supplementary experiment where subjects had to match the target object orientation with another hand-held object.

flat, right, left, front or back condition. The object that the subjects had in their hand was similar to the target object, and was held with the precision grip described in the method section above. The hand was slightly elevated relative to the table, and located either 35 cm in front and 35 cm on the right of the target object (a condition *near* the subject which corresponds to the previous "starting position"), or simply 35 cm on the right of the object (a condition *far* from the subject). Four repeated trials were performed for these two possible locations of the hand. The subject could see both the target and his or her hand, and no time limit was imposed.

As before, we computed the plane passing through the thumb, index and middle finger tips. Figure 6b shows the slant and tilt of this finger-tip-plane, relative to the flat condition. In this supplementary experiment, the slant was not underestimated. On the contrary, both the slant and tilt variations were exaggerated. In addition, no difference was found between the two possible hand locations.

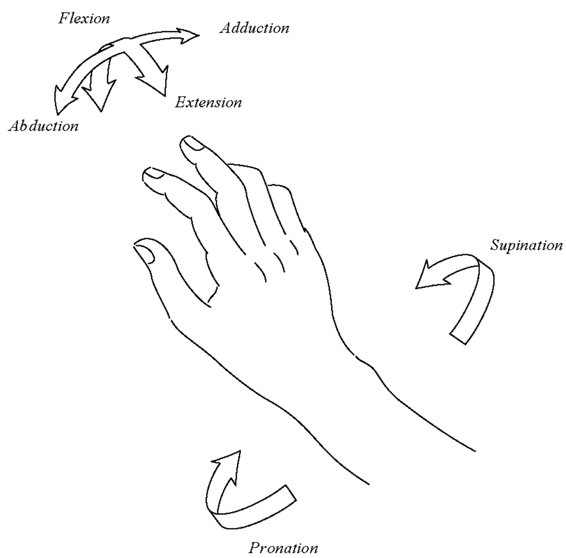


Figure 7: The three degrees of freedom of the wrist and radioulnar joints.

Hand Orientation

At this point, it is worth recalling the three degrees of freedom at the wrist joint (Figure 7). On one hand, the relative motion of the forearm bones (radius and ulna) produces a pronation of the hand if the palm is turned downwards, and a supination if the palm is turned upwards. On the other hand, the complex shapes and arrangement of the

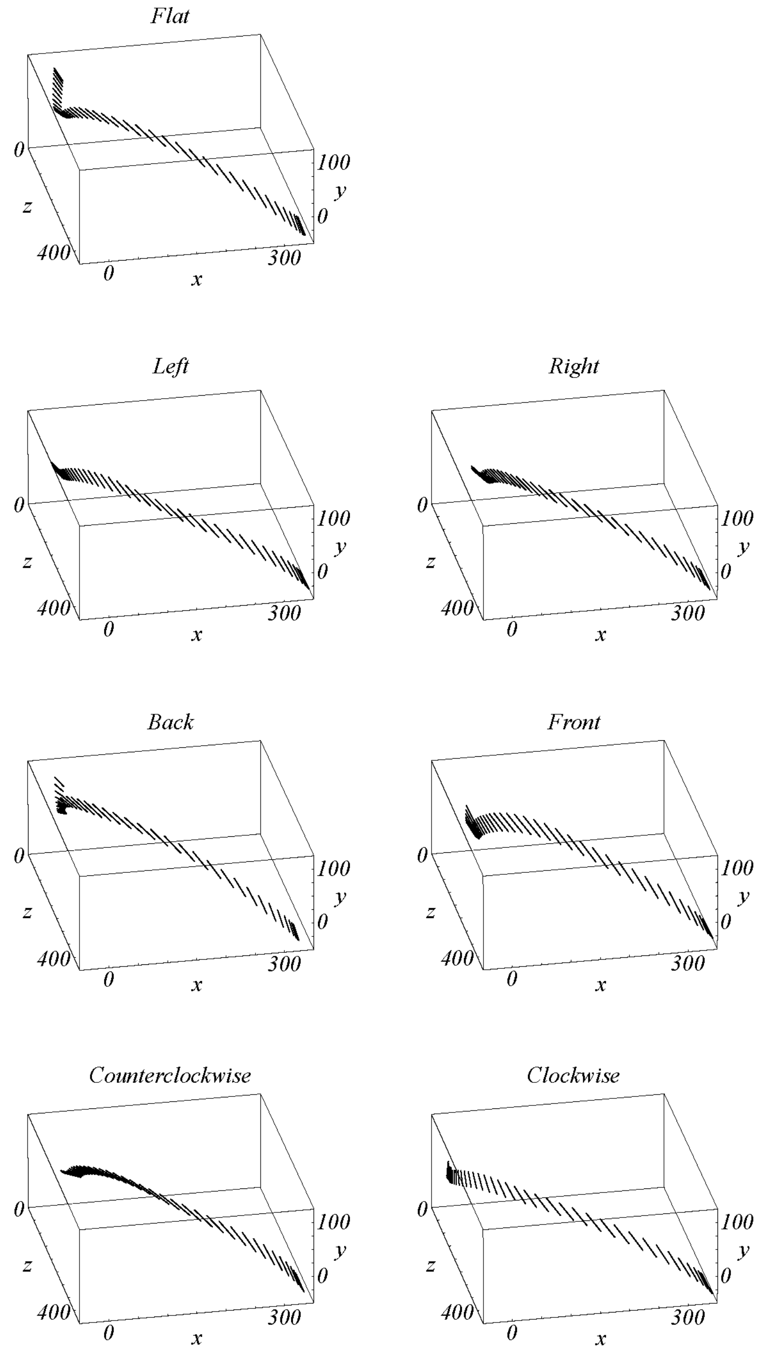


Figure 8: Progressive orientation of the hand towards the orientation of the object, for the seven experimental conditions. See text for details.

eight small bones of the wrist (scaphoid, lunate, triquetrum, pisiform, trapezium, trapezoid, capitate and hamate) provide the remaining two degrees of freedom for the hand orientation (Berger and Garcia-Elias, 1991). The first degree of freedom can be described as an extension or flexion of the wrist, which produces an elevation or a depression of the hand, respectively. The second degree of freedom can be described as an abduction (resp. adduction) of the wrist, which corresponds to a movement of the hand away from (resp. towards) the body midline, when the arm is resting along the body, the palm facing forward.

Figure 8 shows the evolution of the orientation of the hand as it approaches the object. Each plot shows the orientation of the hand every 25 milliseconds. This orientation is symbolized by a segment whose tail is located at the center of rotation of the wrist (the tail is at the bottom of the segment). The origin of each plot is the center of the object to be grasped, and the xz-plane the orientation of the table, with x pointing to the right of the subject. The units are distances in millimeters.

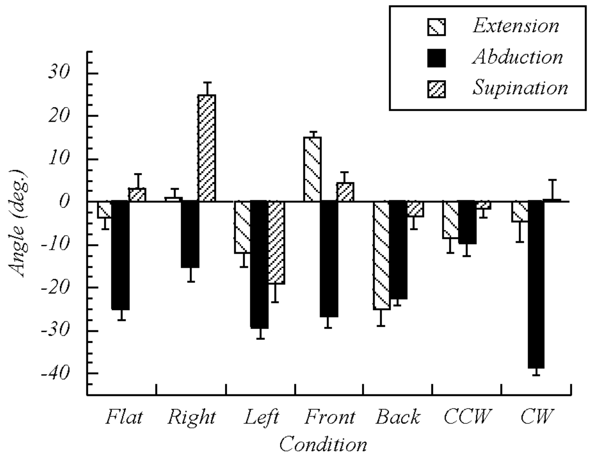


Figure 9: End orientation of the hand for the seven conditions, expressed in terms of extension, abduction, and supination angles.

From these plots, one can see that the different object orientations induce different wrist rotation patterns. In particular, a tilt of the object either to the left or to the right produces a pronation or a supination of the forearm; a slant of the object either backward or forward produces a flexion or an extension of the hand; and a rotation of the object either clockwise or counterclockwise produces an adduction or abduction of the hand. This differential behavior can be appreciated by looking at the orientation of the hand just before contact with the object (Figure 9). We see that indeed, the largest difference between the left and right orientations is along the supination dimension, between the backward and forward conditions along the extension dimension, and between the clockwise and counterclockwise conditions along the abduction dimension.

It is important to remark that the mapping between object orientation in the world coordinate system on one hand, and hand orientation in the radioulnar/wrist joint coordinate system on the other hand, is not one-to-one. In particular, a same object orientation will require different hand orientations depending of the position of the object relative to the body. Furthermore, the relative position of the fingers allow a limited final "re-orientation" of the hand to securely grasp the object. It is therefore quite remarkable to find such a consistency between object orientation and radioulnar/wrist angles.

Hand Orientation Kinematics

As briefly outlined above, the three degrees of freedom at the wrist level can be decomposed into one degree at the radioulnar joint and two at the wrist joint. The degree of freedom at the radioulnar joint can be accounted for by one scalar, for instance the supination angle. The two degrees of freedom at the wrist joint can then be accounted for by two scalars, for instance the extension and abduction angles. It is important to realize that this orthogonal decomposition into extension and abduction angles is quite arbitrary, since neither the wrist bone surfaces nor the wrist muscles provide any obvious ground to describe these two degrees of freedom. In our kinematics analysis of hand orientation, we shall therefore consider the temporal variation of the supination angle, and the combined temporal variation of the extension and abduction angles.

Figure 10 shows the temporal variation of the supination angle, while Figure 11 shows the temporal variation of the combined extension and abduction angles. We note that these variations tend to be fairly straight on some temporal intervals, which signifies that the joint angles are discretely re-oriented during the hand movement. We thus fit piece-wise linear approximations to the supination variation, and independently to the extension/abduction variation.

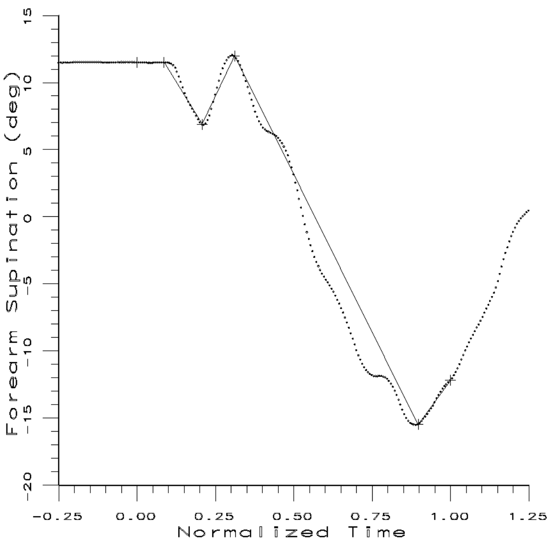


Figure 10: Temporal variation of the supination angle for a single trial. The time axis was normalized to the reach duration. Each dot represents one computed angle every 5 milliseconds. Superimposed on the graph is the piece-wise linear approximation of the supination variation for this trial.

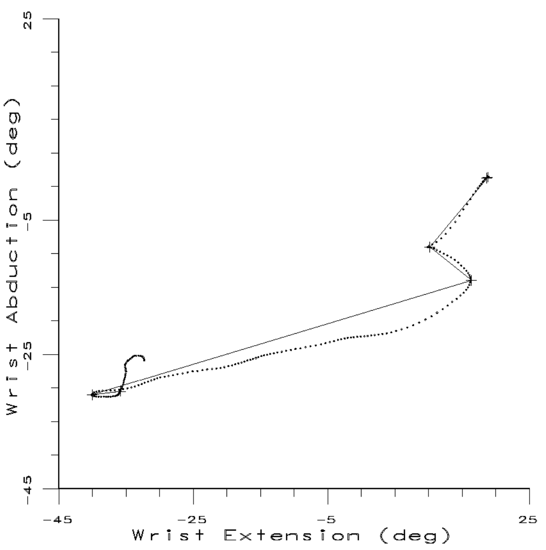


Figure 11: Temporal variation of the extension and abduction angles, for the same trial as in the previous figure. The movement starts at the top right of the plot. Each dot represents the two computed angles every 5 milliseconds. Superimposed on the graph is the piece-wise linear approximation of the extension/abduction variation for this trial.

Linearization of the Hand Orientation Kinematics

Following the idea that the hand re-orients itself in a discrete manner, it is natural to expect that the hand will slow down before being directed in another direction. The boundaries of the linear segments approximating the angle variations should therefore correspond to the troughs of the velocities of this angle. We have thus collected the local minima of the hand velocity along the supination dimension, and along the extension/abduction dimension. In order to decrease the effects of muscle tremor and measurement errors, which were magnified by differentiation and referential transformation, the angle amplitudes were smoothed by a discrete-time low-pass filter of cutoff frequency 10 Hertz. Two successive linear segments were then merged if the angle speed difference between the two segment did not exceed 40 degrees per second. These values were chosen on pragmatic grounds, after screening all trials individually. The piece-wise linear approximations so computed for the trial displayed in Figures 10 and 11 is traced over the plots.

To estimate a goodness of fit for the piece-wise linear approximation, we need a linearity index (Mathew and Cook, 1990). For this purpose, we computed the *covered angle* as the incremental angle variation within one linear segment, and the *straight angle* as the distance in angle space between the end and the beginning of the segment. The *linearity index* is then just the ratio of the straight angle to the covered angle; it varies between 0 (highly sinuous segment) and 1 (perfectly straight segment). Over all segments per trial and all trials per subject, the average linearity index reached 0.891 for the supination angle (standard deviation 0.217), and 0.907 for the extension/abduction angle (standard deviation 0.112). It should be noted that higher linearity indices could have been obtained had we segmented each reach into a larger number of segments. In our analysis, the average number of segments per reach was 3.98 for the supination angle (standard deviation 1.76), and 5.54 for the extension/abduction angle (standard deviation 1.51).

The piece-wise decompositions of the supination and extension/abduction angle variations are convenient entities to study the hand orientation kinematics. We can look at the regularity of the time occurrence of the linear segments. Figure 12 shows the distribution of the boundaries of these linear segments for both the supination and the extension angles. We note a trough in the distributions,

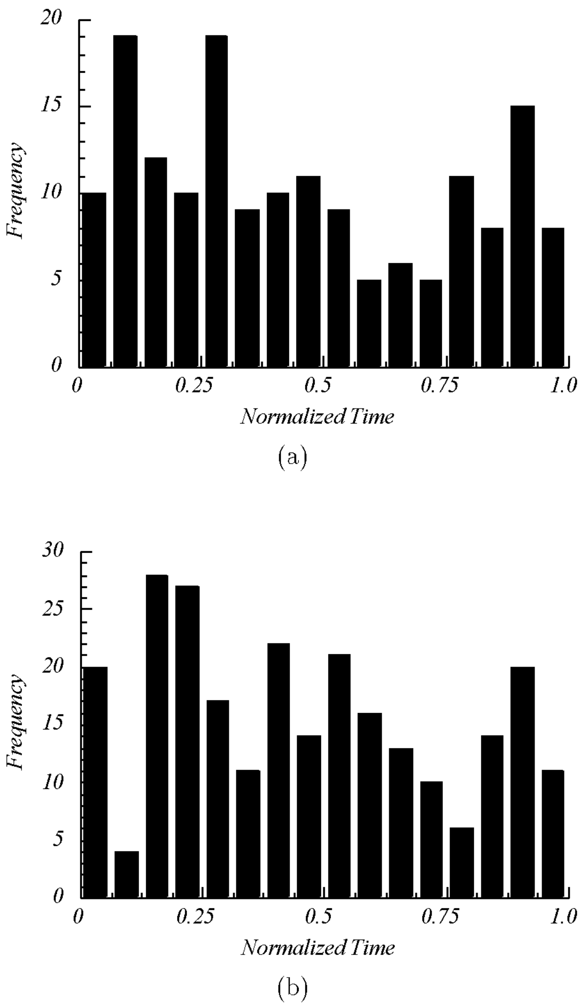


Figure 12: Distribution of the boundaries of the piece-wise linear approximation of the supination angle (a), and the extension/abduction angle (b). The time occurrence of these boundaries are plotted in bins of normalized reach time, origin and end of the reach excluded.

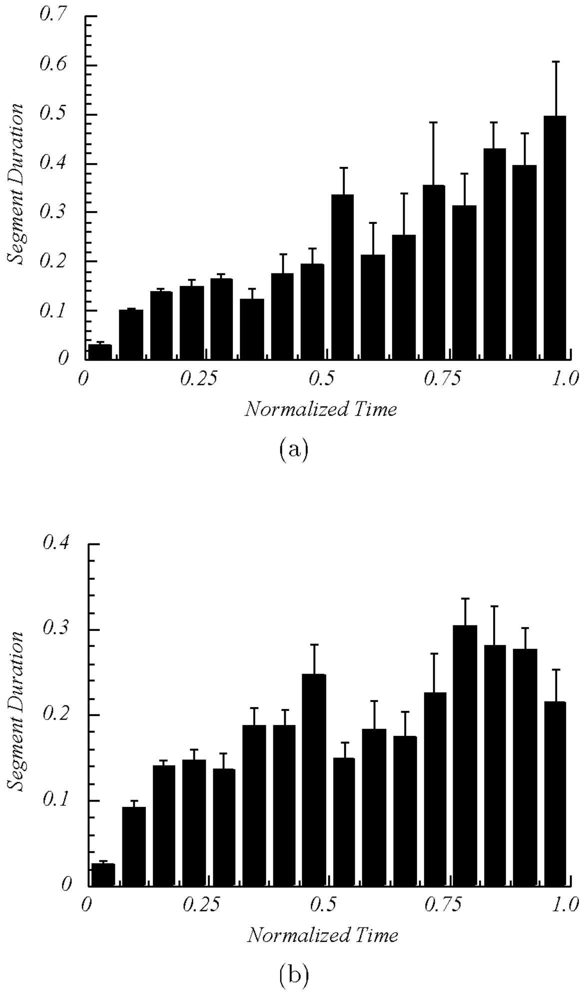


Figure 13: Durations (in normalized reach time) of the segments of the piece-wise approximations of the supination angle (a), and of the extension/abduction angle (b). The durations are plotted at the end boundary of the segments.

located at about two thirds of the reach duration for the supination, and at about three quarters of the reach duration for the extension/abduction. This trough can be interpreted as a long and smooth rotation of the hand until the time the hand touches the object. In other words, the final orientation of the hand seems to be programmed early in the reach.

In order to justify this interpretation, we computed the duration spent on each segment (Figure 13). We note an increase of segment duration as the hand approaches the object. An examination of each trial revealed that, indeed, the longest

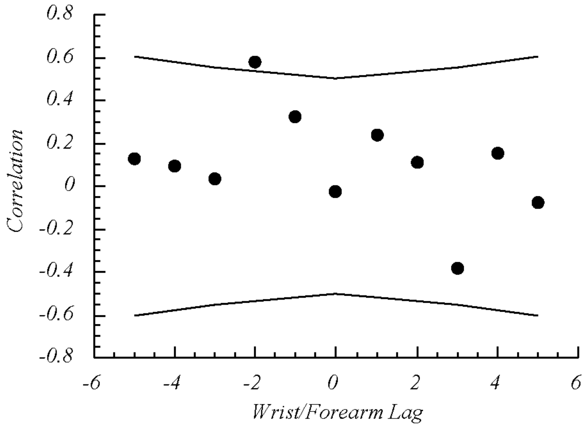


Figure 14: Cross-correlation of the time-occurrence distributions of the extension/abduction angle and supination angle. The two symmetric curves show the significance boundaries at two standard errors of the correlation estimate. We note a significant cross-correlation for a negative bin lag of 2, the size of a temporal bin being 1/16th of the reach duration.

segment was almost always the last one, or the next to last one in which case the last one was less than 100 milliseconds long. If the segment boundaries are interpreted as the results of sensory feedback (visual or kinesthetic) on the motor control, this result suggests *very little feedback control on the second half of the reach*, and, given the final precision, a very robust motor program.

Joints Coordination

Finally, we have been interested in knowing whether the radioulnar and the wrist joints were synchronized. To investigate this issue, we can compute the cross-correlation of the two distributions of segment boundaries displayed in Figure 12. This cross-correlation, which takes into account the fact that more segments were found for the radioulnar joint than for wrist, is very weak ($R = -0.023$).

Even though the radioulnar and the wrist joints are not found to be synchronized, their motion can still be governed by a single command. It is for instance not unreasonable to expect a temporal time lag of more distal segments, due in particular to different inertial moments (Lacquaniti and Soechting, 1982). We can therefore complete our cross-correlation computation with the same distributions, but now temporally shifted to one another (Figure 14). We find a large positive correlation for a negative temporal bin lag of 2 ($R = 0.58$). Since each temporal bin was one sixteenth of the reach duration, which itself was on the average close to one second, we conclude that *the wrist motion was correlated with the forearm motion which occurred about 100 milliseconds before.*

6 Summary and Conclusions

In this paper, we have discussed how visual information might be used to guide the hand, while reaching for a distant object at one of several possible orientations. We summarize and discuss here the key findings of our experiment.

While the object was always located at the same position in space, the orientation of the object affected the position of the wrist just before grasping, and consequently, the length of the trajectory traveled by the wrist. Since, on the other hand, no difference was found in the total time to reach the object (as imposed by the experimenter), we concluded that the orientation of the object was appropriately taken into account during the programming of the transport of the hand.

From the analysis of the hand opening, we found that the peak aperture of the hand was constant across different object orientations. Since we know from earlier studies that peak aperture is a function of the size of an object, and that the apparent size of an object is function of the object's orientation, we concluded that the orientation of the object was also appropriately taken into account during the programming of the hand shaping.

Since object orientation seems to belong both to the extrinsic (hand transport) and intrinsic (hand shape) visuo-motor channels, our experiment seems to refute the framework proposed by Jeannerod (1981). It should be said, however, that we considered an extreme view of this framework, in which extrinsic and intrinsic channels are completely independent processing pathways. Even for the original dichotomy between object distance and object size from which this framework takes its roots, minimal cross talk between the channels is necessary because perceived distance (an extrinsic object property) is inversely proportional to perceived object's size (an intrinsic property). Nevertheless, it seems that our data are more parsimoniously interpreted in the light of an alternative framework in which a model of the world is fully constructed before a motor program is built.

When considering the orientation of the plane passing through the tip of the thumb, index, and middle fingers (the finger-tip-plane), we found an underestimate of the slant of this plane relative to the orientation of the object. However, when the same subjects had to match the orientation of a separate object held at a distance from the target object, no such slant underestimation was obtained. Two possible hypotheses could explain these results: either the reaching duration was too short for the subject to worry about the precise object orientation (no time limit was imposed in the supplementary experiment), or the subject was not able not estimate correctly the orientation of his imaginary finger-tip-plane.

Finally, we analyzed the kinematics of the joints participating in the orientation of the hand. This analysis started with a linearization of the wrist and radio-ulnar joints kinematics into four or five segments. From these piece-wise linear fits, and in particular the length of the last segment of these fits, we concluded that the hand orientation was programmed early during the reach, in a very robust manner. We then looked at the synchronization of the joint motions at the wrist and radio-ulnar levels, and found a delay of the wrist of about 100 milliseconds.

The ensemble of our results seems to fit the framework under which a complete model of the world is first built from visual information, and only then a motor command is generated. In addition, it seems that this mechanism is mainly feedforward. Evidence for this latter claim comes from the analysis of the wrist and radioulnar kinematics, and is also consistent with one interpretation of our result on the finger-tip-plane (namely that the reach duration was too short to enable a recalibration of the hand orientation). This framework is also consistent with recent neurophysiological findings (reviewed earlier in this paper) which suggest that an extrapersonal space is represented within the posterior parietal cortex. The most challenging part of such a framework is naturally the coordination between intrapersonal and extrapersonal frames of reference, and the neural mechanisms underlying this coordination.

7 References

Albus, J. S. (1975a). A new approach to manipulator control: the Cerebellar Model Articulation Controller (CMAC). *Journal of Dynamic Systems, Measurement and Control, 97*, 220-227.

Albus, J. S. (1975b). Data storage in the Cerebellar Model Articulation Controller (CMAC). *Journal of Dynamic Systems, Measurement and Control, 97*, 228-233.

Andersen, R. A. (1987). The role of the inferior parietal lobule in spatial perception and visuomotor integration. In F. Plum, V. B. Mountcastle, & S. R. Geiger (Eds.), *The Handbook of Physiology, Section 1: The Nervous System Volume V, Higher Functions of the Brain Part 2* (pp. 483-518). Bethesda, MD: American Physiological Society.

Andersen, R. A., Essick, G. K., & Siegel, R. M. (1985). The encoding of spatial location by posterior parietal neurons. *Science, 230*, 456-458.

Aslin, R. N., & Salapatek, P. (1975). Saccadic localization of peripheral targets by the very young human infant. *Perception and Psychophysics, 17*, 293-302.

Berger, R. A. & Garcia-Elias, M. (1991). General anatomy of the wrist. In K.-N. An, R. A. Berger & W. P. Cooney III (Eds.), *Biomechanics of the Wrist Joint* (pp. 1-22). New York, NY: Springer-Verlag.

Bernstein, N. (1967). *The Co-ordination and Regulation of Movements.* Oxford: Pergamon Press.

Bisiach, E., & Luzzatti, C. (1978). Unilateral neglect of representational space. *Cortex, 14*, 129-133.

Bonin, G. von, & Bailey, P. (1947). *The Neocortex of Macaca mulatta.* Urbana: University of Illinois Press.

Bower, T. G. R. (1972). Object perception in infants. *Perception, 1*, 15-30.

Brodmann, K. (1905). Beiträge zur histologischen Lokalisation der Grosshirnrinde. Dritte Mitteilung: die Rindenfelder der niederen Affen. *J. Psychol. Neurol., 4*, 177-226.

Brodmann, K. (1907). Beiträge zur histologischen Lokalisation der Grosshirnrinde. Sechste Mitteilung: die Cortexgliederung des Menschen. *J. Psychol. Neurol., 10*, 231-246.

Bruner, J. S., & Koslowski, B. (1972). Visually pre-adapted constituents of manipulatory action. *Perception, 1*, 3-14.

Critchley, M. (1953). The Parietal Lobes. New York: Hafner.

DiFranco, D., Muir, D. W., & Dodwell, D. C. (1978). Reaching in young infants. *Perception, 7*, 385-392.

Essock, E. A. & Siqueland, E. R. (1981). Discrimination of orientation by human infants. *Perception, 10*, 245-253.

Faugier-Grimaud, S., Frenois, C. & Stein, D. G. (1978). Effects of posterior parietal lesions on visually guided behavior in monkeys. *Neuropsychologia, 16*, 151-168.

Georgopoulos, A. P. (1986). On reaching. *Annual Review of Neuroscience, 9*, 147-170.

Georgopoulos, A. P., Kalaska, J. F., Caminiti, R. & Massey, J. T. (1982). On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. *Journal of Neuroscience, 2*, 1527-1537.

Georgopoulos, A. P., Kettner, R. E., & Schwartz, A. B. (1988). Primate motor cortex and free arm movements to visual targets in three-dimensional space. II. Coding of the direction by a neuronal population. *Journal of Neuroscience, 8*, 2928-2937.

Gordon, R. F. & Yonas, A. (1976). A sensitivity to binocular depth information in infants. *Journal of Experimental Psychology, 22*, 413-422.

Haaxma, H., & Kuypers, H. G. J. M. (1975). Intrahemispheric cortical connections and visual guidance of hand and finger movements in the rhesus monkey. *Brain, 98*, 239-260.

Halverson, H. M. (1931). An experimental study of prehension in infants by means of systematic cinema records. *Genetic Psychology Monograph, 10*, 107-286.

Hécaen, H., Penfield, W., Bertrand, C., & Malmo, R. (1956). The syndrome of apractonosia due to lesions of the minor cerebral hemisphere. *A. M. A. Archives of Neurology and Psychiatry, 75*, 400-434.

Hildreth, E. C., & Hollerbach, J. M. (1987). Artificial intelligence: Computational approaches to vision and motor control. In J. M. Brookhart & V. B. Mountcastle (Eds.), *Handbook of Physiology, Sect. 1, Vol. 5, Part 2* (pp. 605-642). Bethesda, MD: American Physiological Society.

Hofsten, C. von (1982). Eye-hand coordination in newborns. *Development Psychology, 18*, 450-461.

Hofsten, C. von, & Fazel-Zandy, S. (1984). Development of visually-guided hand orientation in reaching. *Journal of Experimental Child Psychology, 38*, 208-219.

Hofsten, C. von, & Rönnqvist, L. (1988). Preparation for grasping an object: A developmental study. *Journal of Experimental Psychology: Human Perception and Performance 14*, 610-621.

Hollerbach, J. M. (1980). A recursion Lagrangian formulation of manipulator dynamics and a comparative study of dynamics formulation complexity. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-10*, 730-736.

Hollerbach, J. M. (1985). Optimum kinematic design for a seven degree of freedom manipulator. In H. Hanafusa & H. Inoue (Eds.), *Robotics Research: The Second International Symposium* (pp. 215-222). Cambridge, MA: MIT Press.

Hollerbach, J. M., & Flash, T. (1982). Dynamic interactions between limb segments during planar arm movement. *Biological Cybernetics, 44*, 67-77.

Hyvärinen, J. (1981). Regional distribution of functions in parietal association area 7 of monkey. *Brain Research, 206*, 287-303.

Hyvärinen, J. (1982a). *The Parietal Cortex of Monkey and Man.* Berlin: Springer-Verlag.

Hyvärinen, J. (1982b). The posterior parietal lobe of the primate brain. *Physiological Reviews, 62*, 1060-1129.

Hyvärinen, J. & Poranen, A. (1974). Function of the parietal associative area 7 as revealed from cellular discharges in alert monkeys. *Brain, 97*, 673-692.

Jeannerod, M. (1981). Intersegmental coordination during reaching at natural visual objects. In J. Long, & A. Baddeley (Eds.), *Attention and Performance, IX* (pp. 153-168). Hillsdale, NJ: Erlbaum.

Jeannerod, M. (1984). The timing of natural prehension movements. *Journal of Motor Behavior, 16*(3), 235-254.

Jeannerod, M. (1988). *The Neural and Behavioral Organization of Goal-Directed Movements.* Oxford: Clarendon Press.

Jeannerod, M., & Biguer, B. (1982). Visuomotor mechanisms in reaching within extrapersonal space. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Advances in the Analysis of Visual Behavior* (pp. 387-409). Cambridge, MA: MIT Press.

Johnson, P. B. (1992). Toward an understanding of the cerebral cortex and reaching movements: a review of recent approaches. In R. Caminiti, P. B. Johnson and Y. Burnod (Eds.), *Control of Arm Movement in Space* (pp. 199-261). Berlin: Springer-Verlag.

Lacquaniti, F. & Soechting, J. (1982). Coordination of arm and wrist motion during a reaching task. *Journal of Neuroscience, 2*, 399-408.

Lamotte, R. H. & Acuna, C. (1978). Defects in accuracy of reaching after removal of posterior parietal cortex in monkeys. *Brain Research, 139*, 309-326.

Lockman, J. J., Ashmead, D. H., & Bushnell, E. W. (1984). The development of anticipatory hand orientation during infancy. *Journal of Experimental Child Psychology, 37*, 176-186.

Mamassian, P. (1995). *Surface Representations for Visual Perception and Action*, Unpublished Doctoral Dissertation, University of Minnesota, Minneapolis.

Mathew, A., & Cook, M. (1990). The control of reaching movements by young infants. *Child*

Development, *61*, 1238-1257.

Morasso, P. (1981). Spatial control of arm movements. *Experimental Brain Research*, *42*, 223-227.

Mountcastle, V.B., Lynch, J.C., Georgopoulos, A., Sakata, H., & Acuna, C. (1975). Posterior parietal association cortex of the monkey: command functions for operations within extra-personal space. *J. Neurophysiol. 38*, 871-908.

Napier, J. R. (1956). The prehensile movements of the human hand. *The Journal of Bone and Joint Surgery*, *38*(4), 902-913.

Newcombe, F. & Ratcliff, G. (1989). Disorders of visuospatial analysis. In F. Boller & J. Grafman (Eds.), *Handbook of Neuropsychology* Vol. 2 (pp. 333-356). Amsterdam, NL: Elsevier.

Paillard, J. (1991). Knowing where and knowing how to get there. In J. Paillard (Ed.), *Brain and Space* (pp. 461-481). Oxford, UK: Oxford University Press.

Perenin, M.-T. & Vighetto, A. (1988). Optic Ataxia: A specific disruption in visuomotor mechanisms. *Brain*, *111*, 643-674.

Rader, N. & Stern, J. D. (1982). Visually elicited reaching in neonates. *Child Development*, *53*, 1004-1007.

Ruff, H., & Halton, A. (1978). Is there directed reaching in the human neonate? *Developmental Psychology*, *14*, 425-426.

Sakata, H., Shibutani, H., Kawano, K. (1980). Spatial properties of visual fixation neurons in posterior parietal association cortex of the monkey. *Journal of Neurophysiology*, *43*, 1654-1672.

Sakata, H., Shibutani, H., Kawano, K., & Harrington, T. (1985). Neural mechanisms of space vision in the parietal association cortex of the monkey. *Vision Research*, *25*, 453-464.

Schneider, G. E. (1969). Two visual systems. *Science*, *163*, 895-902.

Schwartz, A. B., Kettner, R. E., & Georgopoulos, A. P. (1988). Primate motor cortex and free arm movements to visual targets in three-dimensional space. I. Relations between single cell discharge and direction of movement. *Journal of Neuroscience*, *8*, 2913-2927.

Shibutani, H., Sakata, H., & Hyvärinen, J. (1984). Saccade and blinking evoked by microstimulation of the posterior parietal association cortex of the monkey. *Experimental Brain Research*, *55*, 1-8.

Soechting, J. F. & Flanders, M. (1989a). Sensorimotor representations for pointing to targets in three-dimensional space. *Journal of Neurophysiology*, *62*, 582-594.

Soechting, J. F. & Flanders, M. (1989b). Errors in pointing are due to approximations in sensorimotor transformations. *Journal of Neurophysiology*, *62*, 595-608.

Soechting, J. F. & Flanders, M. (1992). Moving in three-dimensional space: frames of reference, vectors, and coordinate systems. *Annual Review of Neuroscience*, *15*, 167-191.

Stein, J. F. (1978). Effect of cooling parietal lobe areas 5 and 7 on visual and tactile performance on trained monkeys. In G. Gordon (Ed.), *Active Touch* (pp. 79-90). Oxford, UK: Pergamon.

Stelmach, G. E., Castiello, U. & Jeannerod, M. (1994). Orienting the finger opposition space during prehension movements. *Journal of Motor Behavior*, *26*, 178-186.

Taira, M., Mine, S., Georgopoulos, A. P., Murata, A., Sakata, H. (1990). Parietal cortex neurons of the monkey related to the visual guidance of the hand movement. *Experimental Brain Research*, *83*, 29-36.

Ungerleider, L. G. & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale & R. J. W. Mansfield (Eds.), *Analysis of Visual Behavior* (pp. 549-586). Cambridge, MA: MIT Press.

Vogt, C., & Vogt O. (1919). Allgemeine Ergebnisse unserer Hirnforschung. *J. Psychol. Neurol.*, *25*, 279-462.

Westling, G., & Johansson, R. S. (1984). Factors influencing the force control during precision grip. *Experimental Brain Research*, *53*, 277-284.

Woodworth, R. S. (1899). The accuracy of voluntary movements. *Psychological Review, Monograph Supplements*, *3*.

Yonas, A., & Granrud, C. E. (1985). Reaching as a measure of infants' spatial perception. In G. Gottlieb & N. Krasnegor (Eds.), *Measurement of audition and vision in the first year of life: A methodological overview* (pp. 301-322). Norwood, NJ: Ablex.