Coordinated Control Programs for Movements of the Hand[1]

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Abstract

We use *perceptual and motor schemas* to postulate *coordinated control programs* for hand movements involved in reaching to grasp an object, reaching to lift a mug, and putting down an object. We sketch an articulated language in which to develop precise models of human and animal performance subject to behavioral and neurophysiological testing. We offer evidence for the concept of the *virtual finger* as a hierarchical substructure in hand control. We provide a brief introduction to simulation methodology. We discuss neural and behavioral correlates of schemas with special attention to concurrency and localization of schema activation, new experimental support for the Pitts-McCulloch paradigm for distributed motor control, and a two-phase analysis of discrete activation feedforward.

§1 Introduction

We use schema theory to analyze perceptual structures and distributed motor control. In the present paper, we study the control of an articulated manipulator (primate hand or robot gripper). Actions performed by the manipulator will provide new sensory input which can be used to modify further actions, thus constituting the Action/Perception Cycle [Neisser 1976] . Reaching and grasping movements have been used widely in both the psychological [Howarth and Beggs 1981, Jeannerod and Biguer 1982, Paillard 1982] and neurophysiological [Smith and Bourbonnais 1981, Humphrey 1979, Muir and Lemon 1983] literatures. There also exists detailed literature on the shaping of the human hand for grasping [Napier 1956, 1962].

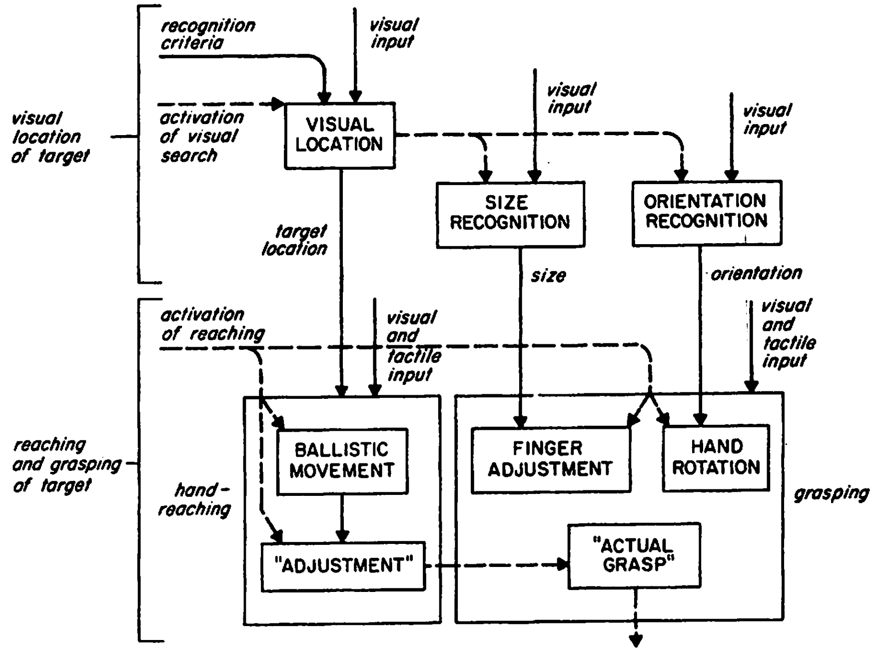
Following [Arbib 1981], we distinguish perceptual and motor schemas. A *perceptual schema* is an internal model of a section of the environment with which the organism has preconstructed plans for interaction. The contents of the perceptual schema are dictated by the interaction plan, which is called a *motor schema.* An object is, in basic cases, only perceived in terms of the task in which it is being used.

Every motor schema has an embedded perceptual schema, with which it can parameterize movements. Parameters to a motor schema represent properties about facets of the environment: size, location, orientation, relative motion, etc. The motor schemas provide a unit of motor control within an overall *coordinated control program.* A motor schema is a control system, continually monitoring feedback from the system it controls to determine the appropriate pattern of action to achieve its goals. The embedded perceptual schema provides an "identification procedure", which estimates parameters relevant to the controlled system.

The *activation level* of a perceptual schema represents the credibility of the hypothesis that the task represented by the schema is indeed afforded by the environment. The activation level of a motor schema is an indication of how useful this schema is in dealing with the present environment as perceived. A motor schema may have its activation level affected by other motor schemas as well as by dynamic perception. Cooperating schemas will increase each other's activity; competing schemas will attempt to decrease each other's activity. The overall behavior of the system is the combined behavior of all of its component schemas.

A coordinated control program is the structure that interweaves activation of motor schemas to control action. We first give a broad-brush view of such a program for a human reaching to grasp an object (Figure 1, from [Arbib 1981]). We have a ballistic movement towards the target concurrently with which the fingers are adjusted to the size of the object and the hand is rotated to the correct orientation. When the hand is near the object, a final feedback adjustment is made in the position of the hand. Tactile feedback then shapes the hand to the object.

Figure 1: Hypothetical coordinated control program for human's visually directed reaching to grasp an object. Dashed lines carry activation signals; solid lines transfer data.



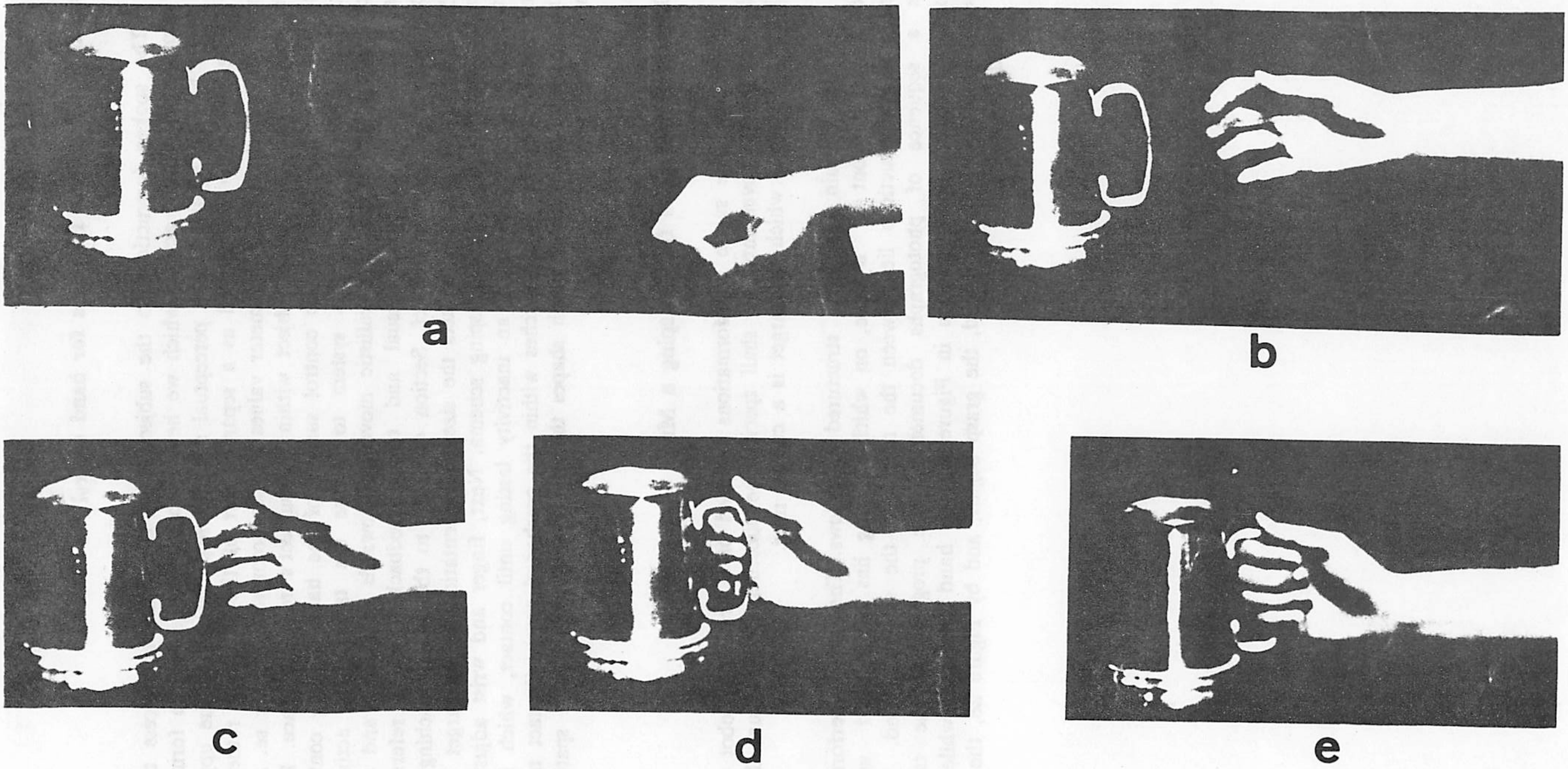
The spoken instructions to the subject drive the planning process that creates the appropriate plan of action, which we here hypothesize to take the form shown in the lower half of Figure 1. The perceptual schemas hypothesized in the upper half of the figure need not be regarded as a separate part of the program; rather they are invoked to pass the proper parameter values to the motor schemas per se. Analysis of visual input locates the target object within the subject's reaching space. Information about the location is fed to the control surface of the hand-reaching control system (i.e., it is not the job of this system to choose the target). On activation, the hand-reaching system directs a ballistic movement towards the target and activates a tuning mechanism to utilize visual and tactile feedback (this is referred to as 'discrete-activation feedforward', cf. Section 4). Prior to the actual reaching, however, analysis of visual input also extracts the size and orientation of the target object and feeds this information to the grasping schema. Next, finger and wrist adjustments are coactivated. This is followed by an inactivity lasting until contact, which is attained when a portion of the object touches within the preshaped grasp. Contact triggers the "actual" grasping movement, which shapes the hand on the basis of a spatial pattern of tactile feedback.

§2 Detailed Subschemas for Grasping a Mug

To pinpoint the subtle transformations required of a brain (or robot controller) in directing hand movements, we shall specify the subschemas of Figure 1 in more detail for the case in which the target is a cup or mug.

The task domain has been structured as follows. The task is performed by a subject seated in front of a table, on which a mug has been placed within arm distance. No obstructions lie between the mug and the subject's hand. Figure 2 shows a sequence of photographs documenting the progress of the task being performed. From a resting position in Figure 2a, the hand preshapes while the arm reaches (Figure 2b,2c). In Figure 2d, the grasp begins, and by Figure 2e, the mug has been actually grasped.

Figure 2: Grasping a mug involves object parameters (handle size, orientation, etc), a target (within handle), and body parameters (wrist reference point, hand orientation, hand size, etc)



The preshaping of the hand involves object parameters, such as a visually-determined estimation of the handle's size and orientation. In this task, the five fingers of the hand have three major functions: to provide a downward force from above the handle, to provide an upward force from within the handle and, if necessary, a third force to stabilize the handle from below. We hypothesize that each of these functions can be represented as the task of a *virtual finger*. The fingers within a virtual finger move in conjunction, and have the same characteristics as real fingers. This both limits the degrees of freedom to those needed for a given task, and provides an organizing principle for task representation at higher levels in the brain. It is then a subtask at a lower-level to perform the actual mapping to real fingers, making task implementation somewhat "tool-free". We note studies of other tasks performed quite well in spite of imposed variant mappings; e.g., standard handwriting with pen, chalk, or a pen on a pole.

As evidence for the concept of virtual finger, consider the behaviors pictured in Figure 3. In all of them, the thumb is mapped into VF1, the first virtual finger function, which is to provide a force from above the handle.

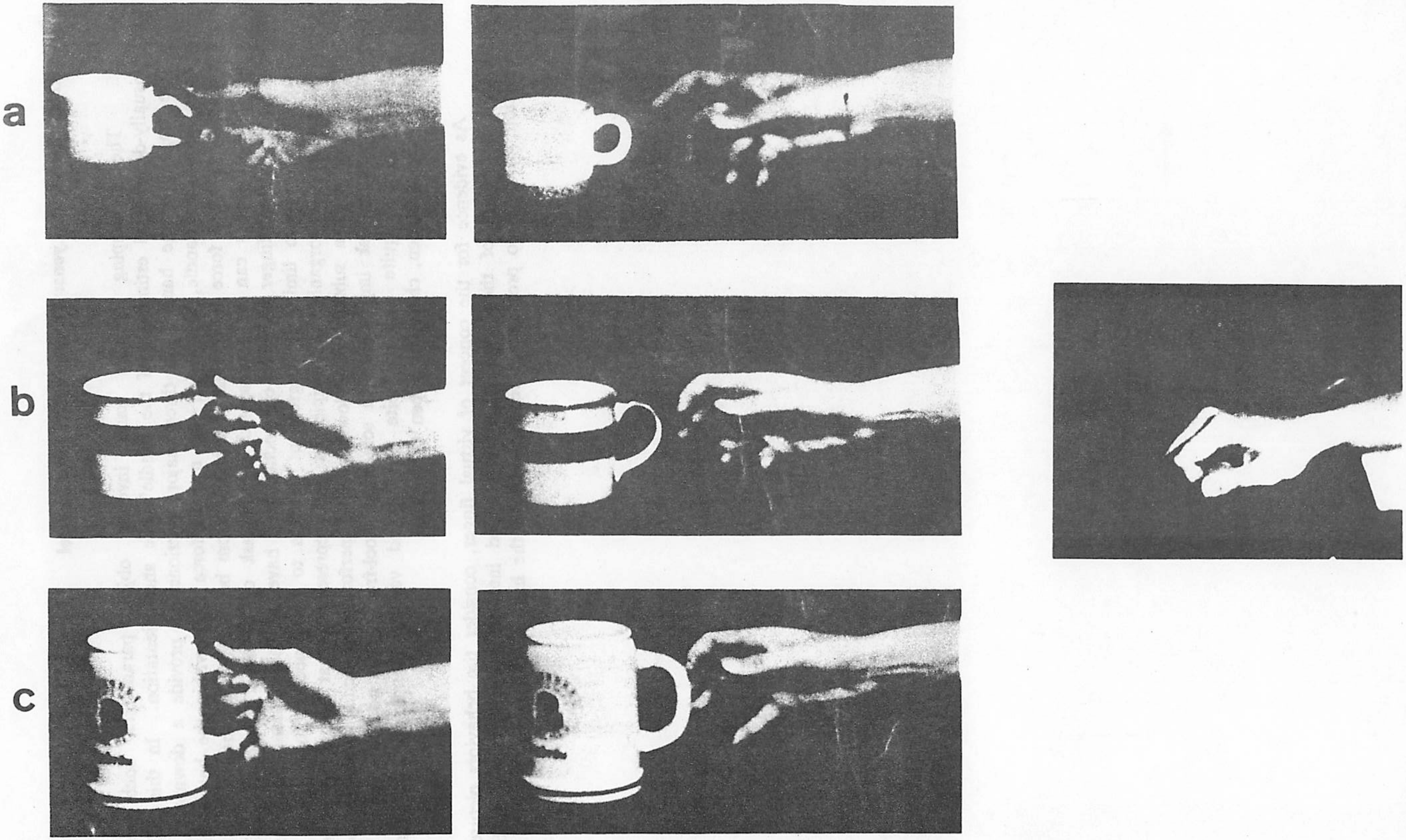


Figure 3: Various combinations of real fingers can be mapped into virtual fingers for different size objects.

For a teacup with a very small handle (Figure 3a), only one finger will fit inside the handle. During the preshaping, only the forefinger is mapped into VF2, the second virtual finger function, that of providing an upward force from within the handle. The rest of the fingers become VF3, virtual finger three, to provide support for cup stabilization. For a coffee mug of the kind pictured in Figure 3b two fingers will fit within the handle to form VF2, with the other two fingers becoming VF3. For the mug of Figure 3c, VF2 will comprise three fingers, while Figure 2 demonstrates the case in which all four fingers are mapped into VF2, with an empty mapping to VF3.

The arm movement needs a visually-determined target parameter, A, which in this task we assume to be inside the hole defined by the handle. However, the body referent for this movement, which we posit could be located at the center of the wrist, must be aimed not at A, but at a point displaced from A by the vector linking the wrist to the intended contact point on the hand. The hand, no matter its dynamic shape or what it is carrying, will thus have a size parameter to which the motor schema controlling the arm move must adjust. This schema can then direct the wrist reference point to a target which is offset from the target by the dynamic hand size.

The arm move and the hand preshape are concurrent. Both work from a feedforward model supplied by the *Grasp Schema.* The move terminates when the hand is at the required working offset from the mug. The preshape terminates when a satisfactory shape (a model-determined set of finger positions) has been assumed, or when the move terminates.

Schemas can be generated from the task description in a top-down fashion. The highest level schema under consideration is the Grasp Schema.

Grasp Mug Schema

The embedded perceptual schemas for grasp will provide three visual cues: a target near the inside of the handle, the size of the handle, and the orientation of the handle. These can be used as parameters to the lower-level motor schemas necessary for carrying out the task.

Grasp activates in parallel a "Reach" Schema to move the hand to a position near the mug, ready for the grasp to begin, and a "Preshape" Schema. Preshape must first activate a schema to map the task's virtual fingers into real fingers. If any of these schemas fail, then the grasping process fails, perhaps calling for replanning at a higher level. One reason for failure might be contact with another object before the mug is near. We describe these three subschemas before describing the program for the final stage of the movement. These are as follows:

Virtual Finger Mapping Schema

The Virtual Finger Mapping Schema maps virtual fingers onto real fingers, depending on the visually-determined size of the handle, as described in our discussion of Figure 3. All other schemas will deal with virtual fingers. If this schema remains active as long as the hand is preshaping, the fingers can be remapped dynamically (i.e., on finding that the initial estimate of the handle size was wrong).

Preshape Hand Schema

This schema defines the hand in terms of three virtual fingers, one for each of the forces needed in the grasping of the handle. The Preshape Hand Schema positions the three virtual fingers in anticipation of the following roles:

- VF1 provides an opposing force on the top of the handle against VF2
- VF2 grasps the handle and provides stabilization
- VF3 provides stabilization against the bottom of the handle, if needed

This schema is provided with the visually-defined target, handle orientation and handle size as parameters, and it will call upon low-level subschemas to move the virtual fingers into some standard preshaped pattern relative to the handle. It will also provide other schemas with the current preshaped size of the hand; in this task it will provide the reach schema with the vector from the tip of VF2 to the wrist reference point. It will terminate with success when the shape is achieved, or when the tip of VF2 comes into contact with the handle. Actual contact is not really necessary, and so it also terminates when the tip gets to a near enough location. Preshape fails if there is contact anywhere else, letting higher level schemas know. Once Preshape terminates, other schemas will call upon the same low-level subschemas to move the virtual fingers. This provides a smooth transition from contact-free preshaping to contact-oriented grasping movements.

Reach Schema

This motor schema will handle the details of moving the wrist reference point toward the mug. The Grasp Schema passes the visually defined target for the move to this schema, as well as the handle orientation, and an expected contact point on the body. The Preshape Schema passes the size of the hand (from the tip of VF2 to the wrist reference point) to it. The Reach Schema will then call the Move Wrist Schema to move the wrist reference point to the target, and it also calls the Orient Hand Schema to point the hand in the right direction. It will terminate successfully when either contact is made on the body referent (in this case, it is also the tip of VF2) or else when it is near the target. The current location of the body referent redefines the target location. If contact is made anywhere else, this schema will terminate with a failure.

We now briefly expand the description of the two subschemas embedded within the Reach Schema. The *Orient Hand Schema* is responsible for aligning the hand with the axis of the handle of the mug. It rotates the wrist until virtual finger 2 is in a position to slide through the mug handle. It must call elementary motor-servo routines to control the actual joints in the hand. The *Move Wrist Schema* will inspect the position of the desired object in body centered co-ordinates. The co-ordinates are mapped onto arm extension co-ordinates, and the wrist is moved to a location near the target but offset by the hand size. If any tactile contact is made in the duration of this schema, it will return indicating failure. It is up to the higher level Reach Schema to decide if this return is acceptable. This schema must call motor-servo routines to actually move the arm joints.

Once the hand is preshaped, and in a position to grasp, the grasping process begins. This consists of the parallel actions of hooking the second virtual finger around the handle, bringing the first virtual finger down onto the top of the handle, and bringing the third virtual finger upwards to a position of support. The visually defined target provided by the embedded perceptual schema becomes tactilely-defined after the successful completion of the Reach Schema. Subschemas activated in the grasping process can use the redefined target.

Hook Virtual Finger Schema

This will incrementally close all joints of a virtual finger until all have achieved tactile contact. Once tactile contact is achieved for a joint, that joint stops moving. When all joints are stopped, the schema terminates. The schema curls the finger towards the the handle even prior to tactile stimuli. This schema is used to hook VF2 around the handle.

This schema may activate the Reach Schema if it has determined that the wrist reference point must be moved backwards in order to achieve contact. It will do so using the inside of VF2 as the expected contact point, as well as using the body referent in aiming.

Oppose Virtual Finger

VF1 is brought to a tactilely-defined target. In this case, VF1's target is where VF2 is touching below the top of the handle. The movement is made as a "curl" of the virtual finger until it makes contact on its tip; contact anywhere else is a failure. It successfully terminates on contact with the handle, before it actually reaches its target.

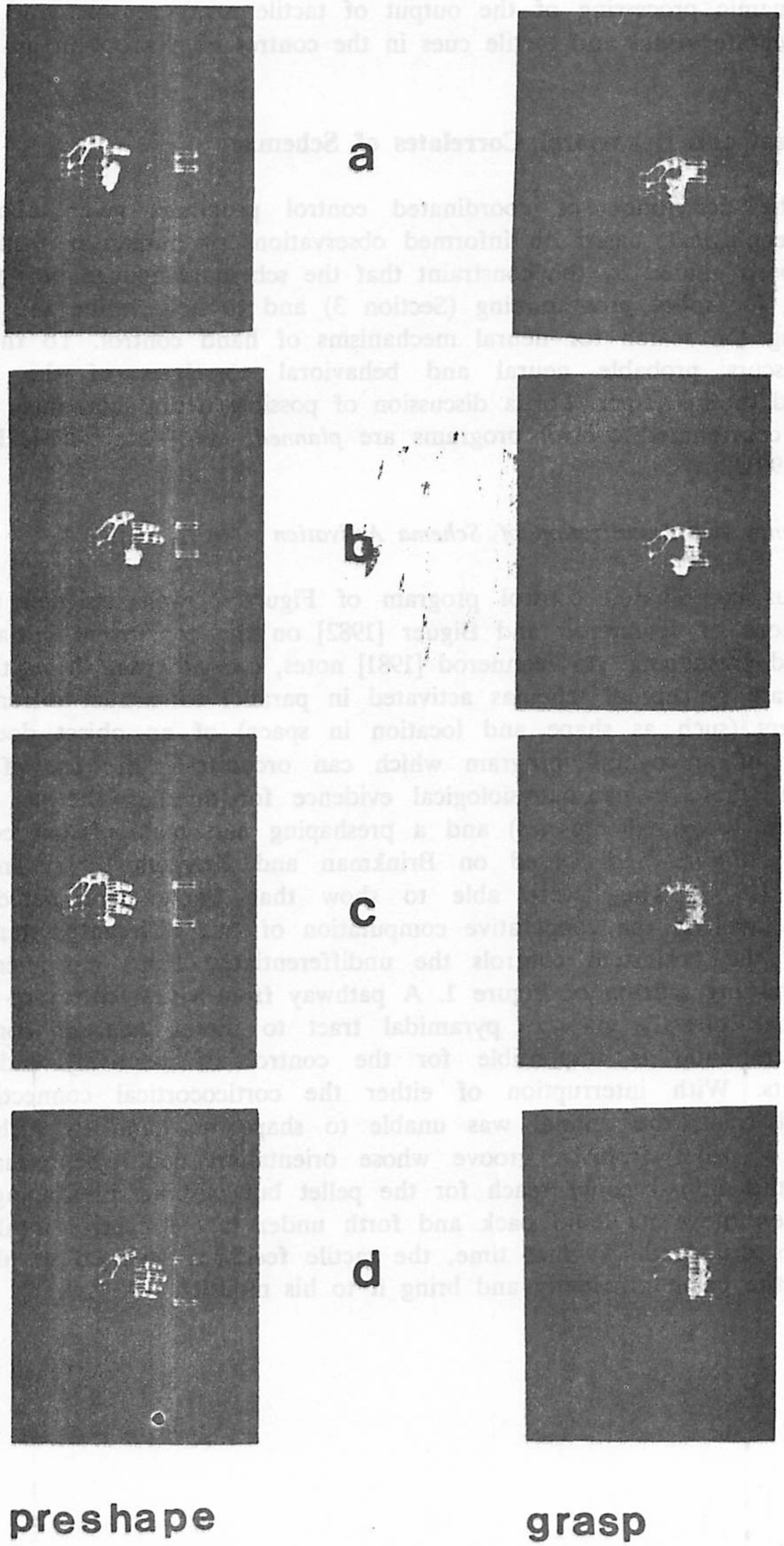
Extend Virtual Finger

If there is a VF3, it is extended towards the underside of the handle. When contact is made with the handle, or when the virtual finger cannot move anymore, successful termination is made.

§3 Schema Language and Simulation

The informal description of schemas given here is being extended to provide a formal schema-based language [Iberall and Lyons 1983] to be used to control robot hands, as well as to describe primate hand control. Further, to test the ideas postulated in this paper, a computer simulation has been constructed. This program simulates parallel schema interactions. The output of the program is a graphic model (Figure 4) of a human or robot hand [Lyons and Iberall 1983]. The model simulates the kinematic structure of the hand, but not its dynamics at present. Joint angles are controlled directly from active schemas without reference to a muscular structure. Included in the simulation is a world model which maintains a database of the hand and any defined objects. The world model then feeds back simulated sensory information corresponding to visual, tactile, and proprioceptive stimuli for a real hand movement. The simulation can be used to provide statistical data for comparison of schema generated movements with recorded human behavior.

Figure 4: Computer simulation of the handle-dependent virtual finger formation, preshaping and grasping behaviors of Figures 2 and 3.



Our work in providing visual and tactile systems for robots is reviewed by Arbib, Overton and Lawton [1984]; while Overton [1983] presents algorithms for static and dynamic processing of the output of tactile array sensors, and analyses schemas that integrate visual and tactile cues in the control of a robot in an assembly task.

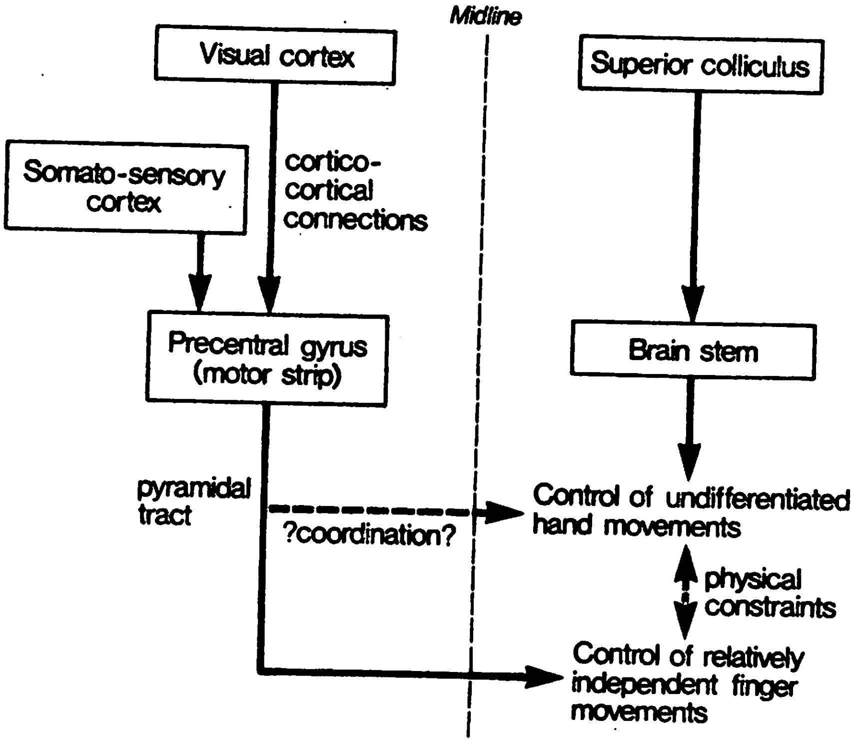
§4 Neural and Behavioral Correlates of Schemas

The description of coordinated control programs given above is essentially phenomenological, based on informed observations of human performance. However, it has been guided by the constraint that the schema language be precise enough to be used for robot programming (Section 3) and to help refine the language used in specifying the search for neural mechanisms of hand control. To the latter end, we now discuss probable neural and behavioral correlates of the schema concepts presented in this paper. For a discussion of possible neural correlates for the processes wherby coordinated control programs are *planned*, see [Arbib 1981, Brooks 1979, and Evarts 1981].

Concurrency and Localization of Schema Activation

Our coordinated control program of Figure 1 was designed to formalize the observations of Jeannerod and Biguer [1982] on the concurrent initiation of reaching and hand preshaping. As Jeannerod [1981] notes, our program shows that the existence of separate perceptual schemas activated in parallel to extract different, task-related, parameters (such as shape and location in space) of an object does not deny the existence of an overall program which can orchestrate the use of these channels. Moreover, there is neurophysiological evidence for dividing the act into a reaching component (proximal muscles) and a preshaping and manipulation component (distal muscles). Figure 5 is based on Brinkman and Kuypers [1972] and Haaxma and Kuypers [1974]. They were able to show that finely coordinated visually-guided behavior involved the cooperative computation of two different systems. A pathway involving the brainstem controls the undifferentiated hand movements akin to the simple grasping schema of Figure 1. A pathway from visual cortex to precentral gyrus and thence directly via the pyramidal tract to motor neurons controls the distal musculature, and is responsible for the control of relatively independent finger movements. With interruption of either the corticocortical connections or of the pyramidal tract, the animal was unable to shape its hand in such a way as to dislodge a pellet from a groove whose orientation could be visually determined. Instead, the animal could reach for the pellet but without preshaping its hand, and would then move its hand back and forth under tactile control until by chance the pellet was dislodged. At that time, the tactile feedback sufficed to allow the animal to grasp the pellet efficiently and bring it to his mouth.

Figure 5: Pyramidal pathway supports schemas for differentiated finger movements, while the extrapyramidal system provides the substrate for a rough grasp schema.



Muir and Lemon [1983] add further support to the hypothesis that direct corticomotoneuronal connections confer the ability to perform discrete finger movements, but their work further suggests that cells of motor cortex may be seen as not related to specific muscle contractions so much as to the activation of muscles within the execution of a specific motor schema. They identified a subpopulation of pyramidal tract neurons (PTNs) with direct influences on motor neurons of small hand muscles, finding that these PTNs are active in the "precision grasp schema" when the muscles are used to position the fingers independently, but not in the "power grasp schema" when a generalized co-contraction flexes all muscles together. The "power grasp schema" must thus be represented by neurons elsewhere. (For more on the power and precision grips, their anatomical basis, and how the decision about which grasp to use depends on the task rather then the shape of the tool, see Napier [1956, 1962]).

Distributed Motor Control

Pitts and McCulloch [1947] offered a model of the superior colliculus in which each collicular neuron was connected to motoneurons whose firing would cause a contraction of oculomotor muscles that would turn the eye in such a way as to center gaze in the direction corresponding retinotopically to the given point in the superior colliculus. Crucially, the model predicts that the response to a complex visual stimulus will be such as to drive the gaze to the center of gravity of the visual pattern. This led Arbib [1972, p.160] to postulate a topographically structured "distributed motor controller" as a basic component of motor systems. The controller has an input surface, stimulation at a point of which will be transformed into the appropriate sequence of motoneuron commands for movement to a spatially corresponding target position. An array of inputs would then yield movement to the average of the encoded motor targets (see the corresponding discussion of "maps as control surfaces" in Arbib [1981]). The hypothesis, then, is that when we look for motor schemas as instantiated in the brain, we should look for a brain region in which inputs are coded retinotopically or somatotopically, and in which activity of an input population yields movement to an average target. Such structures have been found by McIlwain [1982] and Georgopoulos et al [1983a,b], working independently of each other and, apparently, of the earlier theoretical studies.

McIlwain [1982] finds that microstimulation in the intermediate grey layer of cat superior colliculus yields *widespread* synaptic activation of the layer. Yet such stimuli evoke saccades whose metrics seem to depend primarily on the location of the stimulating electrode. This leads McIlwain to postulate, in what may be seen as an updating of the Pitts-McCulloch model in the light of the findings of Robinson [1972, 1981] in the monkey, that the spatial densities of the cells projecting to vertical and horizontal generators of the saccadic system vary systematically beneath the retinotopic collicular map.

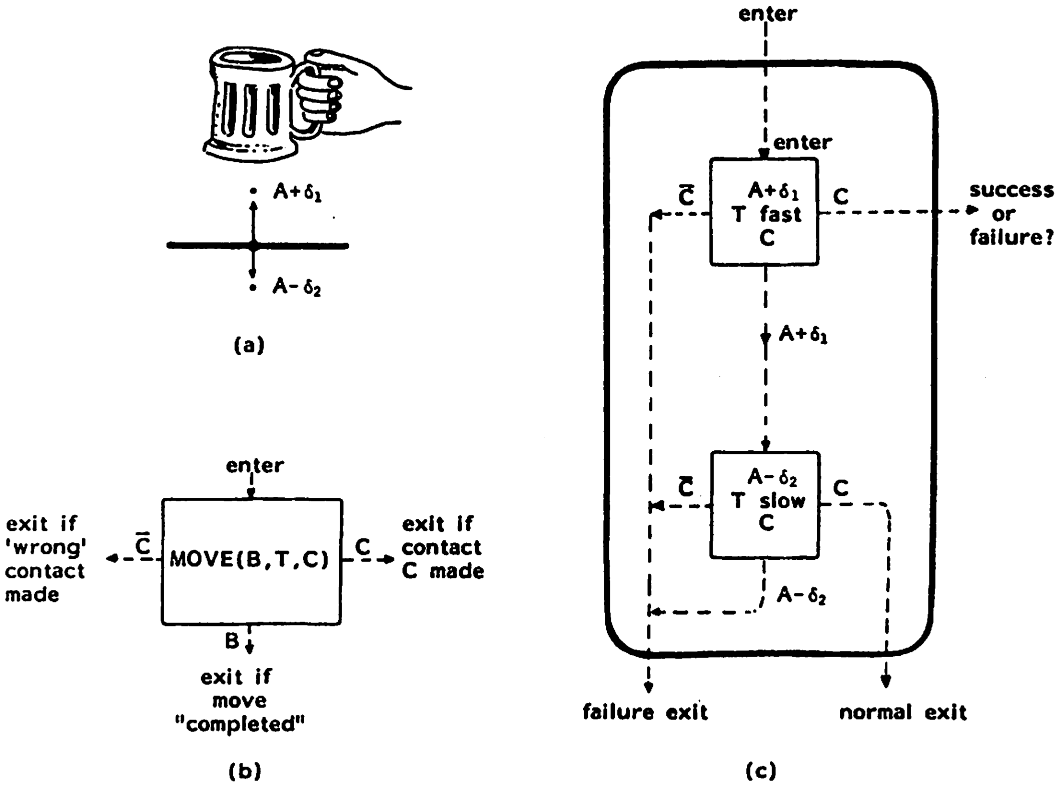
In studies more closely related to hand control, Georgopoulos et al. [1983a,b] recorded neurons in motor cortex of rhesus monkeys contralateral to the arm engaged in moving a manipulandum to capture a visual target. They found that 75% of the task-related cells discharged with higher frequencies with movements in a particular direction, and at progressively lower frequencies with movements made in directions further and further away from the preferred one. Thus, a large population of cells was involved in each movement. In their variant of the Pitts-McCulloch hypothesis, the vector model, Georgopoulos et al advanced the hypothesis that each cell should be viewed as casting a "vote" for movement in its preferred direction, with the weight of that vote given by the amount (positive or negative) by which its firing rate exceeded the average rate; they were then able to show that the corresponding vector sum of neurally coded directions did indeed closely match the direction of arm movement.

Note, however, that their results suggest that for this motor schema it is the *direction* of movement and not its endpoint that is the principal determinant of cell discharge. Since Polit and Bizzi [1979] have posited that the endpoint of the movement is the controlled spatial variable, this suggests that we must search for a re-coding process elsewhere than in motor cortex. Of course, the problem is ever more subtle, as can be seen by examining Figure 3 of Georgopoulos et al. [1983b], which shows the time course of EMG activity of 13 muscles during movements in one direction. We note that there is not only a (frequently bimodal) time course for each EMG trace, but that most muscles have different resting levels of EMG before and after the movement. We may thus suggest that these traces exhibit the activity of two motor schemas, the "move" (which will involve both acceleration and deceleration) and the "hold", with the "hold" perhaps coextensive with the second schema of the two-phase analysis to which we now turn.

Two-Phase Analysis of a Motor Schema

In an informal study of the motor skills involved in drinking beer, [Lyons 1982] observed that the placing of a beer mug could be separated into two phases: a fast movement to a target above the table, followed by a slower movement lowering the mug gently to make contact with the table top (Figure 6a).

Figure 6: (a) The placing of a mug on a table may be seen as composed of two movements: a fast movement to a target $A+\delta_1$ above the intended resting point A on the table (with the 'safety undershoot' increasing with an estimate of decreasing accuracy of the movement), and a slow movement towards a point $A-\delta_2$ just below the table, designed to terminate under feedback control on contact. (b) The basic move schema. (c) The coordinated control program for the movement of (a), involving two calls of the schema of (b), each with different parameters.



Moreover, the distance δ_1 of the first target above the table seemed to increase with decreasing sobriety - suggesting a deliberate undershoot to insure that the first, rapid, movement would not end in a too sharp contact with the table top. This leads us to posit that such a movement can be seen as involving two activations of a basic motor schema, but with different parameters. The basic schema MOVE(B,T,C) is shown in Figure 6b: move to target B with timing parameters T and expected contact C. In the beer-mug example, C is the subtle spatiotemporal tactile pattern to be experienced on the hand when the mug hits the table from above. (Note, again, the need for a complex visual-tactile transformation to anticipate C.) Just what constitutes the timing parameters T is a matter for experiment: candidates include movement duration, peak velocity, average velocity, peak force, etc. All that matters for the present discussion is that we can speak of "fast T" and "slow T". Note that MOVE(B,T,C) has three paths whereby activation can be transferred to other schemas: B (move completed, though probably near B, rather than exactly at B - thus the need for feedback tuning); C (if contact is made with an expected tactile pattern); and C (if contact is made with the "wrong" tactile pattern).

Figure 6c shows the coordinated control program for the two-phase movement of Figure 6a. Activation of the overall program activates MOVE($A+\delta_1$, T fast, C) which should normally terminate by reaching the position (near to) $A+\delta_1$. If contact C is made, there is a "failure exit" - some error-correction schema must be activated - while contact C may be treated either as failure (completion unexpected; check for spilled beer) or success (mug on table). On normal exit from the first schema, control is transferred to MOVE ($A-\delta_2$, T slow, C), with a normal exit occurring on contact C (termination under tactile feedback "in the right ballpark"). Both C (unexpected contact) and $A-\delta_2$ (the table is not where it was thought to be!) are failure exits from the overall schema. We may compare the first schema to a ballistic phase and the second schema to a feedback phase, refining the discrete-activation feedforward schema of [Arbib 1981, Figure 11]; compare Navas and Stark [1968] for the idea that the low-velocity terminal part of the trajectory is a guided phase, while the earlier, high-velocity, phase is ballistic. Jeannerod [1981, 1983] found that prehension movements (cf. Figure 1) involved a fast-velocity initial phase and a low-velocity final phase, with (but not in all subjects) the peak velocity highly correlated with amplitude and total duration independent of amplitude. Moreover, he posits that the reaching and grasping components are temporally coordinated - the fingers, having formed the pregrasp, begin to close in anticipation of contact at the transition from the high-velocity to the low-velocity phase of reaching. However, where Jeannerod would suggest that the timing of the two components is achieved by a centrally generated temporal pattern, we would hypothesize that the activation signal (Figure 6c) from the first subschema to the second schema of a reach movement also serves to activate a second subschema in the grasp - which is precisely the hypothesis (though with a more primitive analysis of the subschemas) embodied in the activation arrow from "adjustment" to "actual grasp" in Figure 1.

§5 Conclusion

This paper has looked at a common hand task and, using the schema architecture postulated by [Arbib 1981], has proposed a small set of interacting motor schemas which will perform the task in a robust way. In the process a schema language was outlined which allows the description of hand tasks in a formal manner. Two crucial concepts of our theory are that the schemas for hand movements are at the level of virtual fingers, and that discrete-activation feedforward may involve the consecutive activation of two instantiations of a given subschema, but with different timing parameters and exit conditions. We have also indicated a few behavioral and neural correlates which test our schema concepts. Other papers will describe the formalism of our schema language [Iberall and Lyons 1983], and its use in computer simulation of hand movements [Lyons and Iberall 1983]. Future work will proceed in two mutually supportive but somewhat divergent directions: the full articulation of a programming language for distributed control of robots with dynamic sensing; and the use of schemas to develop precise models of human and animal behavior subject to behavioral and neurophysiological testing.

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