Chapter 1: Introduction

The act of reaching out, grasping, and manipulating an object involves the integration of information from a variety of sources (MacKenzie & Iberall, 1994). From the information available just prior to the start of movement, the monkey (or human) must be able to select a general grasping strategy. Visual information allows the monkey to extract the identity of an object as well as an estimate of its shape, size and localization in space. This information, combined with the behavioral context in which the monkey finds himself affects the choice of grasp that is to be made. The behavioral context can include task constraints (such as the goal of manipulation after the grasp is established), the position of obstacles relative to the target object, instruction stimuli provided by an experimenter or teacher, or memories of recently executed grasps. This plan is then refined depending upon the details of the situation, some of which may become available only as execution progresses. As contact is made with the target object, tactile and kinesthetic information yields an even more detailed description of the shape and locality of the object. This information is used by the monkey to further fine tune his arm and hand movements during the manipulation phase of the motor task.

In this thesis, we investigate the cortical mechanisms involved in:

1. The translation of a visual description of an object and a representation of the task into an appropriate hand configuration.
2. The unfolding of this description in time in driving execution of the preshape, enclose, grasp, and ungrasp phases of movement.

Two cortical regions have been studied in monkey that are particularly compelling in their neural responses during the execution of grasp. These are the rostral inferior premotor cortex (referred to as F5), and the anterior intra-parietal cortex (AIP). Cells in F5 often demonstrate selectivity towards the type of grasp that is made by the monkey (Rizzolatti, Camarda, Fogassi, Gentilucci, Luppino, & Matelli, 1988). In addition, cells fire in relation to specific phases of the executed preshape and grasping movement. Within AIP, cells demonstrate a variety of selective responses, including those towards the type of object presented to the monkey, the size of the object, and its position in space (Murata, Gallese, Kaseda, Kunimoto, & Sakata, 1993; Taira, Mine, Georgopoulos, Murata, & Sakata, 1990). What is striking about many of these cells is that their firing rate is also modulated during execution of grasping movements.

In this thesis, we propose a computational model of the grasping process, which is derived from behavioral, cell recording, and anatomical data from both human and monkey. This model focuses on the roles of the intra-parietal areas (specifically AIP, PIP, and VIP), inferior premotor cortex (F4 and F5), pre-SMA (F6), frontal cortex (area 46), inferiotemporal cortex (IT), and the secondary somatosensory cortex (SII).

In the development of the model, we hypothesize specific computational roles for several cortical regions:

1. AIP is responsible for extracting from the visual representation of an object the appropriate set of *affordances* for that object. By *extracting an affordance*, we mean that AIP highlights the properties of the object that are explicitly relevant for physically interacting with it in a particular way.
2. The continued activity of many AIP cells through the execution of the preshape, grasp, and holding of an object maintains an *active memory* of the grasp that is being planned or that is being executed. This active memory is important for the organization of the global aspects of the grasp during execution. After a secure grasp

is established, this memory can also be used to recalibrate the visual-motor mapping through an associative process between the visual representation of the object and the active memory of the grasp that was actually executed (as opposed to the grasp that was originally planned).

3. F5 is the site responsible for integrating the many constraints that are used to decide on the single grasp that is to be executed. These constraints include visual information (from the affordances extracted by AIP), task information, instruction stimuli, and working memories of recently executed grasps.
4. F5 is responsible for the high-level execution and subsequent monitoring of the planned preshape and grasp.
5. We explicitly address the issues involved in the neural-level encoding of object, grasp, and phasic information, and show how the populations of cells can capture the critical information that is required to perform the necessary computations.

The model makes several key predictions relating to:

1. The encoding of object- and grasp-specific information in AIP and F5 at both the single-cell and population levels.
2. The behavior and timing of the grasp decision process when an object affords multiple grasps.
3. The behavior and timing of neural responses when there is a discrepancy between the visually-programmed grasp and the actual size of the object.
4. The changes in regional synaptic activity as a function of the task that is performed (as measured by synthetic PET imaging).

Finally, we present results of a PET (positron emission tomography) study in human that:

1. Compares brain activity during the performance of a precision pinch and a power grasp.

2. Examines the brain regions involved in the processing of an abstract stimulus that instructs the subject as to which of the two grasps must be performed.

The results of this study are related to our model through the synthetic PET imaging technique.

Outline of the Thesis

Chapter 2 will focus on the key aspects of the monkey neurophysiological data from which we derive our model. The computational background of this work (schema theory and opposition spaces) are examined in Chapter 3.

The core model described in this thesis is developed in Chapter 4; the low level details of the model are described in Chapter 5; Chapter 6 is dedicated to the demonstration and validation of the model behavior, as well as the testing of the model with several novel tasks.

Chapter 7 focuses on relating the model (derived primarily from monkey data) to human PET experiments. We first describe the synthetic PET imaging technique, through which it is possible to make predictions from the model about the what we can expect in human PET experiments. We then present a set of real human PET results, and show how they may be used to further constrain our modeling work.

Chapter 8 steps back from the primary model, and asks how the grasping motor programs that are represented in AIP and F5 might be acquired automatically through a trial-and-error learning procedure. A model is presented which learns (via reinforcement learning) a mapping from object and task parameters to a description of a grasp that is appropriate for that object.

Finally, Chapter 9 summarizes the key aspects of the presented models, and concludes with a discussion of future directions for model development.