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The Representation of Objects for Grasping

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ABSTRACT.

As the human hand reaches out to grasp an object, it preshapes into a shape suitable for the anticipated interaction. As it gets close to the object, it encloses it. Behavioral studies have shown interactions between grasping components and arm transport components. Biomechanical studies look at human hand postures, while neurophysiologists try to suggest how those postures are formed and controlled. In order to evaluate such studies, models are needed which can be used to predict grasping behavior characteristics from a few basic object properties. By looking at the action-perception cycle in primate hand movement, we hope to gain insight into neocortical organization, thus being able to suggest algorithms which could also be at work at all levels of human intelligence.

INTRODUCTION

> *"Our hands become extensions of the intellect, for by hand movements the dumb converse, with the specialized fingertips the blind read; and through the written word we learn from the past and transmit to the future."* – Sterling Bunnell

Over the last 30 years, artificial intelligence research has been trying to capture key aspects of higher cognitive thought [e.g., Shank & Colby 1973]. In the human brain, complex skills such as language, conceptual thinking, and planning have evolved due to the information processing capability of the neocortex [see, for example, Eccles 1977, Arbib 1972]. At the low end of the cerebral cortex, in terms of its distance from the periphery, sits motor cortex. In the neurophysiological literature, it has been noted that the control of fine, fractionated finger movements [Kuypers 1973] is permanently impaired in monkeys, apes, and man by ablation of motor cortex [Denny Brown 1966]. Also, Brinkman and Kuypers [1972] have shown that after a pyramidotomy (which cuts the direct pathway from motor cortex to the motoneurons), a monkey cannot grasp small objects between its fingers or make isolated movements of its wrist. As a way of gaining insight into neocortical organization, we therefore look at primate hand movement, with the goal of being able to suggest algorithms which could also be at work at all levels of human intelligence.

We focus our studies on one specific type of hand movement, that of *prehension*, or the grasping of objects. As a movement, we note its complexity, which is in part due to it involving some level of object recognition. While objects present to the central nervous system (CNS) an infinite number of sensations, only a few properties seem to affect prehensile movements. The efficacy of the action perception paradigm [Neisser 1976, Arbib 1972] has been demonstrated through artificial intelligence research into attention focusing mechanisms for goal directed behavior [see, for example, Barr & Feigenbaum 1981]. We therefore direct our research to determining what properties are being perceived, and how the CNS might be translating them into goals for prehensile movements.

In terms of movement, joints between bones provide one or more degrees of freedom, or *dofs*. Active movement of the hand is caused by intrinsic muscles within the palm, and also by extrinsic muscles in the forearm, which send tendons through the wrist into the digits. When the human hand is used in prehension, particular styles of postures have been noted [Cutkosky and Wright 1986, Lyons 1985, Iberall & Lyons 1984, 1985, Landsmeer 1962, Napier 1956, Schlesinger 1919]. The classifications of Schlesinger [1919] and Napier [1956] continue to be frequently used in the literature. Schlesinger [1919] noted 6 types of postures, including palmar and tip prehension, cylindrical and spherical prehension, hook prehension, and lateral pinch. Napier defined precision grip and power grip as basic prehensile postures, with the hook grip as a non-prehensile posture for grasping. In our own first attempt at a prehensile classification [Iberall & Lyons 1984, 1985], we suggested six postures, using such terms as basic precision, basic power, basic precision/power, modified power, modified precision/power, and fortified precision/power. In that attempt, we were searching for a way to capture the fact that hand postures are not as discrete as most classifications suggest. Objects are not as regular as Schlesinger noted, and yet the hand can pick up a vast range of object shapes. Forces are subtly applied at multiple places around an object, indicating that more than one type of grip is being used at a time, instead of the either/or nature of these classifications. Even Napier stated that 'although in most prehensile activities either precision or power is the dominant characteristic, the two concepts are not mutually exclusive' [Napier 1956, p 906].

Stereotypical descriptions of this sort suggest that there are anatomical and physiological constraints in the hand-object interaction, which the CNS may in turn use. These could include stability constraints, such as postures involving stress limiting coadaption of articular surfaces [Kapandji 1982, Chao *et al* 1976], and leverage maximizing wrist positions [Hazelton *et al* 1975, Pryce 1980, etc]. Also at issue is the use of the frictional characteristics of the skin [Thomine 1982], and the location of tactile receptors [Johannson & Vallbo 1983], both of which are notably specialized at the finger pads [Glicenstein &

Dardour 1981].

However, while these classifications are useful as broad general descriptions, they do not provide a useful mechanism for describing the complete grasping process, from perceiving an object, to capturing and manipulating the object. We feel that a classification is needed which describes a prehensile posture in goal-directed terms; i.e., in terms of the number of forces needed in the task, in what direction they are to be applied, and at what strength must they be applied. We define the goal of prehension to be ***the bringing to bear of functionally effective forces around an object for a given task given the hand's anatomical constraints.*** The style of posture chosen by the CNS must then match the task requirements (the forces and *dofs* needed in the task) with the hand's capabilities (the forces and *dofs* available at the hand).

FUNCTIONAL ANALYSIS OF PREHENSION

Prehension involves applying opposition to the forces arising during interaction with an object, and stable prehension adds the requirement that opposition is applied by hand surfaces against other hand surfaces [Iberall, Bingham & Arbib 1985]. We call the applications of forces between hand surfaces ***oppositions***. In order to apply those forces, the hand preshapes into a suitable posture during the reaching phase of the movement [Jeannerod 1981], thus setting up the required oppositions for the task. The fingers and thumb extend, creating a space within the hand, with characteristics which are highly task dependent. An obvious example of task dependency deals with object width: the larger the object width, the larger the maximum aperature between the thumb and fingers [Jeannerod 1981]. Enclosing the hand around an object works within that area defined by the preshaped hand, by increasingly flexing the fingers and thumb until they contact the object and can then apply the required force.

In studying these data, we ask ourselves what is the subject perceiving about the object that determines a particular hand posture as being functionally effective for the stated task. We call that perception the ***task requirements***, and it is our goal to be able to describe prehensile movements in terms of those task requirements.

To gain some intuition for this analysis, we initially observed [Arbib, Iberall & Lyons 1985] the task of picking up different size mugs by their handles. We noted that three basic forces were being applied: one to provide a downward force from above the handle, one to provide an upward force from within the handle and, if necessary, a third force to stabilize the handle from below. We hypothesized that each of these functions could be represented as the task of a ***virtual finger***. Real fingers move in conjunction within a virtual

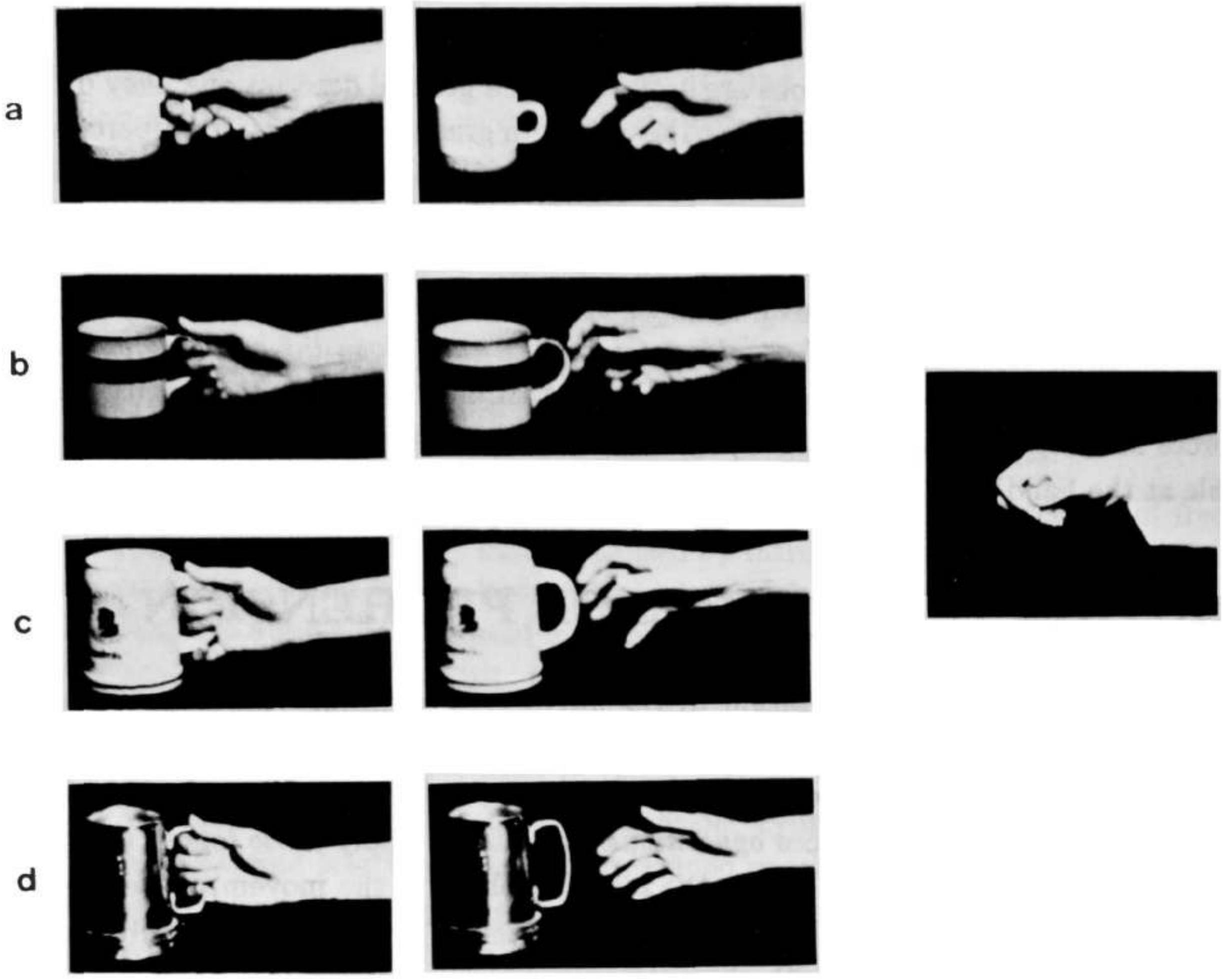
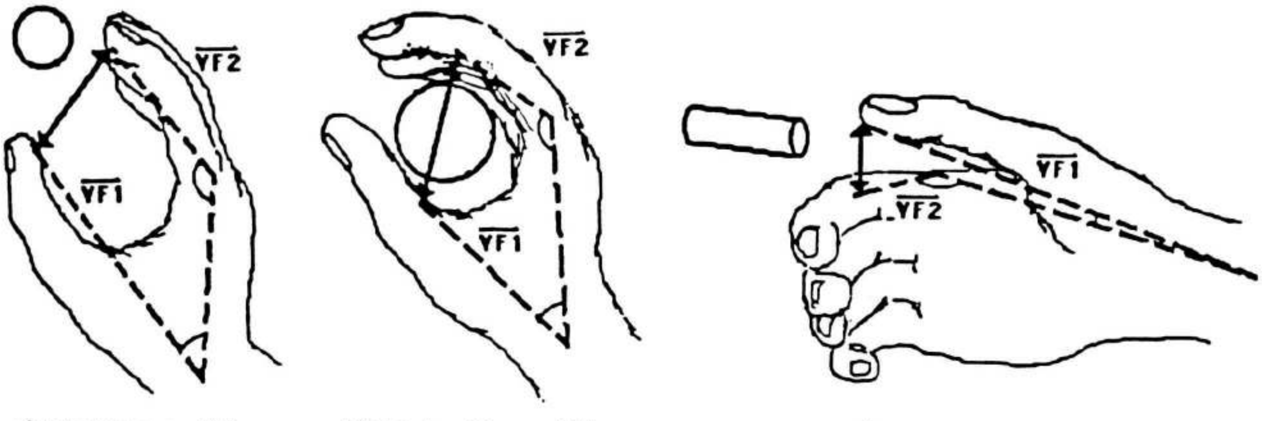


Figure 1: Grasping mug task. The number of real fingers which map into the second virtual finger varies, depending on the size of the handle.

finger, which has the same characteristics as real fingers. This both limits the *dofs* to those needed for a given task, and provides an organizing principle for task representation at higher levels in the CNS. It is then a subtask at a lower-level to perform the actual mapping to real fingers, making task implementation somewhat "tool-free".

Figure 1 shows an example of the use of virtual fingers. In the four examples, the thumb, mapped into the first virtual finger or VF1, provides a force from above the handle. For a teacup with a very small handle (Figure 1a), only one finger will fit inside the handle. During the preshaping, only the index finger is mapped into the second virtual finger VF2, which provides an upward force from within the handle, and which opposes the force applied by VF1. The rest of the fingers map into VF3, which provides support for cup stabilization. For a coffee mug of the kind pictured in Figure 1b, two fingers will fit



a) Pad Opposition b) Palm Opposition c) Side Opposition

Figure 2: Basic oppositions (a) Pad opposition along axis generally parallel to palm (b) Palm opposition along axis generally normal to palm (c) Side opposition along axis generally transverse to palm. Solid lines show axis of opposition, dashed lines show virtual finger vectors $\overline{VF1}$ and $\overline{VF2}$.

within the handle to form VF2, with the other two fingers becoming VF3. For the mug of Figure 1c, VF2 will comprise three fingers, while Figure 1d demonstrates the case in which all four fingers are mapped into VF2, with an empty mapping to VF3.

We suggested in [Iberall, Bingham & Arbib 1985] that prehensile postures are constrained by the way the hand can apply opposing forces around an object for a given task, and noted that there are three basic ways that the hand can apply these oppositions. *Pad opposition* (Figure 2a) between the finger pads (VF2) and the thumb pad (VF1) occurs along an axis roughly parallel to the palm. Opposition at the digit pads offers greater flexibility in finely controlled manipulations of an object at the expense of stability and maximum force. These pads are highly specialized for prehension, in that they provide friction, due to the epidermal ridges, sticky excretions, and their ability to comply [Glicenstein & Dardour 1981]. They also have numerous tactile receptors, more so than most other parts of the body, thus giving the CNS much information about the object with which they come into contact [Johannson & Vallbo 1983]. *Palm opposition* (Figure 2b) between the digits (VF2) and the palm (VF1), sacrifices flexibility in favor of stability. Essentially the object is fixed in hand coordinates, along an axis roughly normal to the palm of the hand. Greater stability is achieved by a combination of factors [Thomine 1982]: the larger palmar surface area providing more friction, greater forces available from proximal finger areas [Hazelton *et al* 1975, Chao *et al* 1976], the ability to passively cancel torques, and the use of the thumb against the fingers for adding force and changing the size of the palm. As more fingers are included in VF2, the magnitude of the applicable force increases. Finally, *side opposition*, either between the thumb pad (VF1) and the side of the index finger (VF2) (Figure 2c), or else between the sides of the fingers, is a compromise between flexibility and stability. Its opposition axis occurs primarily along a transverse axis to the palm. The thumb, due to the orientation of its articular surfaces, has its pad oriented toward the sides of the other digits, giving side opposition using the thumb the extra frictional component. Side opposition between fingers is stronger (but less flexible) if the object is held proximally in the fingers, and weaker (but more flexible) if held more distally.

Each opposition has particular features which are related to the hand's anatomical and physiological structure, and thus define the nature of applicable forces and usable *dofs*. We suggest that the shape the hand takes on during the grasp reflects the use of one or more of these oppositions. In the grasp mug task, side opposition is used between the thumb and index (see Figure 1), and palm opposition occurs between the palmar surfaces of the fingers. Since the mug is grasped off-center from its center of mass, VF3 applies an opposition to the torque which brings the mug into the hand. In general, a complete functional description of each opposition would discuss the direction of the applied force, the magnitude of the applied force as related to the number of real fingers involved (in terms of minimal, maximal, and mean forces), the direction of available movement (*dofs*), the range of available movement, and the amount of control over those movements. A complete functional description of prehensile movement would show the how these oppositions are seen and used in the emergent postures.

OPPOSITION SPACE

Using the concept of virtual fingers, and noting how the hand can apply forces through oppositions, we defined *opposition space* [Iberall, Bingham & Arbib 1985] as the coordinates within which opposition can take place between virtual fingers; specifically, opposition space defines *the functional capabilities of the hand for executing stable grasps and object manipulations*. To completely characterize opposition space, we specify here:

1. a description of the task-relevant object features, or *task requirements*
2. a coordinate frame with relevant grasping parameters, or *opposition space*
3. a mapping between the task requirements and opposition space

Task Requirements

While it is not our goal to model how the CNS might do it, we suggest that perception of the object involves extracting a set of properties relevant to the person's ***intent*** for the use of the object in the task. The perceived task requirements, which help determine the shape of the hand, consist of both functional constraints and physical constraints. Functional constraints, coming from what must be accomplished in the task (the intent), include issues such as: don't drop the object, (stably) manipulate the object, and overcome anticipated forces. Physical constraints, based on object properties and hand properties, include such issues as properties of opposing surfaces, available forces, and available ***dofs***. As a first approximation toward quantifying these, a working set of task requirements is as follows:

- a set of opposable surfaces
  - length of each opposable surface
  - radius of curvature of each surface
  - surface compliance
- an opposition vector between pairs of opposable surfaces
  - magnitude of opposition vector
  - orientation of opposition vector (relative to a vector between the opposition space origin and the center of the opposition vector)
- functional degrees of freedom about an opposition vector
  - direction of movement
  - range of movement
  - resolution of control
- a set of anticipated forces
  - object weight vector
  - inertial force vector
  - torques at the opposition vector

Objects have infinitely many properties, but we suggest that for prehensile movements, an object is perceived by its opposable surfaces, and only those relevant to the task. Between every two relevant opposable surfaces exists an opposition vector. The mug, for example, having a cylindrical body and a curved cylindrical handle, has an infinite number of possible opposition vectors between the infinite number of points along its surfaces. But, due to its construction and due to the person's intent of drinking from the top opening, it provides at least three solutions in terms of task requirements:

1. an opposition vector, between body surfaces slightly above the center of mass, will allow the task-related rotation (i.e., drinking from the opening) of that opposition vector while stably overcoming the object's weight vector. By choosing the particular opposition vector which has its origin near the proximal surface of the mug and placing the thumb there, the object's (changing) weight vector will be opposed by the thumb as the mug is tilted to the lips.
2. an opposition vector, between the top and bottom body surfaces, will also allow the task-related rotation. It is, however, off the center of mass, and has smaller opposable surfaces, and is usually blocked by other obstacles, such as the table. (This of course focuses on the fact that other issues, missing in this first approximation, are at work; these include object temperature, obstacles, etc).
3. two opposition vectors, one through the top of the handle and one through the side of the handle, will also allow the task-related rotation. By choosing two particular opposition vectors, one with an origin on the top of the handle and one on the distal surface of the handle, the object's (changing) weight vector can be overcome by accounting for the torque caused by being off the center of mass. While these opposition vectors are off the center of mass and the surfaces smaller, they provide a solution to the temperature problem.

In our example of Figure 1, when the subject was told to 'Pick up the mug to drink out of it', she chose the third solution in each case.

Coordinate Frames

In order to now match the task requirements to the hand's capabilities, we define here a coordinate system for the three oppositions, as shown by the dashed lines in Figure 2. In pad opposition (Figure 2a), $\overline{VF1}$ describes where the thumb pad is, as it extends and flexes through its 'workspace', relative to the palm. The virtual finger vector $\overline{VF2}$ similarly describes where the finger pad is, relative to the palm. These vectors increase and decrease in length and orientation as the thumb and fingers extend and flex. The dark line indicates the opposition vector along which the opposition is occuring. For palm opposition (Figure 2b), the virtual finger vectors are initially shorter, ending on the palmar

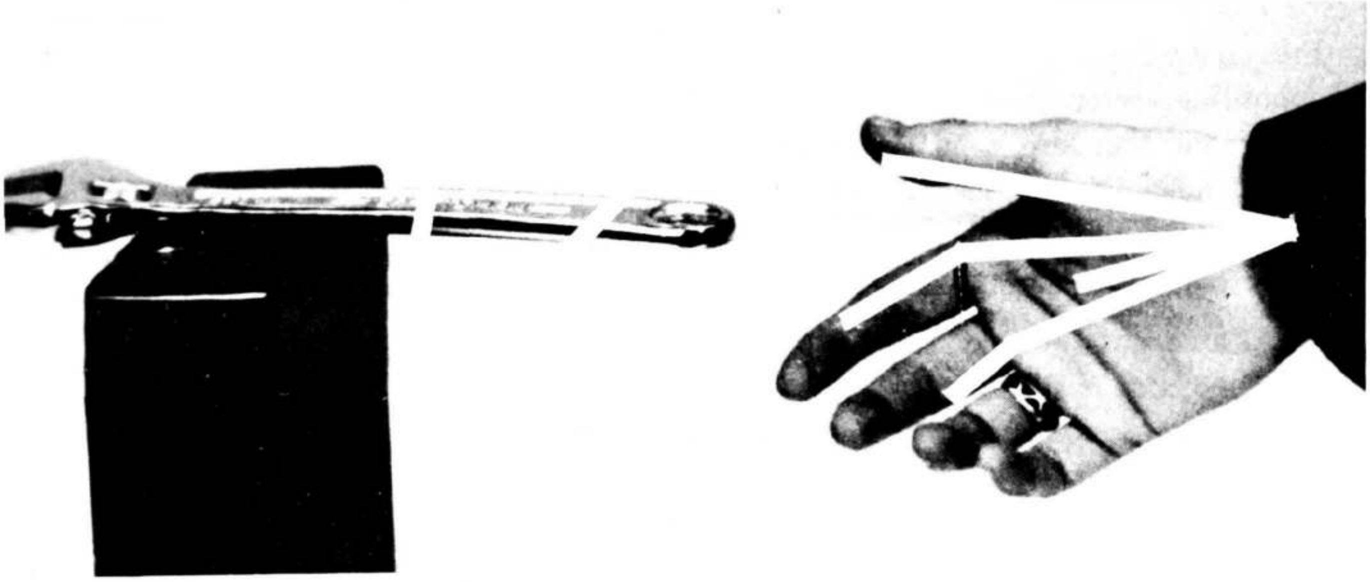


Figure 3: Composite grasp involving palm and side opposition. Grasping medium-sized wrench involves both power and control components.

surfaces where the opposition is taking place. In side opposition (Figure 2c), $\overline{VF2}$ stops at the proximal interphalangeal joint of the index finger.

An example of these coordinate systems being used in a composite grip is seen in Figure 3. The object is perceived with two opposition vectors, one matching to the thumb (VF1) and index finger (VF2) in side opposition along the transverse axis, and the other matching the palm (VF1) and the four fingers (VF2) in palm opposition.

Mapping from Task Requirements to Opposition Space

The general problem that the CNS has in an action/perception paradigm [Neisser 1976, Arbib 1972] such as grasping an object, is in transforming perceived object properties into useful motor spaces. We use schema theory [Arbib 1981, Neisser 1976] to describe perceptual structures and units of motor control. To focus attention, perceptual schemas in the CNS must somehow extract relevant information about that object, in this case, a reasonable opposition vector (or set of opposition vectors) for the particular task, transformed from retinotopic coordinates into a three dimensional space. The Preshape motor schema will map the current hand posture (which also must be perceived) into a suitable opposition space, from where the Enclose schema will bring the hand actually around the object.

This problem can be defined as an inverse kinematic problem, in the sense that the Preshape schema must determine the correct angles for $\overline{VF1}$ and $\overline{VF2}$ given a particular opposition vector. However, the inverse kinematics do not necessarily give a unique solution, and therefore, a further analysis of the goals is needed. We can also ask what is the intended direction for the application of the forces (i.e., what is a solution of the task requirements which accounts for stably overcoming the anticipated forces), and what are the forces available from various hand postures.

As an example toward looking at the first question, we can look at what happens in a pad opposition involving the thumb (VF1) and index finger (VF2). The intended direction of force application is to apply forces through the index finger and thumb pads along the opposition vector. As a first approximation, we can just look at the direction of a normal through the index finger and one through the thumb pad, and see how they vary as the finger and thumb move within their anatomically-constrained 'workspace'. We measured the workspace of the index finger pad and that of the thumb pad for one subject, and from sample data points, we did a linear interpolation to produce the plot seen in Figure 4. Each arrow shows the direction of a normal with respect to the pad, when the thumb vector $\overline{VF1}$ (on the left side of the figure) or the index finger vector $\overline{VF2}$ (on the right side of the figure) is at a given angle and length. The dots are areas outside the workspaces. The abscissa values are in opposite direction, thus graphically showing how the normals become colinear but opposite at various locations in the workspaces.

Such a description of the workspaces of VF1 and VF2 provides a first attempt at a functional analysis of hand capability. If, somewhere in the CNS (in cortical motor and/or premotor areas), such a representation of the hand existed, it would act as both a motor map, providing a goal for lower level systems to achieve through proprioceptive feedback, and also as a cognitive map, providing a description of the hand's functionality in that part of opposition space. The Preshape Schema could look into this map for an orientation of the pad normals which would satisfy the magnitude and orientation of the opposition vector. However, the hand must be positioned at a distance and orientation from the opposition vector, along an approach vector, where that solution exists. There are, however, an infinite number of approach vectors, in terms of the distance at which the maximum aperature between VF1 and VF2 occurs and the approach angle at which it happens. How might the Preshape Schema decide which solution is best, or at least reasonable?

The selection of this solution can be done using a competition model involving computations in a neural network [Amari & Arbib 1977]. Of all the given inputs to such a network, the node receiving the maximum input is selected. In our case, for a given op-

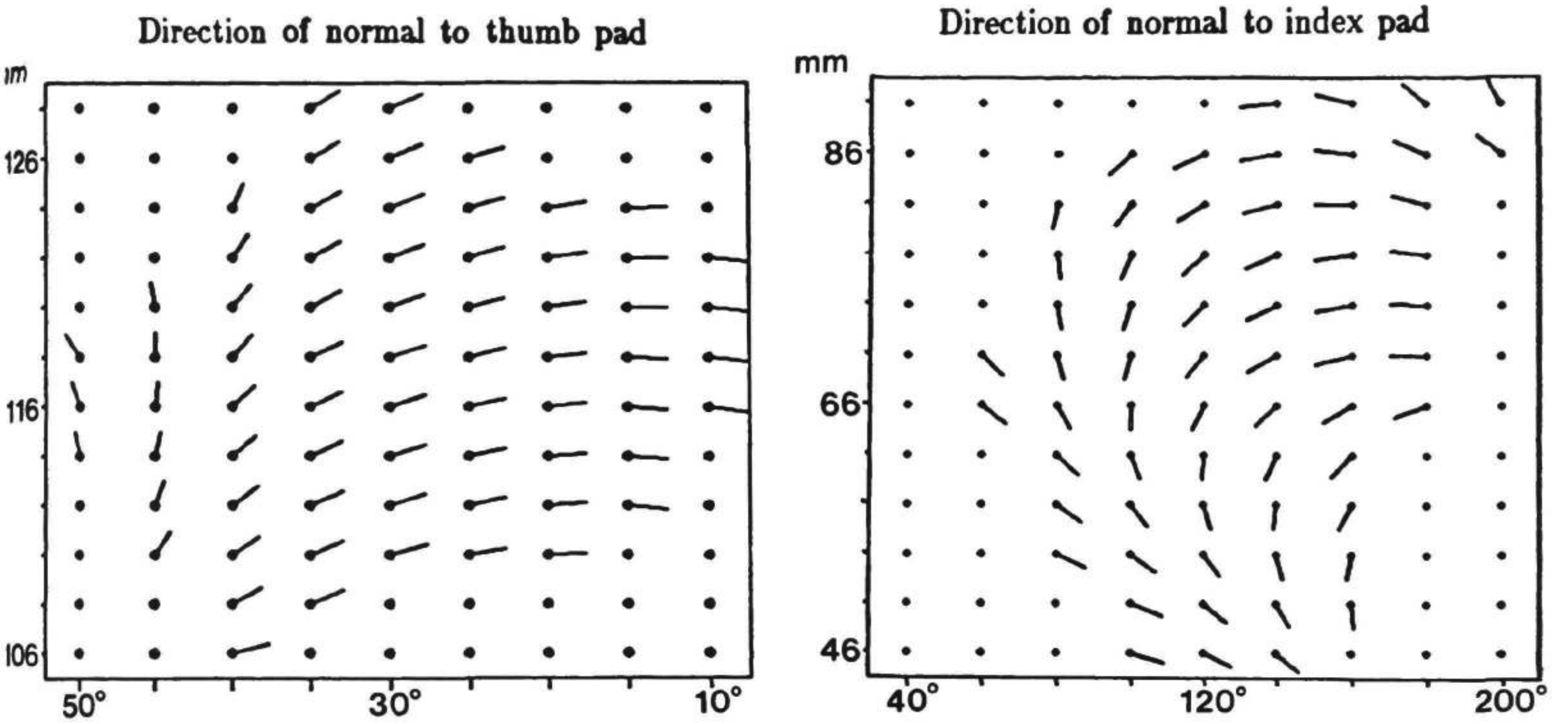


Figure 4: Direction profiles for pad opposition of thumb pad normals (left figure) and index finger normals (right figure). The abscissas, opposite in direction, represents the angle between $\overline{VF1}$ or $\overline{VF2}$ and the palm. On the ordinate is the length of the virtual finger vector.

position vector magnitude, all possible distances and orientations of the opposition vector relative to the opposition space origin would compete in an excitation/inhibition network. Distances and orientations outside the range of opposition space would die out. VF1 and VF2 configurations which correspond to colinear pad normals would reinforce each other's excitation level, thus allowing peaks in the network model to grow. A competition model of this type is currently being developed, and should show how the mapping of task requirements into opposition space constrains various aspects of prehensile movements, such as the approach vector the arm takes in reaching.

The actual posture chosen by the Preshape Schema would also incorporate a small buffer zone, the size of which is dependent on many task features such as Fitt's Law (for a review see [Keele 1981]). This issue, however, is beyond the scope of this paper.

The second question looks at what forces are available from various hand postures. In this broader issue of mapping from task requirements to opposition space, we have yet to determine how do interactions of task requirements lead to interactions of oppositions and to real-to-virtual finger mappings, producing observed postures. We suggest that perceptual schemas extract an opposition vector at each place where an opposition is needed in a task, along with all the necessary task requirements. As was noted, the grasp mug task is an example of multiple oppositions.

As an example toward answering this second question, we look at the task that was seen in Figure 3, where the person is reaching for a medium-sized wrench. The fact that there are two opposition vectors anticipates the need for two types of oppositions, thus capturing the two characteristics of the task (i.e., power and control). The lengths of opposable surfaces for each of the opposition vectors are longer than the hand is wide, and so do not present a virtual finger size constraint. The width of the opposition vectors are not particularly big, indicating that the object is not particularly heavy. The anticipated task torque (tightening the nut) indicates the need for palm opposition, using as many fingers as possible in VF2. However, during the first part of the task (fitting the jaws of the wrench around the nut), some control is needed. This, along with the fact that only coarse resolution of control over the task *dofs* (turning the wrench) is needed, indicates that side opposition would be more useful than pad opposition for the second opposition, with the index finger mapped into VF2 and the thumb into VF1. This allows all four fingers to map into VF2 and the palm into VF1 for the palm opposition.

CONCLUSION

Research in artificial intelligence has demonstrated the efficacy of attention focusing mechanisms for goal directed behavior. In terms of natural intelligence, the CNS is presented with an infinite number of sensations when dealing with even one object. In order to successfully interact with such an object, only information specific to the interaction is desireable. Important perceptions for prehensile movements involve: what surfaces can be grasped given a particular intention, what are the characteristics of those surfaces, and what will happen when they are grasped. In attempting to capture this information in a computational model of prehensile movements, we call these features the *task requirements* and list them, in a first approximation, as a set of opposable surfaces, an opposition vector between pairs of opposable surfaces, the functional degrees of freedom about an opposition vector, and a set of anticipated forces arising relative to an opposition vector.

The human hand, having anatomical and physical constraints, applies oppositions around objects along three basic axes using the fingers in groupings called virtual fingers. Prehensile postures reflect the combined use of one or more of these oppositions. Each type of opposition has particular functional capabilities, involving the direction and magnitude of the applied force, the direction and range of available movement, and the amount of control possible. We call the collective set of these oppositions the *opposition space* of the hand, and use the coordinate system described here to describe the prehensile postures of opposition space. The goal of a preshape schema in the CNS is to map task requirements into opposition space so that functionally effective forces can be brought to bear around a perceived object for a given task. In order to apply those forces, the hand must be positioned at a distance and orientation from the opposition vector where a solution in opposition space exists. A competition model of neural networks would allow possible kinematic solutions to compete, with a solution that is within opposition space being selected when the model converges. Such a model for mapping perceived task requirements into hand functionality presents a mechanism for explaining goal-directed movement in somatotopic, distributed processing terms, while also allowing for the eventual incorporation of learning algorithms.

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