

Haptic aspects of motor control

Susan J. Lederman¹ and Roberta L. Klatzky²

¹Queen's University, Psychology, Computing and Information Science, Kingston, Ontario, K7L 3N6, Canada and

²Carnegie Mellon University, Psychology, Pittsburgh, PA 15213, USA

Introduction

Psychologists commonly distinguish between channels that process input from sensory activity to representation, and those that process output, to plan and ultimately control action. On the input side, there are numerous studies that have addressed psychophysical and higher-level issues relating to human sensation and perception. On the output side, too, there has been a substantial amount of research, much of it regarding how people plan and control limb movements to accomplish motor goals, such as pointing, grasping, and producing a stable stance. However, there has been noticeably less consideration paid to the nature of the interface between sensory and motor systems: how action is used to effect perceptual goals, and conversely, how sensory systems are used to achieve action goals.

The current chapter attempts to reduce this gap by considering relationships between haptics, a perceptual system that processes both cutaneous and kinesthetic inputs, and the motor system that is used to control the upper limbs (particularly, the hands). We address such relations within the domain defined by hand-object interactions.

In the first part, we examine ways in which people employ systematic patterns of manual exploration, in conjunction with their knowledge of objects, to obtain information about the perceptual properties and identities of objects. In the second part, we consider how sensory inputs and higher-level knowledge are used to achieve predictive, feed-forward control of action.

Action for perception

In this part, we consider selected aspects of our research program on haptics that pertain primarily to knowledge-driven, manual exploration of objects. Such exploration is a form of action that occurs directly in the service of perception. In addition to documenting links between action and perception, the following results serve to elucidate the nature of haptically derived object representations and the underlying perceptual processes used to generate them.

Constrained motion

We begin by considering the consequences for perception of constraining manual exploration. The results of a recent research program on early haptic processing determined which features can be processed relatively quickly following only brief contact that restricted finger motion (Klatzky and Lederman, 1995; Lederman and Klatzky, 1997). A feature is defined as a value or narrow range of values on a perceptually relevant dimension.

The experimental criterion that was used to decide acceptance for inclusion in this set of features was determined by evidence of flat or very shallow haptic search slopes, which were obtained using a haptically adapted version of Treisman's visual pop-out paradigm (see e.g. Treisman and Gormican, 1988). Subjects haptically searched for a designated target (e.g. rough) among varying numbers of distractors (e.g. all smooth) delivered to combinations of from one to six

fingers. The target and distractors differed in terms of their value on a single dimension.

The results of a large set of experiments (Lederman and Klatzky, 1997) suggested that easy intensive discriminations involving material properties and abrupt surface discontinuities were processed in parallel across the entire display, regardless of display size. For most of these tasks, subjects chose to perform haptic search with few, if any, finger movements. In contrast, most discriminations between target and distractors on dimensions involving spatial relations (e.g. planar and 3D orientation, relative position) produced item-by-item search, even when the spatial discriminations were made maximally distinct. For these spatial discriminations, subjects often performed contour-following movements; the latter were observed without exception when the discrimination involved left/right spatial position. Such results indicate ways in which early haptic processing may be constrained when only limited manual exploration is permitted.

The results of another study (Klatzky and Lederman, 1995) address the consequences of permitting such brief manual contact for haptic identification of common objects. Subjects were asked to identify a touched object in one of the following cue conditions: with no advance cue ('what is this?'), with a superordinate-level name as cue ('is this an abrasive surface?'), or with both superordinate and corresponding basic-level names as cues ('is this abrasive surface a piece of sandpaper?'). In the conditions of interest here, haptic exposure was limited to about 200 ms. The objects varied in the most diagnostic attribute (i.e. the property judged by a previous group to be most useful in identifying the object), which was either texture or shape. Even with no cue, confusion errors resembled the target object and indicated extraction of material and local shape information that was sufficient to provide 25% accuracy. Although above chance, this level of identification is well below that achieved when objects are freely explored (see below). Performance improved with cueing, indicating the compensatory effects of top-down processing on restricted feature availability that resulted from constrained motion.

In the next section, we consider why the most accu-

rate haptic object recognition performance can only be achieved through extended, systematic manual exploration on the order of seconds, rather than milliseconds.

Extended manual exploration

Haptic object classification

We turn now to haptic object recognition based on unrestricted manual exploration: under conditions of free exploration, adults are highly skilled at haptic object identification (Klatzky, Lederman and Metzger, 1985). In this study, blindfolded subjects successfully identified 100 common objects (e.g. toothbrush) with almost complete accuracy in just 2-3 s. When asked to explain the basis of their identifications, subjects emphasized the diagnostic importance of a variety of different object properties e.g. surface texture, compliance, thermal conductivity, weight, shape, size, function, etc. The multidimensional nature of the information would seem to be an important factor in determining subjects' successful performance. But how are such features extracted?

Exploratory procedures

The results of the next study (Lederman and Klatzky, 1987) highlight the importance of systematic exploratory hand movements for haptic feature extraction, and more generally, for haptic perception. In the first experiment, blindfolded subjects performed a 'match-to-sample' task. At the start of each trial, subjects were told to manually explore a set of four objects, which varied on many dimensions (texture, hardness, shape, etc.). They were instructed to learn about only a single dimension that was designated by the experimenter (e.g. weight). The first object presented was called the 'standard'; the next three sequentially presented objects were the 'comparison' objects. The subject was instructed to select the comparison object that best matched the standard in terms of the dimension named at the start of the trial. Across the entire experiment, a number of different four-object, custom-designed sets were used in conjunction with each dimension-matching instruction, as shown in Fig. 1. The hand movements for each trial were videotaped and

LATERAL MOTION/
TEXTURE



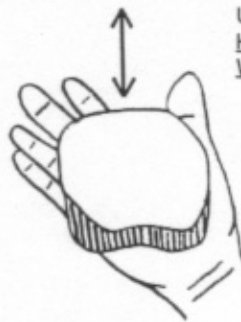
PRESSURE/
HARDNESS



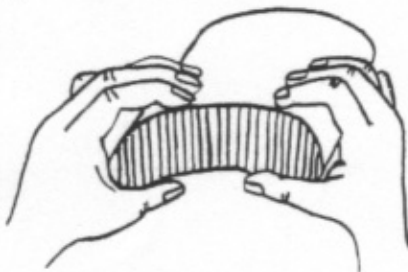
STATIC CONTACT/
TEMPERATURE



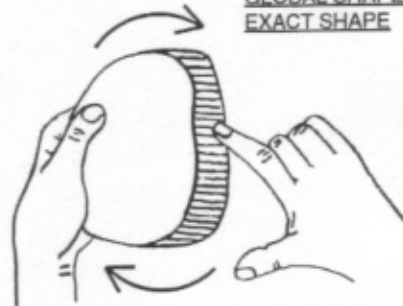
UNSUPPORTED
HOLDING/
WEIGHT



ENCLOSURE/
GLOBAL SHAPE,
VOLUME



CONTOUR FOLLOWING/
GLOBAL SHAPE,
EXACT SHAPE



FUNCTION TEST/
SPECIAL FUNCTION



PART MOTION TEST/
PART MOTION

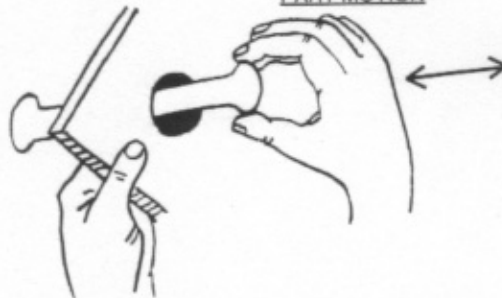


Fig. 1. Schematic representations of exploratory procedures and the properties with which they are most closely associated (reprinted with permission from Lederman, 1991, and revised from Lederman and Klatzky, 1987).

subsequently categorized in terms of common patterns.

The exploratory movements proved highly system-

atic. It was possible to classify them into a number of stereotypical hand-movement patterns, which we have named 'exploratory procedures' (EPs); each EP could

be described in terms of the necessary and typical features of exploration. It was also apparent that subjects deliberately chose to execute specific EPs in conjunction with particular dimension-matching instructions. We present the EPs most relevant to this chapter in Fig. 1.

To match for texture, subjects performed a Lateral Motion procedure; this typically involved repetitive, side-to-side or circular motions across a surface. With familiar objects, this procedure may be reduced to a brief sideways 'swipe'. A Pressure EP was chosen for obtaining information about object hardness or compliance; it required application of a force normal to the object surface, or a torque about one axis of the object. Static Contact was selected to learn about the thermal properties of surfaces; it involved statically resting much of the palm and/or fingers on the surface. Unsupported Holding was used when matching for weight; for this procedure, subjects lifted the object away from a supporting surface, and usually hefted it dynamically. An Enclosure procedure was preferred for extracting both volumetric and global (i.e. low-spatial frequency) shape information; in this case, the fingers and/or palm molded to the object contours. Contour Following, or edge following, was used to extract both global and precise (i.e. high spatial frequency) shape information.

EP characteristics: relative precision, breadth of sufficiency, and duration

By altering one feature of the match-to-sample experiment above, it was possible to gather additional information about the relative performance of the six EPs considered in this chapter. Instead of allowing subjects to manually explore freely, as before, we now asked them to execute only one specific EP in conjunction with a particular dimension-matching instruction (Lederman and Klatzky, 1987, Expt. 2). As an example, on one trial the subject might have been told to make the best texture match using Unsupported Holding, the EP usually selected for weight judgments. Across the full experiment, it was possible to compare the relative precision of the feature information extracted by each EP by pairing each EP with each dimension-matching instruction.

We differentiated EPs in terms of relative performance of a given dimension-matching task. Performance was measured by relative accuracy (and in the case of ties, by speed). For a given dimension, each EP was classified in one of four ways, as follows. An EP was considered to be 'at chance' when subjects were unable to perform the dimension-matching task above chance level using that EP (e.g. texture matching by Unsupported Holding). An EP was classified as 'sufficient', when it produced above-chance, but not optimal, performance (e.g. texture matching by means of Pressure, Static Contact, Enclosure or Contour Following). An EP was classified as 'optimal' when it proved both optimal and sufficient, but not necessary (e.g. texture matching by Lateral Motion). An EP was classed as 'necessary', when it was required for above-chance performance; only Contour Following could be described as 'necessary' (for performing precise-shape tasks). Those EPs that were freely selected in the earlier free-exploration experiment tended to produce optimal performance in the constrained version.

The accuracy data described above provided additional EP information. By summing the number of tasks for which an EP was sufficient, it was possible to evaluate each EP's relative 'breadth of sufficiency'. Thus, Lateral Motion and Pressure each provided sufficient information about several different properties, while Enclosure and Contour Following provided coarse information about most object properties examined in this study (see Lederman and Klatzky, 1987, for details.) Nonetheless, to evaluate overall relative EP efficiency, breadth of property information should be considered along with the execution times obtained in the preceding experiment. The clearest discrepancy applies to Contour Following, which was the most broadly sufficient EP, but also the slowest to execute.

EP characteristics: EP compatibility

Whether or not EPs can be performed concurrently, that is, co-executed, is also relevant to EP selection and implementation. We have developed a set of four visible static and dynamic kinematic parameters with which it proved possible to differentiate EPs. These

were derived from an extensive body of hand-movement data obtained from performance with a large domain of custom-designed and common objects that varied on many dimensions, and that had been tested across a wide range of experimental conditions. Across many different conditions, values for these four parameters regularly occurred for a particular EP. Each parameter can be treated as a constraint inherent in an EP when it must be performed to pick up a particular kind of information. The parameters and their possible values (in parentheses) are as follows: Movement (static or dynamic), Direction of Movement (normal or tangential to the surface), Region (of the object contacted, i.e. surface, edge, or both), and Workspace Constraint (i.e. whether a supporting surface is necessary or not).

To be differentiated, any pair of EPs must differ in terms of one or more parameters. However, if such differences may be reconciled, the EPs are then capable of being co-executed. EP compatibility was assumed to exist when the parameter values for two EPs can be satisfied at the same time by means of some form of exploration. For example, Pressure and Lateral Motion are considered compatible because the normal and tangential forces required by these two EPs, respectively, may be simultaneously satisfied with a single hybrid movement, in which one presses into the surface while simultaneously rubbing across it. In contrast, Static Contact and Lateral Motion are judged to be incompatible because the mismatch between the two movement parameter values cannot be resolved. A set of rules for parameter reconciliation has been developed by Klatzky and Lederman (1993), where the compatibilities and incompatibilities are presented in further detail as well.

The EP characteristics described in this and the previous subsection have also been used as decision rules for predicting how people select and order the sequence in which EPs are performed during various perceptual tasks. We (Klatzky and Lederman, 1993) have modeled the EP selection/property extraction process as a constraint-satisfaction algorithm, using a connectionist approach.

In summary, this section has considered the nature of extended manual exploratory patterns, which we

believe underlie people's considerable skill in recognizing objects haptically.

Further evidence of knowledge-driven exploration

In this section, we expand the perceptual contexts under which evidence for knowledge-driven manual exploration was initially obtained (cf. Lederman and Klatzky, 1987). These studies document a variety of situations in which such movements are used to facilitate perception.

A two-stage sequence of manual exploration during cued object identification

The Lederman and Klatzky (1987) study clearly showed that EP selection is guided by specific task goals: the choice of hand-movement pattern was strongly influenced by the object dimension designated in the match-to-sample instruction. The results also highlighted the fact that EP selection constrains the quality of information (precision, speed of access) and the type of information (breadth of sufficiency) available for further processing.

Based on these earlier results, we predicted that if a person wishes to obtain as much information as quickly as possible about a multidimensional object, he or she should begin exploration with an Enclosure, because it is broadly sufficient and can be rapidly executed. If, however, more precise information about a property is desirable, the haptic explorer might choose to perform the optimal EP, that is, the one known to provide the most precise information about the targeted property.

These predictions were confirmed in a cued, object-identification task (Lederman and Klatzky, 1990). Knowledge of the most diagnostic properties of common-object classes was initially obtained in a questionnaire. This information was used in a subsequent experiment to predict how people would explore actual common objects, that is, which EPs they would choose and the order in which subjects would perform them. In the questionnaire, subjects were asked a number of questions pertaining to which properties determined that an object belonging to a relatively less inclusive class, such as a writing implement, was also

a member of a more specific class, such as a pencil (for a discussion of object classification taxonomy, see Rosch, 1978). Subjects chose diagnostic properties in order of importance from a closed set. They selected 'shape' as the most diagnostic property for the preceding example.

In the subsequent experiment, we implicitly designated an EP for selection by naming the object class for which the property was most diagnostic. (In the 1987 study, we produced differences in EP selection by stating the target property explicitly.) Blindfolded subjects were required to decide whether or not an object, which was physically placed in their hands, was a member of a named category; as before, the name was at either a relatively inclusive or a specific level. Subjects were permitted to explore the objects haptically. Hand movements were videotaped on each trial.

Each trial was analyzed as a sequence of EPs. The analysis showed that subjects consistently ordered the EPs into two distinct classes. This is shown schematically in Fig. 2: percent cumulative occurrence of each EP is plotted as a function of its position in the EP sequence. Stage 1 (thick lines) involved a grasp and lift sequence (Enclosure and Unsupported Holding), regardless of the class targeted in the question. We

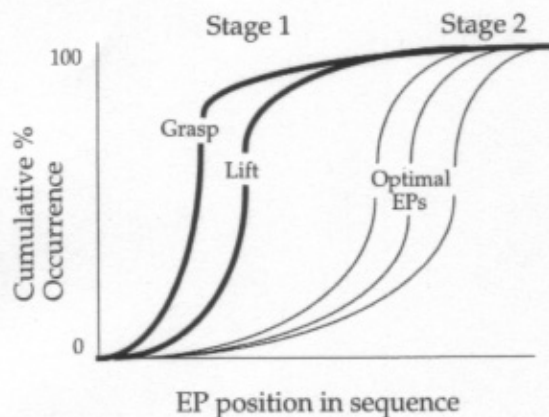


Fig. 2. Schematic representation of the two-stage sequence of manual exploration in a common haptic object-classification task (with permission from Lederman and Klatzky, 1994). EP occurrence is plotted as a function of its temporal position in the EP sequence.

had previously shown that both EPs are relatively broadly sufficient, in that they provide coarse information about most object properties; they are also relatively quick to execute. Stage 2 (thin lines) included optimal EP(s), that is, those that made available the most precise information about the property found to be most diagnostic of the targeted object class.

To summarize, the cued, haptic object identification study demonstrates how EP characteristics (i.e. relative breadth of EP sufficiency; relative EP precision) influence the selection and temporal course of haptic exploration. It also indicates that the value of a property needed for object identification drives exploratory action in the service of perception.

Sorting objects by perceived similarity

We have learned that EPs vary in the relative efficiency with which they provide information about object properties, both when compared to one another and to visual exploration. Both Lateral Motion and Pressure can be performed relatively quickly; they also provide relatively precise information about two dimensions pertaining to the object's material composition, texture and hardness. In contrast, the EPs used to extract information about an object's spatial structure are less effective, being constrained by either their lengthy execution time and/or by the precision of spatial information they can provide: Enclosure is performed relatively fast, while Contour Following can be very time consuming; neither EP provides high-precision spatial information. Compared to haptics, vision is often less efficient at extracting material object properties (e.g. Heller, 1989), and considerably better at extracting fine spatial details (e.g. Walk and Pick, 1981).

Based on documented differences in EP efficiency, we predicted that if subjects had to perform tasks that neither explicitly nor implicitly targeted a particular property, when using touch alone they would attend more to material than to geometric object properties. In contrast, we predicted that when vision was also permitted, subjects would emphasize the geometric properties more strongly; we reasoned that in this case, vision should be considerably more efficient than

any haptic EP at extracting geometry, but less effective at extracting object material properties. Finally, we predicted that the relative 'cognitive salience' of material versus geometric object cues would reflect the subjects' manual exploration patterns, that is, the relative frequency of occurrence with which the associated optimal EPs were performed. We define cognitive salience as the subjective weighting of perceptual dimensions. When no object property is targeted and dimensional variations are perceptually equated (as in the following experiments), we argued that perceptual weighting of properties would reflect general biases for performing the most efficient EPs (re. accuracy and speed).

These predictions were confirmed in two studies (Klatzky, Lederman and Reed, 1987; Lederman, Summers and Klatzky, 1996). In these studies, subjects were asked to sort objects that varied in their material and geometric dimensions: for example, in texture, hardness, apparent temperature, or weight (a hybrid of density and size) vs. shape and size, respectively. The objects represented factorial combinations of values on selected target properties. Thus, for example, in the Klatzky et al. study, three values each were used for texture, hardness, shape and size variation to create a pool of 81 objects. Subjects were required to manually sort the 81 objects into three piles according to perceived object similarity. This meant that if subjects chose to sort by texture, they would have had to aggregate objects on the other three dimensions (i.e. objects with different hardness, shapes and sizes would be placed in the same similarity pile). A sorting pattern of this kind would be interpreted as indicating that subjects judged texture to be more cognitively salient than the other dimensions. Patterns of manual exploration associated with the sorting responses were also analyzed.

The results of both studies (Klatzky et al., 1987; Lederman et al., 1996) confirmed that the relative cognitive salience of material versus geometric object properties is strongly influenced by a modality-encoding bias favoring performance of the most efficient EPs. In each of the four following sorting conditions, subjects manually sorted the objects into piles. When the instructions were neutral ('sort objects into

similar piles') or explicitly biased toward haptic encoding ('sort objects into piles that feel most similar'), subjects emphasized object material more strongly in their sorts than geometry. When the instructions biased subjects toward visual encoding ('sort objects into piles in terms of the similarity of your visual images', or 'sort objects into similar piles' using vision in addition to touch), subjects' judgments indicated that the geometric properties (particularly shape) were more cognitively salient than any material property. In terms of EP selection, subjects' hand movements tended to reflect the perceptual weighting patterns.

The similarity-sorting experiments suggest that in the absence of vision, and when neither explicit nor implicit property goals are designated, subjects form object representations that weight material more strongly than geometric object properties. In contrast, when vision (real or imagined) is also available, subjects tend to emphasize object geometry more strongly in their representations. As explained above, we have argued that this reflects a preference for performing the most efficient EPs.

Haptic exploration in the presence of vision

We (Klatzky, Lederman and Matula, 1993) have also examined the role of manual exploration in perceptual discrimination tasks in which vision was available, but manual exploration was optional. These tasks involved either material (texture, hardness, thermal, weight) or geometric (shape and size) variations. We wished to determine whether constraints on the use of haptic exploration, derived from studies of free sorting without vision, apply when vision is available as an alternative exploratory procedure. The same constraints on performance were assumed to apply for vision as for haptic EPs. Based on the relative efficiency with which haptics and vision extract material versus geometric properties, we expected that subjects would use vision alone for geometric judgments and coarse judgments of material, but that when precise discriminations on material dimensions were required, subjects would use touch, and more specifically, would perform the appropriate haptic EP. In the latter case, the speed with which the haptic EP was initiated was used

to indicate whether visual processing was exhausted prior to invoking the EP.

Subjects were presented with pairs of objects, and asked to decide which object was rougher (harder, etc.). For each dimension, subjects were required to perform both easy and difficult discriminations. So for texture, the subject might be asked: which is rougher: sandpaper or binderpaper? (easy); a marble or a teaspoon? (difficult).

Subjects never used manual exploration when the discriminations were easy. Presumably these tasks could be solved semantically and/or by discriminations that are visually apparent. However, haptic exploration was used reliably during the difficult material discriminations. Moreover, haptic EPs were elicited for material judgments well before the time required to produce a judgment by vision alone, indicating that visual processing was not exhausted before haptics was invoked. Although touch was also invoked for the difficult size discriminations, the movements in this case appeared to help vision more than to effect haptic perception. That is, subjects grasped the objects and moved them closer to their eyes, presumably to improve the visual viewing conditions.

The results of the studies with vision available confirm those for the similarity-sorting experiments in emphasizing the relative importance of material properties of objects for touch (cf. vision). Even when the tasks did not demand the use of touch, subjects chose to use manual exploration to extract precise information about the material properties of objects, and they did so early in processing. Presumably, this is because the perceiver knows that information about object material properties extracted by the associated optimal EPs is of better quality than what can, and was, obtained visually.

Imaging hand movements during imagined perceptual tasks

We (Klatzky, Lederman and Matula, 1991) have also examined imagery involving the haptic system, and whether or not people might use some form of it to facilitate their judgments of object properties under certain circumstances. We began by testing whether haptic exploration might be featured within visual

images of tasks that typically rely on haptic perception, and thus, require actual manual exploration. This hypothesis is based on the idea that invoking haptic exploration within an image would be functional for judging haptically relevant properties, just as visual processes can be invoked within visual imagery for judging visually relevant properties. We expected haptic exploration to occur within visual images, since we assumed that vision is a dominant modality for imagery, whereas haptic imagery is relatively weak (as observed by Katz in 1925).

We tested two predictions. First, visual imagery of manual exploration should occur most often when accessing information about properties that would tend to be extracted haptically, that is, material properties of objects. It should occur less, if at all, with properties that would likely be extracted visually without contact or movement; for reasons explained above, these would tend to include geometric properties and could also include visually obvious material discriminations. Haptic imagery should also occur less when judgments can be made on the basis of a priori semantic knowledge, which precludes the need to extract perceptual properties (e.g. we know that a brick is rougher than a piece of satin). Second, we expected imagined manual exploration (and more specifically, imagined EPs) to be appropriate for the property of interest, as shown in Fig. 1.

An initial experiment confirmed that appropriate haptic exploration occurred within subjects' visual images, when information was required about haptically salient object properties. Each subject was asked to scale the magnitude of a given property of a single common object (e.g. the roughness of a pear). (Only a single question was asked, to preclude prejudicing judgments.) Across subjects, questions requested information about material (texture, hardness, apparent temperature, and weight) and geometric (shape and size) properties of common objects. After completing the scaling task, the subject was asked whether he or she had formed a mental image during the response, and if so, what it was like. Finally, the subject was prompted to say whether or not a hand had appeared in the image, and what it was doing. In keeping with our predictions, a significant proportion (30–35%) of

the subjects not only reported mental imagery, but also saw their hands performing the optimal EP for the dimension named when a material dimension was relevant; in contrast, few such reports were obtained with the size and shape questions.

In a second experiment, each subject performed a single perceptual discrimination between a named pair of common objects. Questions pertained to the six dimensions considered in the first experiment. To test the second prediction further, that exploratory imagery was most likely to occur when a priori semantic information was not available, both easy and difficult perceptual discrimination questions were used (see previous subsection). A substantial proportion (50–60%) of the subjects reported imaging their hand as it executed the EP that was optimal for extracting specific information about a named material property; however, with the exception of the weight dimension, this only occurred with difficult discriminations.

The results of the present study indicate that the importance of motor movements for haptic perception extends to imagined haptic perceptual judgments that cannot readily be solved by visual processing alone or by memory retrieval.

'Perceptual gating' due to constraints on EP selection and implementation

In other work, we (Klatzky, Lederman and Reed, 1989; Reed, Lederman and Klatzky, 1990; Lederman, Klatzky and Reed, 1993) have explored the role played by purposive exploration in constraining the kinds and relative precision of information available for simultaneous haptic processing along multiple dimensions. We examined the extent to which variation along one dimension might affect the speed with which subjects learn to classify unfamiliar objects that vary on more than one dimension. A number of dimensions were considered across the complete set of experiments. However, we will discuss the principal findings by considering only three: texture, hardness and shape.

We began this program using the set of planar objects described in the similarity-sorting studies in 'Haptic exploration in the presence of vision' above

(Klatzky et al., 1989). Subjects were required to learn to identify a particular set of objects by name (i.e. 'A', 'B', 'C'). The objects in any given set were grouped according to different classification rules of which the subjects were unaware. A one-dimensional rule classified multidimensional objects by changes on just one dimension (texture, hardness, or shape). Various two-dimensional (texture/hardness; texture/ shape; shape/hardness) and three-dimensional (texture/ hardness/shape) redundancy rules classified objects by redundant variation on two dimensions (e.g. hard and rough vs. soft and smooth; hard and rough and one-lobed vs. soft and smooth and two-lobed, respectively). Adding redundant information speeded object classification, such that the mean response time averaged across all two-dimensional tasks was shorter than for all one-dimensional tasks, particularly for texture/hardness vs. either texture or hardness alone. In keeping with Garner (1974), we call this a 'redundancy gain' effect. However, adding a third redundant dimension had no additional positive effect on response times. We suggested the differences in dimensional integration were due to whether or not subjects could extract the dimensional variations simultaneously, which as discussed in 'EP characteristics: EP compatibility' above, depends in turn on EP compatibility.

We then employed a different experimental paradigm known as 'redundancy withdrawal' to explore this interpretation further. Subjects initially learned a two-dimensional redundancy rule in which one of the two dimensions was targeted; when their performance asymptoted, the non-targeted dimension was withdrawn, unbeknownst to the subject; that is, it was held constant. The increase in response time following withdrawal of the non-targeted dimension served as a measure of the extent to which the two sources of information were integrated. For example, as above, we found that redundant variation in both texture and hardness was well integrated, regardless of the dimension withdrawn (i.e. there was an increase in response time). However, there was little or no effect of redundancy withdrawal when either texture or hardness varied redundantly with shape (i.e. no change in response time following withdrawal of information

about the non-targeted dimension). This is not surprising, because neither Lateral Motion (optimal for texture) nor Pressure (optimal for hardness) is compatible with Contour Following (optimal for shape, which for these planar objects was only available along the edges).

Haptic integration was also investigated using spatially 3D ellipsoids of revolution that varied in shape (ratio of major to minor axes) and texture (Lederman et al., 1993). Unlike the planar objects used previously, information about both dimensions was potentially available through a local contact. Recall that for the planar objects, texture was located on interior surfaces whereas shape information was restricted to the outer edges. In this case, unlike the planar objects, there was a redundancy gain across shape and texture. (An alternate paradigm, known as 'orthogonal-insertion, produced results that converged nicely with those obtained with the redundancy-withdrawal paradigm; for details, see Lederman et al., 1993).

In summary, the studies in this section clearly highlight ways in which EP selection and implementation necessarily limit the type and precision of property information available for further object processing.

Summary

In the first part, we considered how action, and more specifically, hand movements, are employed in the service of perceptual goals. The emphasis was primarily on knowledge-driven influences on hand movements. We found that exploratory action could be predicted by perceptual goals in a variety of contexts: when a specific property was targeted for perception by instructions, or when a property was diagnostic of an object that was to be identified, exploratory hand movements were optimal for the desired information and/or were broadly sufficient. The same principles applied when vision was an exploratory option, even in the imagery domain. Conversely, exploration constrains perception: in free exploration, efficiency of exploration determined what EPs were executed and thus influenced the cognitive salience of perceptual properties. When multiple properties were relevant to

a task, the ability to simultaneously execute multiple EPs limited which and how many were perceived.

Perception for action

The focus of the second part parallels that of the first in its emphasis on anticipatory feedforward control, here specifically of kinematic and kinetic hand/arm parameters during pre-contact and early post-contact phases of the action cycle. We focus on what is known about anticipatory control via visual and haptic inputs, along with prior knowledge about functional movements.

Pre-contact

Anticipating some motoric interaction between hand and object, a person needs to adjust the position of the arm-hand system, and to alter the shape of the hand appropriately. Jeannerod (e.g. 1981, 1984) has proposed that there exist two separate, but temporally integrated, visuomotor channels that handle the pre-contact functions just described: a transport component for arm movement and a grasp component for manual interactions.

Arm transport and hand pre-shaping movements based on visual feedback

An extensive body of research has investigated the role of visual target cues in adjusting the kinematic parameters involved in arm transport and hand pre-shaping. As this topic has been considered in considerable detail elsewhere, we direct the interested reader to recent papers and reviews of this topic by Jeannerod (1988), Lederman (1994) and MacKenzie and Iberall (1994).

Anticipatory effects based on functional interactions with objects

Several experiments have shown that the functional requirements of a specific hand-object interaction strongly influence how subjects set certain kinematic parameters of arm transport and hand pre-shaping prior to contact. These requirements may be communicated through perception of the object and task context or by pre-set task demands.

A study by Marteniuk, MacKenzie, Jeannerod et al.

(1987) demonstrates the influence of functional constraints on the kinematic aspects of arm transport. Among other things, these investigators required their subjects to grasp a light bulb or a tennis ball, thus varying the fragility of the object to be grasped. They examined both movement duration and velocity profiles, with the latter further separated into acceleration (prior to peak velocity) and deceleration (following peak velocity) phases. Movement duration proved to be longer for the more fragile lightbulb. This result appeared to be due primarily to an increase in the length of the deceleration phase. Marteniuk et al. interpreted these findings as being the result of differences in task-precision requirements, with greater precision being required to grasp the lightbulb than the tennis ball.

In a study by Fikes, Klatzky and Lederman (1994), subjects were required to reach and lift a slippery dowel as opposed to a normal (polished metal) or rough-surface dowel in random order (also see Weir, MacKenzie, Marteniuk et al., 1991). Vision was available in all conditions, and the point of visual onset was strictly controlled, allowing for the measurement of pre-movement reaction time and movement time. Since the object's surface characteristics were unknown prior to visual exposure, the reaction time presumably included the time to plan the interaction, given information about the surface. Pre-movement reaction times were similar for all three object conditions, indicating that advance planning for simple grasping does not require additional time when the surface is slippery. However, subjects did spend more time during the pre-contact movement phase when interacting with the slippery object. Fikes et al. interpreted these results in terms of the greater constraints imposed on the geometry of the grasp and the dynamics of the grasping, both of which increase for a slippery object because of the lower tolerance for error. Lower friction between skin and surface requires more precise finger placement on the object relative to its centre of mass. And slowed lifting of the slippery object appears to reflect the additional time needed to apply an adequate grip force. Like the Marteniuk et al. study, increased precision demands on object interac-

tions may translate into effects on movement kinematics.

Klatzky, Fikes and Pellegrino (1995) showed similarly that when an object was placed on a slippery surface and subjects had to make contact without moving it, movement time decreased. In this case, however, there was also a clear increase in the pre-movement reaction time, relative to a condition with a stable surface. They attributed this effect to planning of arm transport in the period prior to the onset of movement, not just the interval between movement onset and contact. This planning presumably adjusted the anticipated force at contact to accommodate the slippery surface.

Arm-movement planning has been demonstrated in a series of experiments by Rosenbaum and associates (Rosenbaum, Vaughan, Barnes et al., 1990). They asked subjects to grasp and turn a handle, thus rotating a disk from a starting to an ending orientation. The subjects had to determine whether to grasp the handle overhand or underhand. The probability of an overhand vs. underhand grasp was found to depend on the end position of the handle, indicating that subjects planned the arm orientation for initial contact on the consequences of the subsequent action. The authors proposed a planning constraint called 'end-state stability', according to which subjects tried to complete the arm movement with the arm at an intermediate, resting orientation.

More recently, Rosenbaum, Engelbrecht, Bushe et al. (1993) have devised a 'knowledge model' for reaching movements, in which pre-movement planning, based on movement constraints, plays a critical role. The model assumes the existence of a base of stored postures that can be evaluated before a movement is executed. Each posture is considered as a possible final posture for the movement, and a cost function is computed, reflecting the resulting spatial error and the cost of travel from the current posture, the latter in terms of degree of displacement and biomechanical factors. A target posture is then computed by averaging over all candidate postures, each weighted according to its cost, so that the average is dominated by those postures having low total cost. The requisite

movement to achieve that average posture is then generated.

Klatzky and her colleagues have argued that pre-contact planning processes concern not only movement of the arm, but also pre-shaping of the hand for functional interaction with the contacted object. They have extensively examined the effects of task-function demands on the selection and formation of hand shapes. They distinguish among four general categories of hand shapes used in functional interaction with objects, representing the crossing of two binary variables: whether or not contact involves prehension, and the size of the hand surface contacting the object (large; small). The resulting four hand shapes are clench (large surface with prehension), palm (large surface without prehension), pinch (small surface with prehension), and poke (small surface without prehension).

Klatzky, McCloskey, Doherty et al. (1987) showed that when subjects freely select the most natural hand configuration to use with an unfamiliar object, in the absence of any functional requirement, there is a reliable mapping between the hand shapes and structural properties of the object. Small object surfaces tend to elicit small hand shapes, and the tendency to use prehension increases with the degree to which the contacted object surface extends outward from the background support surface. There are also reliable associations between hand shapes and actions on familiar objects, and in some cases, these associations violate the mapping based on structure alone. For example, function overrides form in determining that a needle must be grasped for use.

Pellegrino, Klatzky and McCloskey (1989) showed that the four hand shapes can be distinguished early (within 150 ms) in the course of reaching for an object with the goal of functional interaction. The short latency for pre-shaping, less than the typical duration of a simple reaction time, suggests that the pre-shape was planned prior to the start of reaching, that is, before movement onset.

Klatzky et al. (1995) tested a model that proposed two pre-movement planning processes, one for the hand shape and one for arm transport. These were assumed to operate in parallel, with the onset of arm

movement delayed until both processes were completed. This model predicts that when one of the planning processes is very slow, it will dominate the pre-movement time (i.e. movement onset must wait for the completion of this slow process), so that a variable that alters the duration of the other, faster planning process will have no observable effect. In support of the model, consider the effect on pre-movement time of the slipperiness of the object support surface, which should influence the planning of arm transport (especially terminal force). The slipperiness effect was robust when highly compatible mappings between hand shapes and objects were used, but was reduced when incompatible mappings were introduced, presumably because those mappings slowed the time to plan the hand-shaping component. Hand-shape planning then dominated the pre-movement time and obscured variations in the time to plan arm transport, as a function of slipperiness.

In summary, given comprehensive descriptions elsewhere, this section only mentions the important role played by visual cues in the anticipatory adjustment of the kinematic parameters affecting the arm transport and hand pre-shaping phases that precede contact. It focuses primarily on anticipatory effects produced by functional interactions with objects.

Post-contact

Following contact with the object, one must coordinate the manual forces applied to the object, whether this serves to achieve a stable grasp, to hold it above the supporting surface, or to move it about in space.

Anticipatory adjustment of grip forces during grasp/vertical lift sequences

Johansson and his colleagues (e.g. Westling and Johansson, 1984; Johansson and Cole, 1994) have performed a comprehensive examination of the adjustments in grip force as a person grasps an instrumented object with thumb and forefinger, lifts it vertically from a supporting surface, holds it there, and then returns it to the surface. Normal grip force and tangential load force appear to be coordinated over the sequence of phases that delimit the task (Fig. 3).

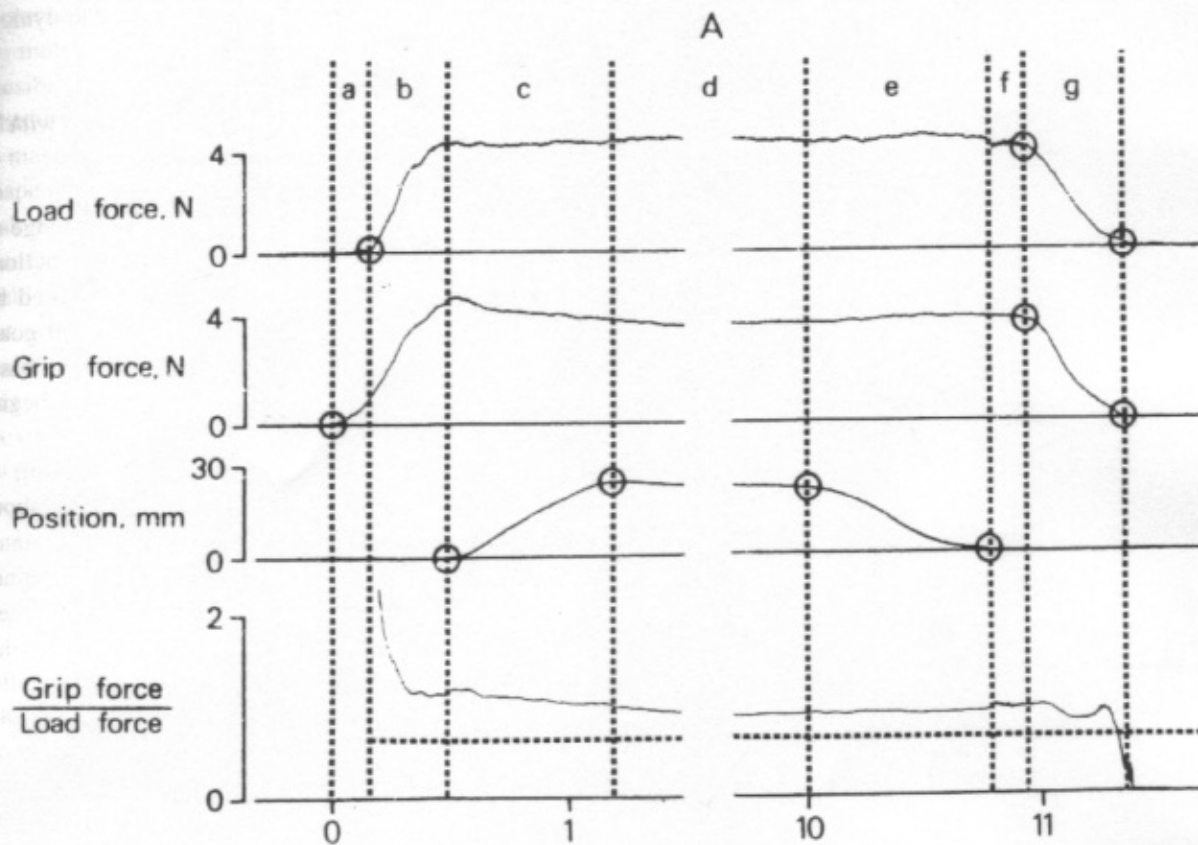


Fig. 3. Load force, grip force, vertical position and ratio between grip and load force as a function of time for a sample trial (weight of object = 400 g, surface structure = sandpaper). The phases indicated were common for lifting trials: (a) preload contact phase; (b) loading phase; (c) transitional phase; (d) static phase; (e) replacement phase; (f) delay; (g) unloading phase. (Reprinted with permission from Johansson and Westling, 1984.)

Contact with the object marks the start of the first interval of the lift (a). Following contact, the grip and load forces increase in parallel, ending when the load force is greater than the object's weight, and the object begins to move (b). The object is moved vertically to the desired terminal position (c), and held there statically (d). The succeeding phases (e-g), in which the object is returned to the supporting surface, mirror those during ascent. The grip/load force ratio is adjusted to achieve a small safety margin that is sufficient to prevent slip, as determined by the coefficient of friction.

The prehension task just described serves as a prototype for a class of grasps shown to operate under predictive feedforward, rather than closed-loop feed-

back, control. Subsequent experiments have shown that subjects modulate the safety margin in an anticipatory fashion, using sensorimotor memories of recent lifts to adjust for expected friction and weight on the subsequent trial (e.g. Johansson and Westling, 1984, 1988). In addition, subjects use visual and haptic feedback about object size (Gordon, Forssberg, Johansson et al., 1991a,b) immediately before an object is lifted, to smoothly modulate the development of isometric forces during the loading phase.

Further examples of anticipatory adjustment of grip forces during translatory arm movements

When a person not only grasps an object but also transports it horizontally through space, the load force

is necessarily increased owing to the additional inertial forces produced by the acceleration and subsequent deceleration of the moving arm. This increase in load force could well exceed the safety margin, causing the object to slip, unless the person upwardly adjusts his or her grip force sufficiently. Flanagan and Wing (e.g. Flanagan and Wing, 1993; Flanagan, Tresilian and Wing, 1993; Wing, 1996) measured load and grip forces as their subjects moved an instrumented object horizontally from right to left, in a 30-cm straight line, at moderate or fast speeds. Grip force increased just before that of the load force (the latter indicates when the object began to move). This result suggests that the increase in subjects' grip force was anticipatory. Faster movements produced larger peak grip forces, as expected, since they are associated with greater acceleration and, thus, with larger load forces. That peak grip force depends on peak load force further suggests that the subject is compensating for the changes in load force resulting from different arm movements.

Subjects were also required to perform movements between endpoint positions that were vertically aligned. Under such circumstances, grip force increased immediately with upward movement, but was delayed (or slightly decreased) with downward movement until the load force increased significantly above the baseline during the later decelerative portion of the arm movement. With faster downward movements, grip force increased earlier in keeping with the substantial load force that developed during the early phase; grip force also attained a higher peak value during the deceleration phase. The authors suggest that the timing of the increase in grip force is associated with the increase in load force, and not the onset of arm movement. The anticipatory modulation of grip force with changes in load force has been observed across a range of grips, e.g. one involving the left and right index fingers, and another requiring outward-directed forces produced by the thumb and the forefinger (Flanagan and Tresilian, 1994).

In summary, this section clearly demonstrates that people adjust their grip force in anticipation of a change in load force, the latter influenced by memory of object conditions during previous trials, by changes

in object texture, size, and weight, and by the dynamics of arm movements.

Cognitive representations of functional actions with objects

In this last section, we address people's knowledge of the movements that underlie functional interactions with objects, where the interactions are described by simple verbal phrases expressing environmental goals (e.g. crush a coke can, fasten a snap). It is on the basis of such knowledge that planning processes can begin, even in the absence of perceptual inputs.

Klatzky and associates demonstrated, using a priming paradigm, that people have knowledge about the hand shapes involved with functional interactions with common objects (Klatzky, Pellegrino, McCloskey et al., 1989b). Subjects were first trained to associate a cue to each of the four hand shapes described earlier (pinch, poke, palm, and clench; e.g. the cue to a clench was <<<<<). In a subsequent task, subjects made timed judgments as to whether an action on an object was sensible (e.g. squeeze a tomato is sensible; crumple a window is not). The time to make the judgments was reliably decreased by a cue to the relevant hand shape (e.g. for squeezing a tomato, the clench shape), indicating that stored knowledge about functional movements included knowledge about the associated hand shape.

Two findings suggested that the knowledge about the hand shapes was a fundamentally motoric representation. First, the hand-shape prime was effective only when subjects were trained to make the shape to the prime cue (i.e. to clench the fist when shown <<<<<), and not when they verbalized the name of the shape. Second (McCloskey, Klatzky and Pellegrino, 1992), motor interference eliminated the priming effect, as follows. Subjects who had been trained to make a hand shape to the prime were transferred to a series of trials in which the prime might be followed by a sensibility judgment, as before, or alternatively, by a motor task: tapping a sequence of buttons or verbalizing a sequence of syllables (the tasks were equated for complexity and difficulty). Because the subjects did not know whether the priming task or the

motor task would be called for, they had to anticipate the motor task during the initial phase of trials where a sensibility judgment eventually ensued. The issue was whether the priming effect (i.e. a reduction in the time to make the sensibility judgment after a relevant hand-shape cue) would still be present, given that the motor task was anticipated between the prime and the judgment. When the possible motor task involved the hand, the hand-shape prime no longer had an effect, but when it involved speech, the priming effect remained. This indicates that the prime representation was interfered with by anticipation of other manual movement but not movement of the speech musculature, indicating that the representation was motorically specific.

In subsequent work, we (Klatzky, Pellegrino, McCloskey et al., 1993b) evaluated other parameters

of functional object interaction that might be represented by motoric knowledge and used in initial stages of action planning. We began by asking subjects to rate each of a large set of actions with respect to six dimensions: the amount of the limb moved (from only most distal to whole limb), the distance moved, degree of forcefulness, the effectors involved, the size of the contact area, and the resemblance to a grasp. Factor analysis of the resulting ratings revealed two distinct underlying factors, one pertaining to limb movement/force and the other to the effector (usually the hand) configuration. We then required subjects to sort a subset of the actions used previously, according to the similarity of movement involved. Cluster analysis (Fig. 4) and multidimensional scaling again showed a primary distinction between the hand and the arm; for example, actions involving full arm motion, like

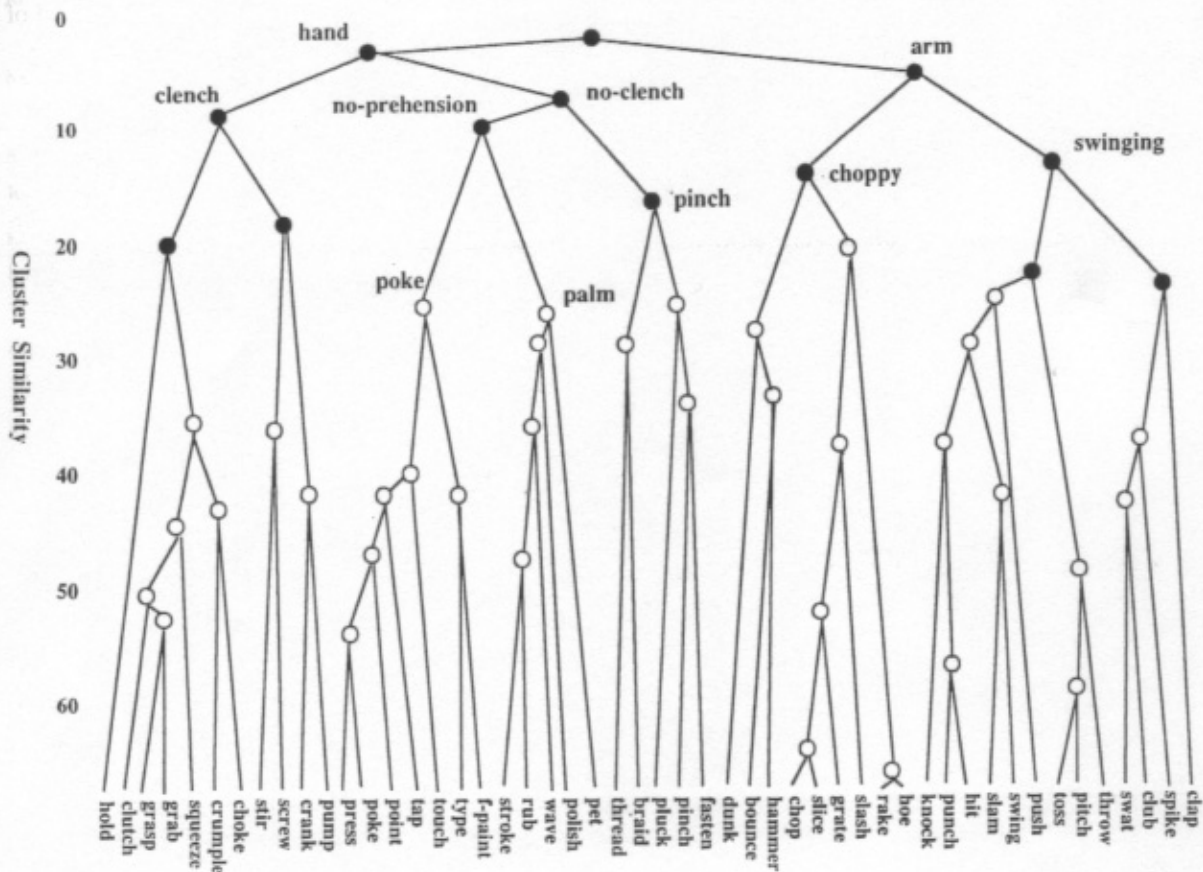


Fig. 4. Cluster solution to the sorting data. Filled circles mark nodes having components with similarity less than 25. Node labels suggest the nature of the component groups. (reprinted with permission from Klatzky et al., 1993b).

throwing a baseball, were maximally separated from actions like holding a water drop. The predictor variables from the initial rating study were highly correlated with analyses of the similarity data from the second. The results support the existence of cognitively accessible, though still relatively specific, representations of functional actions, representations that incorporate biomechanical, kinematic, and dynamic distinctions.

In summary, research results discussed in this section address what people know about the movements that underlie functional interactions with objects. This includes knowledge pertaining to the hand shapes associated with specific interactions; such knowledge is stored primarily in the form of motor representations. Other parameters of functional interactions with objects, which are represented by motoric knowledge, are also considered.

Summary

This part of the chapter has emphasized how perception can serve to guide and control action. We have described work indicating that on the basis of perceptual cues and task demands, people plan movements before starting to make them and make adjustments during the interval between the start of reaching and contact. These plans and adjustment pertain to both the arm and the hand. Subsequent to contact, further adjustments are made on a feedforward basis from perceived tactual and visual cues to prevent slip.

Chapter summary

The present chapter has addressed the nature of the two-way interface between haptic perception and action, specifically with respect to hand-object interactions. The first part dealt with how perceptual goals constrain exploratory actions, and how in turn, exploration constrains what is perceived. In addition to documenting links between action and perception, the results considered here help to clarify the nature of haptically derived object representations and the underlying perceptual processes used to generate them. The second part examined how sensory inputs (haptic,

visual) and higher-level knowledge are used to achieve predictive, feed-forward control of action, particularly grasping and manipulation. We also considered the nature of higher-level knowledge about functional interaction that might constrain manipulation at very early stages.

In this chapter, then, we have emphasized the interplay between perception and action. While they are commonly studied as separate entities, it is crucial to recognize the intimate interconnections between these two processing systems.

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