2. PLANS FOR GRASPING OBJECTS*

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Abstract

Through the lens of prehension research, we consider how motor planning is influenced by people's perception of, and their intentions for how to act in, the environment. We review some noteworthy prehension phenomena, including a number of studies from our own labs which demonstrate the "end-state comfort effect," the discovery of sequential effects in motor planning, and the finding that postural end states are known before movements begin. The existence of these phenomena highlights the role that mental representation plays in motor control. We review a recent model of motor control which can account for both perception-related and intention-related features of motor planning.

Introduction

Humanoid robots have made great strides in the last decade. Some modern versions can walk (Sony QRIO, Honda Asimo), vocalize (KRT-v.3—Kagawa University), smile and frown (WE-4R—Waseda University), play the trumpet (Toyota's Partner robot), and hit baseballs at 300 km/hour (University of Tokyo)[1]. However, robots still cannot pass a Turing test for action. A two-year old human can effortlessly pick up objects and inspect them, but robots need extensive intervention to complete such a task. They have difficulty analyzing unfamiliar scenes and deciding how to grasp and manipulate objects of interest. The problem is not merely that robots are unable to achieve basic visual processing or basic motor control. Instead, the problem is that they are poor at planning actions. In order to follow a simple instruction to pick up a rock, a robot must somehow answer questions such as: "From what directions should I approach it? Should I grab it on that outcropping closest to my left? Which posture will allow me to reach it?" and so on. Progress in robotics, as measured by the ability to endow robots with the capacity for autonomous planning, will have achieved a milestone when such questions can be answered without human intervention and when the solutions that are arrived at are indistinguishable from the solutions that normal humans arrive at. When robots can pass such a Turing test for action, we will be able to say with confidence that we truly understand how actions are controlled.

While the foregoing is concerned with robots, this chapter is not about robotics per se. The focus instead is on human action planning, and in particular on how humans plan the grasping of objects. We focus on this aspect of planning because it has been the center of much of our work in the past several years, owing to our belief that the study of plans for grasping

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[1] See http://informatiksysteme.pt-it.de/mti-2/cd-rom/index.html for the state of technologies in human-computer-interfaces

objects provides a window into the nature of planning generally.

The plan for the chapter is as follows. In the first section we describe studies of how grasps depend on the physical properties of the object being grasped. Here we focus on such variables as the size, distance, and direction of the object to be taken hold of and the way these factors affect prehension. In the next section we focus on the way grasps depend on actors' intentions. We focus here on ways that prehension of the same object changes as a function of what one intends to do with the object. In the third part of the chapter, we describe a computational model inspired by and in turn constrained by the results of the findings reviewed in the first and second sections. In the fourth and final section we offer conclusions and consider challenges for future research.

Some disclaimers are in order. Several topics will not be covered here even though they relate to the general topic at hand. These include the neurophysiology of motor planning for grasping and other tasks (e.g., Jeannerod, 1994), studies of haptics for already picked up objects (e.g., Carello & Turvey, 2004), studies of object manipulation that were mainly designed to investigate perception rather than motor planning per se—for example, studies on the possible dissociation of the "what" and "how" visual systems (e.g., Milner & Goodale, 1995), and studies of auditory depth perception (Clifton, Rochat, Litovsky, & Perris, 1991). We omit these topics because this chapter is intended as a selective review of studies from our laboratory. Our research is psychological rather than physiological. We seek a functional analysis of the *software* involved in the formation and implementation of plans for grasping objects rather than a physical analysis of the corresponding *hardware.* As cognitive psychologists, we are interested in uncovering functional principles that, in principle, can be implemented via different hardware—either neural (as in animals) or electro-mechanical (as in robots).

Grasping Based on Perception

How we grasp an object may be influenced by physical properties (of the environment, the object to be grasped, and our own body) which we perceive, and by the effects (on the environment, the object, or ourselves) which we intend to create with that object. We will first consider the influence of the object's physical properties such as size, direction and distance on grasping. In the next section we will discuss how grasping is affected by intention, or by the object's affordances (Gibson, 1979).

Seminal studies of the kinematics of the upper extremity during reaching and grasping objects of different size, direction, and distance were conducted by Jeannerod (1984; 1994), who focused on the transport of the wrist and the opening and closing of the fingers as normal human adults reached for one object at a time. On the basis of Jeannerod's studies as well as the host of studies that were inspired by his work, a number of empirical relations were demonstrated, which we summarize below, drawing on a review we provided of prehension phenomena in an earlier publication (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). Briefly, the phenomena were as follows:

1. When the hand opens to reach for something, the fingers often move much more than the thumb does.
2. The aperture between the fingers and the thumb generally reaches its widest opening in the second half of the movement time (Jeannerod, 1984).
3. The speeding-up phase of a reaching movement is shorter than the slowing-down phase (Jeannerod, 1984).
4. Elbows and shoulders generally display bell-shaped angular velocity profiles (Jeannerod, 1984).
5. Although maximum aperture increases linearly with object size, the slope of the line relating the two is less than 1.0 (Marteniuk, Leavitt, Mackenzie and Athenes, 1990).
6. Maximum aperture occurs relatively later in the reach for a larger object (Marteniuk et al, 1990).
7. Maximum aperture does not depend on the distance to the object being grasped.
8. Maximum aperture tends to increase as movement speed increases (Wing, Turton, & Fraser, 1986).
9. A low-velocity phase is apparent in some reaching movements but not others (Jeannerod, 1981; Wallace & Weeks, 1988). For example, Marteniuk, MacKenzie, Jeannerod, Athenes and Dugas (1987) found that the shape of the velocity profile was different for a reach to a tennis ball than for a reach to a light bulb. The slowing-down phase lasted relatively longer when reaching for a light bulb than when reaching for a tennis ball.

Grasping Based on Intention

The foregoing studies focused on changes in the kinematics of the hand and arm depending on physical properties of objects to be grasped. Object manipulation also depends on what one intends to do with the object or, said another way, with perception of the object's affordances at the moment.

The first investigation that revealed a dependence of prehension on actors' intentions was conducted by Marteniuk, MacKenzie, Jeannerod, Athenes, and Dugas (1987). After demonstrating (as mentioned above) that light bulbs were reached for differently than tennis balls, Marteniuk et al. showed that a single object (in this case a disk) was approached differently depending on whether it was to be thrown or carefully placed after grasping. These findings led Marteniuk et al. to conclude that the kinematics of prehension reflect intentional states.

END-STATE COMFORT

A series of studies in our laboratory was designed to extend this basic observation. The studies were prompted by the sight of a waiter filling glasses with water. The glasses were inverted when they were in their initial, unfilled state. The waiter took hold of each glass with his hand in a thumb-down position. This enabled him to hold the glass with his hand in a thumb-up position when he poured the water into it and also when he placed the filled glass back down on the table. Apparently, the waiter was willing to tolerate initial discomfort when first picking up the glass for the sake of later comfort or control when dealing with it afterward.

To test the generality of this phenomenon and to evaluate possible interpretations given to it, we launched a series of experiments on intentional factors in object manipulation. In the first experiment (Rosenbaum, Marchak, Barnes, Vaughan, Slotta, & Jorgensen, 1990), we asked college students to take hold of a cylinder lying horizontally on a pair of cradles (Figure 1). Two flat target disks lay on either side of the cylinder, one near the left end and one near the right. Participants were asked to reach out with the right hand and grasp the cylinder firmly. There were four conditions: Either the left or the right end of the cylinder was supposed to be placed on the left or right target. The question was what posture participants would adopt upon taking hold of the cylinder.

As shown in Figure 1, the postures that participants adopted depended on what they planned to do with the cylinder. When the *right* end of the cylinder was supposed to be placed down on either target, participants grasped the cylinder with an *overhand* grip, but when the *left* end of the cylinder was supposed to be placed down on either target, participants grasped the cylinder with an *underhand* grip. Thus, the participants anticipated their future bodily states, much as the waiter had done in the restaurant.

Why did subjects modify their grasps as they did? Were they anticipating the comfort of their final postures? To find out, we asked another group of subjects to give ratings of the awkwardness of each of the possible postures for nine tasks similar to those just described (Rosenbaum, Marchak, Barnes, Vaughan, Slotta, & Jorgensen, 1990). The six postures were the overhand and underhand grips of the cylinder in its horizontal orientation, the overhand and underhand grips of the cylinder in its vertical orientation on one target, and the overhand and underhand grips of the cylinder in its vertical orientation on another target. Subjects in the rating study were asked to hold the cylinder in each of these positions and to indicate how awkward the positions felt, using a 5-point scale, where 1 = least awkward up to 5 = most awkward. Rating tasks like this are common in psychology, although to our knowledge they had not been used before in psychological studies of motor control.

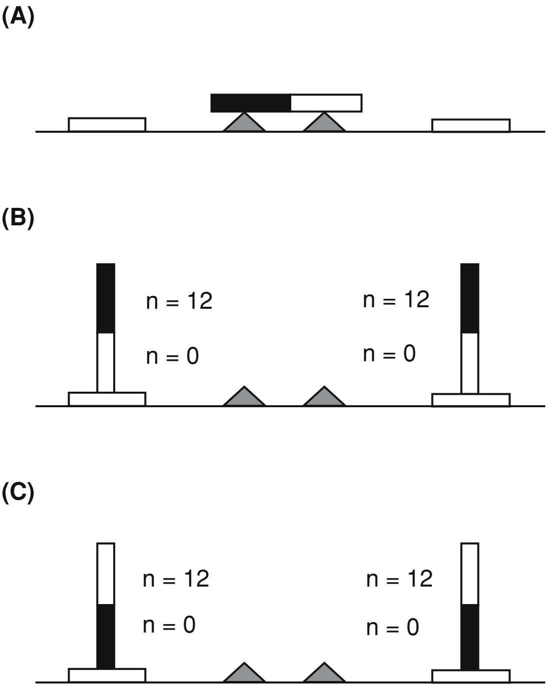


FIGURE 1. (A) Cylinder on the cradle, waiting to be picked up by the participant. (B) Cylinder having been brought to the target with the white side down. The numbers by the black and white ends refer to how many participants grasped at the cradle with the thumb towards that end, when it was to be brought to that target. (C) Cylinder at the target with the black side down. Adapted from Rosenbaum et al., 1990.

The awkwardness ratings that subjects gave are shown in Table 1. In this study subjects had to place the rod in two or three positions in sequence (P1, P2,

TABLE 1. Tasks awkwardness ratings and observed grips (from Rosenbaum et al., 1990).

				Awkwardness Ratings				
Task	*Start*	*Action*	Thumb *Direction*	*P*1	*P*2	*P*3	*Mean*	*Observed*
1	Cradle	White to Red	Black	1.3	1.8	—	1.6	6
			White	3.3	3.1		3.2	0
2	Cradle	Black to Red	Black	1.3	3.1	—	2.2	1
			White	3.2	1.8		2.6	5
3	Red	White to blue	Black	3.1	3.7	—	3.4	0
			White	1.8	1.5		1.7	6
4	Red	Black to Blue	Black	3.1	1.5	—	2.3	5
			White	1.8	3.7		2.8	1
5	Cradle	Black to Red, Black to Blue	Black	1.3	3.1	1.5	2.0	0
			White	3.3	1.8	3.7	2.9	6
6	Cradle	White to Red, White to Blue	Black	1.3	1.8	3.7	2.3	5
			White	3.3	3.1	1.5	2.6	1
7	Cradle	Black to Red, White to Blue	Black	1.3	3.1	3.7	2.7	1
			White	3.3	1.8	1.5	2.2	5
8	Cradle	White to Red, Black to Blue	Black	1.3	1.8	1.5	1.5	6
			White	3.3	3.1	3.7	3.4	0
9	Red	White to Red	Black	3.1	1.8	—	2.5	2
			White	1.8	3.1		2.5	4

Note. All task descriptions assume starting positions with the black end of the bar in the left end of the cradle or in the red (bottom) disk. P1, P2, P3 denote positions 1, 2, 3, respectively.

and P3). Judged awkwardness at the second of these positions (P2) better predicted grasps at the initial (horizontal) position than at P1 or P3, and better predicted grasps than did overall mean judged comfort; 85 percent of all grasps were in the direction predicted by P2 awkwardness ratings. These results demonstrate that the subjects' choice of grips was not determined by the comfort of their final postures, but the comfort of the second posture to be adopted. Another rating study showed that ratings of *movement* difficulty also failed to predict subjects' grasps as well as end-position comfort ratings. These outcomes led Rosenbaum et al. (1990) and Rosenbaum and Jorgensen (1992) to infer that subjects cared more about final position than end position in motor planning. Accordingly, Rosenbaum et al. (1990) referred to the preference for final comfort over initial comfort as the *end-state comfort* effect.

Several additional studies were performed to evaluate and further elucidate the end-state comfort effect. In these studies (Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993) the cylinder that was lifted from the cradle and set down on a target was replaced with a cylinder that was turned from an initial orientation to a final orientation (Figure 2). The cylinder was designed in such a way that the hand could take hold of the cylinder at its axis of rotation. A pointer on one end of the cylinder indicated the cylinder's orientation, and target numbers around the perimeter identified possible orientations to which the cylinder could be brought in each trial (see Figure 2B). Each trial began as in the earlier experiments, with the subject keeping his or her hands by his or her sides. The experiments announced a target to which the pointer should be turned and the subject then reached out with the right hand and grasped the cylinder firmly, rotating it until the pointer was aligned with the target. All required rotations covered 180 degrees.

Figure 3 shows how subjects took hold of the cylinder depending on the orientation to which it would be brought. Subjects were least likely to take hold of the cylinder when the pointer had to be brought to position 4 from position 8 (see Figure 2). As the reader can determine for him or herself, taking hold of the cylinder with the right thumb pointing toward position 8 leaves the arm, after a 180 degree rotation, in a very awkward position. By contrast, taking hold of the cylinder with the right thumb pointing toward position 4 is awkward at first, but the arm ends in a comfortable posture if the cylinder is next rotated 180 degrees. Finding that subjects modify the likelihood of taking hold of the cylinder with the thumb toward the pointer depending on its subsequent position indicates that the end-state comfort effect is a

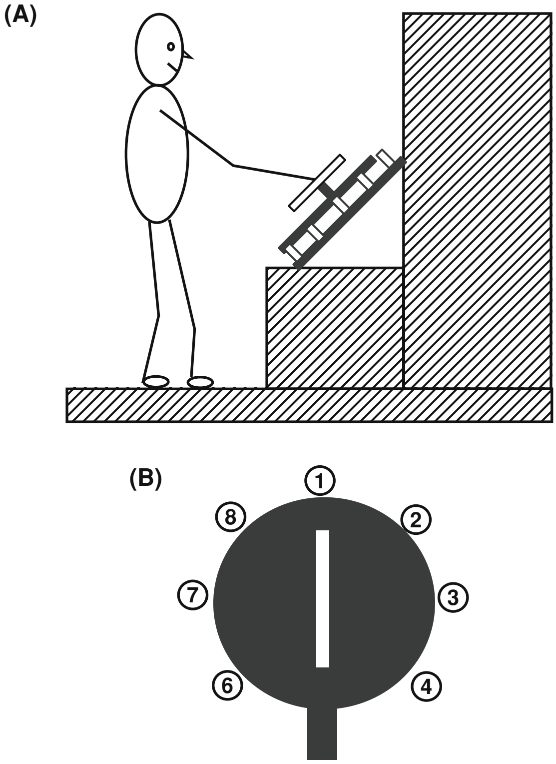


FIGURE 2. Experimental setup with wheel at 45 degrees. From Rosenbaum et al., 1993.

general phenomenon. Further evidence of the generality of the phenomenon is that it holds for the left arm as well as the right.

GRAVITY

Using the rotating wheel allowed us to test alternative accounts of the end-state comfort effect. One account pertained to the exploitation of potential energy. Perhaps when subjects took hold of the cylinder in initially awkward positions, they knew that they would raise their elbows and that their elbows would drop during the subsequent rotation of the apparatus. Conceivably, subjects exploited gravity to simplify the cost of controlling their arm movements.

To test this hypothesis, Rosenbaum, van Heugten, and Caldwell (1996) took the wheel, which was on a 45 degree tilt in the experiments described above, and placed it on the floor. Subjects sat looking down at the wheel, their feet spread apart and their arms dangling by their sides. In all other respects, the procedure was the same as in the original wheel-turning studies. The data from the wheel-on-the-floor study were virtually the same as the data from the titled-wheel study. As before, subjects freely adopted awkward initial positions to ensure comfortable final positions. Their behavior went against the hypothesis that the end-state comfort reflected a tendency to exploit gravity.

PRECISION

Having the wheel on the floor enabled us to test another possible account of the end-state comfort effect. According to this account, ending in a comfortable posture allows for greater precision than does ending in an uncomfortable posture. To test this hypothesis, Rosenbaum, van Heugten, and Caldwell (1996)

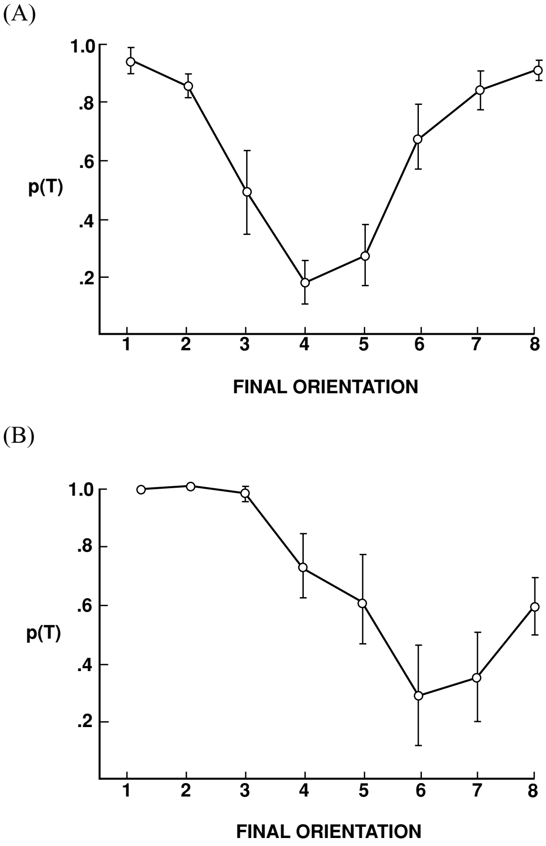


FIGURE 3. Probability p(T) of grasping the cylinder with the thumb toward the pointer-end of the cylinder depending on the required final orientation of the pointer. All the required rotations covered 180 degrees. (A) Data for right-hand turns. (B) Data for left-hand turns. From Rosenbaum et al. (1996).

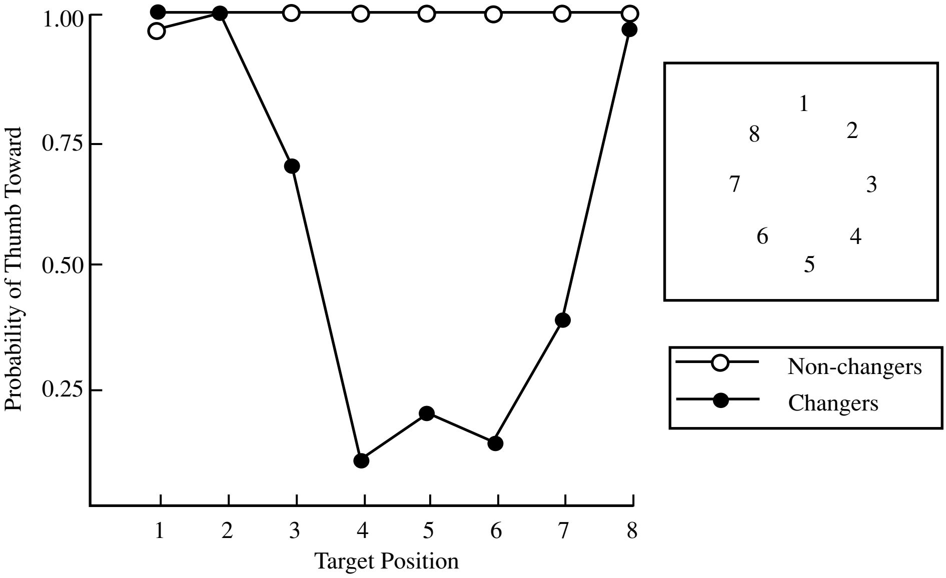


FIGURE 4. Probability of grabbing the cylinder with the thumb toward the pointer-end of the cylinder depending on the required final orientation of the pointer. All the required rotations covered 180 degrees. Inset identifies position numbers. Data for right-hand turns. (Data for left-hand turns looks very similar). From Rosenbaum et al. (1996).

redesigned the wheel on the floor so a bolt dropped into a hole when the wheel reached a target position. This redesign of the apparatus eliminated the need for precise positioning of the wheel near the target locations. The precision hypothesis predicted that the end-state comfort effect would be eliminated in this condition.

The results (Figure 4) were consistent with the precision hypothesis. Whereas virtually all subjects in the previous experiments, where end precision was required, showed the end-state comfort effect, a full half of the subjects in the "dropping-bolt" study did not show the end-state comfort effect. These subjects (the "non-changers") always took hold of the handle with the thumb toward the pointer, which meant that the arm ended up in awkward positions for some required rotations (all of which were 180 degrees, as in the earlier experiments). This *thumb-toward bias* is an interesting example of the use of heuristics in motor planning. The other half of the subjects (the "changers") did show the end-state comfort effect, perhaps because they saw the need for more precise control over the handle's terminal position than was in fact required.

Why would comfortable postures facilitate precision? One possibility is that feelings of discomfort associated with end positions may distract one from attending as fully as needed to precision. A second possibility is that proprioceptive sensitivity is greater at the middle of range of motion than at extreme positions (Rossetti, Meckler, & Prablanc, 1994). A third possibility is that higher torques can be generated at or near the middle of the middle of range of motion than at or near the ends of the range (Winters & Kleweno, 1993). Fourth and finally, people can oscillate the forearm at higher frequencies at or near the middle of the range of motion than at or near the ends, and positions where oscillations are quick may afford more rapid error correction than positions where oscillations are slow (Rosenbaum, van Heugten, & Caldwell, 1996). None of these possibilities is inconsistent with any of the others.

ELASTICITY

Although the precision hypothesis provides the best account of the end-state comfort effect, it is worth mentioning another hypothesis that we considered, partly because the setup used to test it led to the analysis of sequential effects in prehension planning, which is the topic of the next section. According to this other hypothesis, the end-state comfort effect reflected a tendency to store and release elastic energy. The idea was that people effectively wind up the arm and then release it, much as one winds up the rubber band of a toy wooden airplane. Storage and release

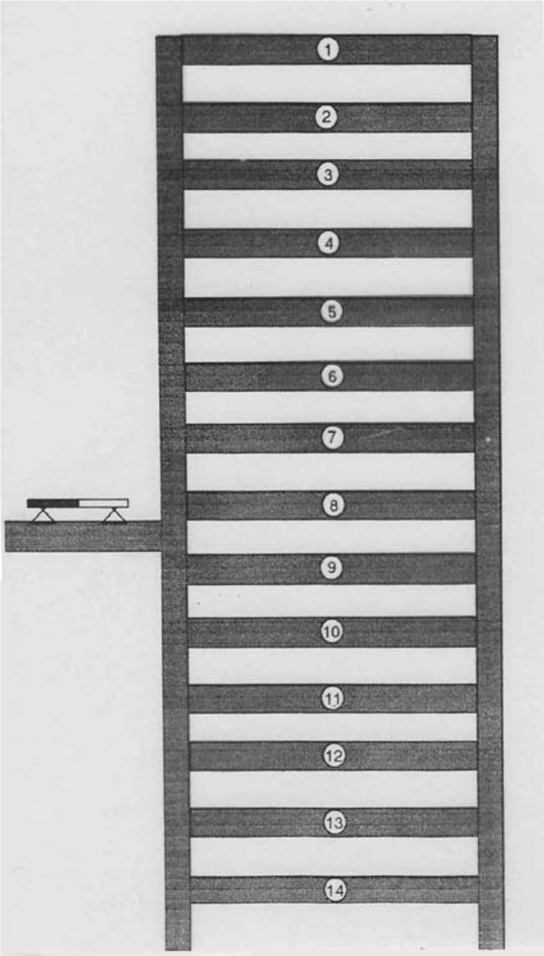


FIGURE 5. Shelf setup used by Rosenbaum and Jorgensen (1992).

of elastic energy is known to play a role in walking and jumping (Alexander & Bennet-Clark, 1977; McMahon, 1984), making conceivable that it plays some role in reaching and grasping.

To test this *elastic energy* hypothesis, Rosenbaum and Jorgensen (1992) devised a task in which the end-state comfort effect would be unlikely to occur if storage and release of elastic energy were actually the source of the effect. In this task (Figure 5) subjects took hold of a cylinder that rested on a cradle and placed the cylinder's left end or right end against a target sitting on the front edge of a shelf. Instructions in each trial indicated which end of the cylinder was to be brought to which target. The main independent variable, aside from which end of the cylinder was supposed to be brought to the target, was the target's height. For most shelves, and especially those that were very high or very low, it was unlikely that the arm could be brought to the necessary position merely by "letting the arm unwind." Accordingly, if the source of the end-state comfort effect was storage and release of elastic energy, the end-state comfort effect would be expected not to occur for these shelves.

Figure 6 shows the results of Rosenbaum and Jorgensen's (1992) "shelf" study. Contrary to the elastic energy hypothesis, the end-state comfort effect was fully replicated at all shelf heights. When subjects, all of whom used the right hand, reached out to take hold of the cylinder to place its *right* end against a target, they were less and less likely to grab hold of the cylinder with an overhand grip the lower the target height. Similarly, when subjects reached out to take hold of the cylinder to place its *left* end against a target, they were less and less likely to grab hold of the cylinder with an underhand grip the lower the target height. This outcome makes sense from the point of view of reducing end-state awkwardness. To push a dowel (even lightly) against a *low* target directly in front of one's body is awkward if the arm is supinated (i.e., if the thumb is away from the target), but to push the same dowel against a *high* vertical target is awkward if the arm is pronated (i.e., if the thumb is toward the target). Both of these positions require the arm to rotate to an extreme degree. The fact that participants in this study exhibited the end-state comfort effect shows that they were aware of this fact. It also argues against the elastic energy hypothesis insofar as the postural transitions that were required in this task were so complex it is unlikely that the simple store and release of elastic energy could underlie the movements. A more plausible interpretation is that subjects sought to adopt end postures that afforded the most efficient means of positioning the cylinder precisely at its targets, as assumed in the precision hypothesis described above.

SEQUENTIAL EFFECTS

The "shelf experiment" of Rosenbaum and Jorgensen (1992) was designed to explore another aspect of the end-state comfort effect besides its possible reliance on elastic energy. In the experiment, target heights were tested in two possible orders—either strictly ascending or strictly descending. Each subject in the experiment was tested in both orders, with half the subjects starting with the ascending order and the other half starting with the descending order. The reason for using ascending and descending orders was to test for *hysteresis*, the tendency for a system to switch from

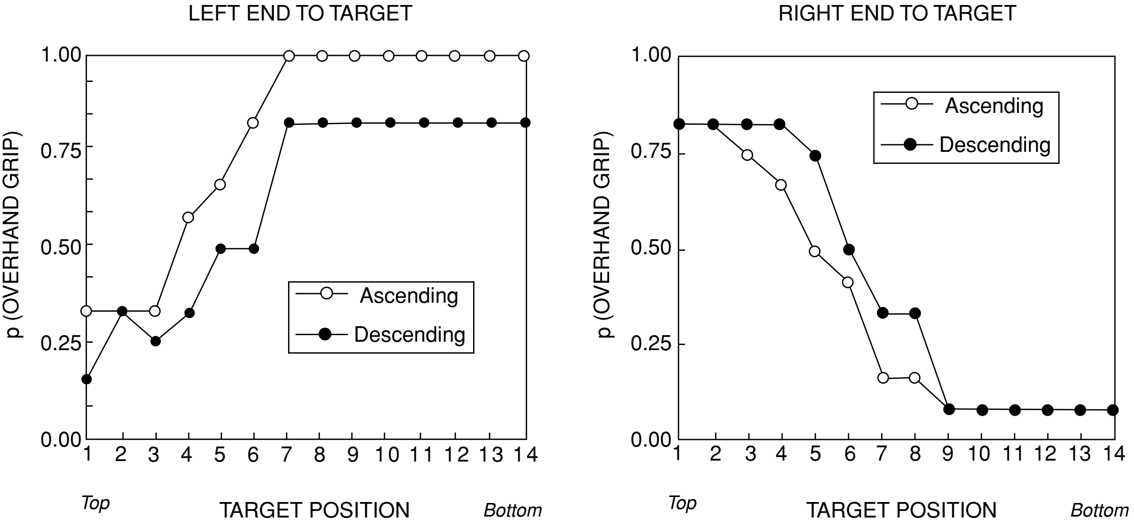


FIGURE 6. Probability of grasping the bar with an overhand grip, depending on the height of the target shelf. From Rosenbaum & Jorgensen, 1992.

one state to another at different values depending on its history.

The data in Figure 6 provide evidence for hysteresis. The height at which subjects switched from an overhand grip to an underhand grip when target heights decreased differed from the height at which subjects switched from an underhand grip to an overhand grip when target heights increased. Thus, there was a sequential effect in subjects' grip choices such that subjects preferred to use the grasp they used before. For this to be true, there had to be a range of heights in which either grasp was tolerable. Rosenbaum and Jorgensen (1992) called this the *range of indifference* for overhand-underhand grasp selection.

MORE EVIDENCE FOR SEQUENTIAL EFFECTS: THE GRASP HEIGHT EFFECT

Do end-state comfort and sequential effects generalize to other grasp tasks? An indication that they do comes from recent work which shifted the focus from choice of overhand or underhand grasps to choice of grasp heights.

An observation in the everyday environment set the stage for this work, much as the observation of the waiter in the restaurant set the stage for the earlier work. One day, the first author walked into his bathroom and saw a toilet plunger standing on the closed toilet lid. He moved the plunger up and to the side to rest it on the counter. After setting the plunger down, he realized he had made an interesting, though unconscious, choice. He had decided where to take hold of the plunger along its length and in so doing had probably anticipated the end state of the plunger, choosing a grasp height that reflected that anticipation. Further informal observations suggested that the measurement of grasp heights could provide a new, potentially sensitive window into plans for grasping objects.

Figure 7 shows the laboratory setup used for the experiments following these initial, informal observations (Cohen & Rosenbaum, 2004). The subject stood before an empty book shelf from which protruded a platform at stomach level. Standing on this "home" platform was a fresh plunger. To the right of the home platform was another protruding "target" platform. The subject was asked to stand with his or her hands by his or her sides and, when ready, to take hold of the plunger with the right hand and move it to the target platform. After doing this, the subject was asked to return his or her hand to his or her side. The performance was videotaped. The height of the home platform was fixed at the middle of the bookshelf. The independent variable was the height of the target platform. The dependent variable was the height along the length of the plunger where the subject took hold of the plunger—what we called the *grasp height.*

Figure 8a shows the result based on freeze-frame analysis of the videotape: The higher the target

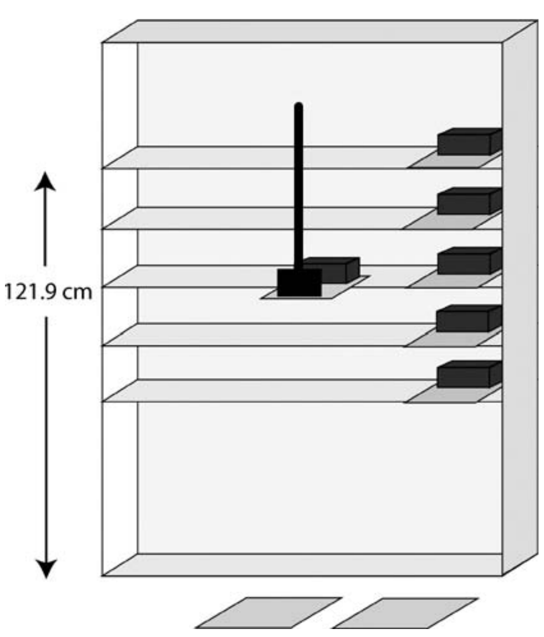
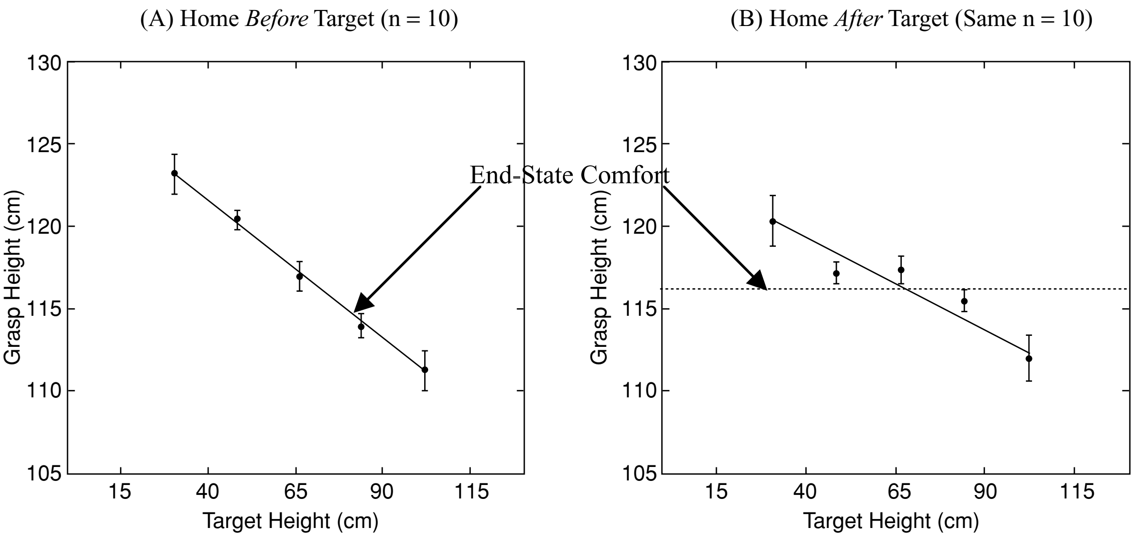


FIGURE 7. Experimental Setup. From Cohen & Rosenbaum, 2004.

platform, the lower the grasp height. The interpretation of this grasp-height effect was not hard to see: Modulating the initial grasp heights so they were inversely related to target heights allowed the hand to come close to the middle of the arm's range of motion at the end of the transport phase of the movement. We concluded that the end-state comfort effect applies in this sort of transport task.

There were sequential effects in this study which, frankly, came as a surprise. In the study, subjects did not just complete a single object transport for each target platform. Instead, after moving the plunger from the home platform to the target platform, they lowered their hands. Next, they reached out again to take hold of the plunger and return it to the home platform, whereupon they lowered their hands once more. Then they repeated the cycle of movements, moving the plunger from the home platform to the target, lowering their hands to their sides, bringing the plunger back to the home platform, and finally resting their hands at their sides. After the second return to home, the experimenter pushed the target platform back into the bookshelf and pulled out the next target platform to be tested. Each of the five target heights was tested in this manner, with the order counterbalanced across subjects. The home platform remained the same throughout the experiment. If grasp heights for the return movements were based entirely on end-state


(A) Home *Before* Target (n = 10)

(B) Home *After* Target (Same n = 10)

FIGURE 8. Grasp height as a function of target height. (A) Moves from a static home shelf to targets of different heights. (B) Moves from the different targets back to home. From Cohen & Rosenbaum, 2004.

comfort, subjects would ensure that the grasp height back at the home position was fixed, regardless of the height from which the plunger was carried. In fact, as shown in Figure 8b, this was not what happened. Rather than grasping the plunger at a new position that ensured a maximally comfortable end state back at the home platform, subjects grasped the plunger close to where they had grasped it for the home-to-target trip. Thus, subjects exhibited a sequential effect. Further experiments by Cohen and Rosenbaum (2004) confirmed that subjects tried to achieve end-state comfort in first plunger transfers but that their subsequent grasp heights were largely determined by what they had just done. Their bias to grasp the plunger as they had before is similar to what the subjects did in the shelf-height studies of Rosenbaum and Jorgensen (1992). Those subjects also persisted in using overhand or underhand grasps. Insofar as choices of grasp height and choices of overhand-underhand positions both reflect choices of body postures, the results of the two studies indicate that people tend to use the same postures in successive tasks if they can. The discovery of this kind of strategy argues against the idea that movement is optimized from a purely physical perspective (as in theories of minimization of work, torque, jerk, etc.). Instead, the outcome suggests that computational efficiency also matters in movement planning. If the current motor plan is generally satisfactory, continuing to use it is less computationally burdensome than generating a new plan. Expressing this in terms of an American idiom, "If the plan ain't broke, don't fix it!"

TIME TO PLAN GRASPS

What are the real-time processes by which grasps are planned? A reaction-time study by Rosenbaum, Vaughan, Barnes, and Jorgensen (1992) suggested that grasp end states are planned even before reaches are physically initiated. In this study (Figure 9), subjects stood facing a wall-mounted panel with a removable handle with magnetic "feet" protruding from the handle's two ends. The feet rested on two iron disks mounted on the panel. The orientation of the handle depended on which pair of iron disks the handle sat on at the start of each trial. When the subject was ready, as indicated by the fact that s/he pressed his or her hand against a button down by his or her side, a target light appeared beside another pair of iron disks located in one of eight radial positions around the home area. The subject's task was to reach out and pull the handle from its home disks and place it as quickly as possible on the pair of disks designated by the target light. The main dependent measures were the delay between illumination of the target light and release of the start button, the orientation of the hand when it grasped the handle (thumb toward the pointer or away from the pointer), and the time to move the handle from its home position to the target position. Subjects were told to minimize the time between appearance of the target light and placement of the handle on the target position, but they were not told that the time to release the hand from the start button (the reaction time) was separate from the time to carry the handle from the home to the target position (the movement time).

One question behind this experiment was whether subjects would behave in accordance with the end-state comfort effect when they performed under speed pressure. The other question was how subjects' reaction times would depend both on what stimuli they saw and also on what movements they chose to make.

With respect to the first question, as shown in Figure 10, subjects did behave in accordance with the end-state comfort effect. The way they took hold of the handle at its home position anticipated the comfort of their final postures at the targets. Thus, performing under speeded conditions did not eliminate the end-state comfort effect.

With respect to the second question, reaction times for the same home-target disk combinations differed depending on whether subjects grabbed the handle with the thumb toward the pointer or away from the pointer at the home position. That is, even though the choice of hand posture was up to the subjects and even though reaction times did not, in principle, have to change depending on what the chosen hand posture would be, it turned out that reaches culminating in thumb-toward grasps had different reaction times than reaches culminating in thumb-away grasps even when the handle's start position and target position were the same. This outcome suggests that subjects decided even before starting their physical reaches how they would grasp the handle. Furthermore, they made the decision in very little time, judging from the fact that the longer of the two reaction times was only about a third of a second. The discovery that subjects knew how they would end their movements before physically initiating the movements helped set the stage for the model of motor planning that we developed, which is the subject of the next section.

A Model of Motor Planning

The model to be presented next was inspired by and also constrained by the results reviewed above. In what follows, we outline the main claims of the model. Then we indicate how the model accounts for the findings covered earlier. Technical details concerning the model

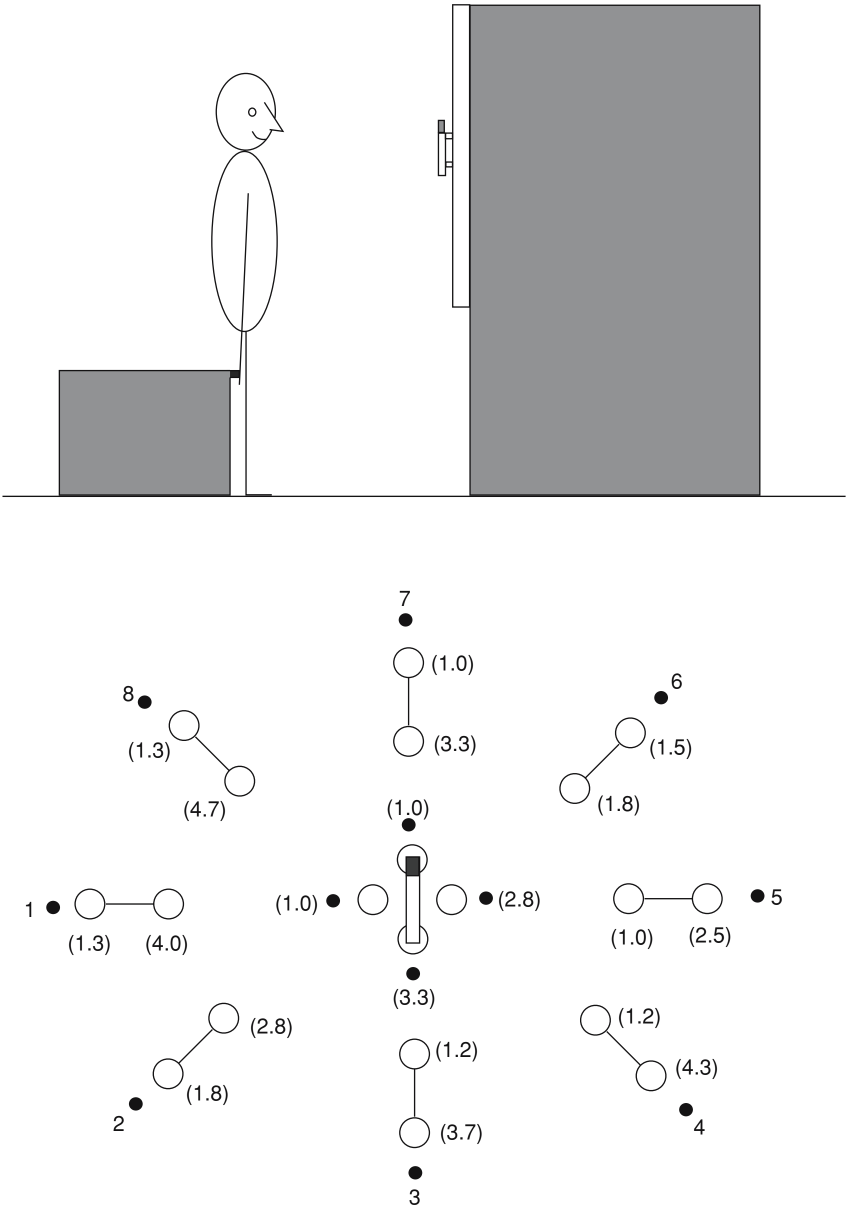


FIGURE 9. Apparatus used in the reaction-time experiment. (Top panel: Side view of a subject, with hand against the start button. The response panel is represented by the white rectangle, and the handle, with the pointer toward the north home position, is represented by the narrow rectangle with the black end on top. Bottom panel: Subject's view of the response panel. The four disks in the center are the four home positions. The handle points to the north home position. The eight pairs of disks surrounding the center are the eight target positions. The small black circles beside each home location and target location represent a light-emitting diode (LED). Target numbers appear beside the target LEDs. In parentheses beside each home and target location is the mean awkwardness rating obtained from raters who held the handle with the thumb toward that location). From Rosenbaum, Vaughan, Barnes, & Jorgensen (1992).

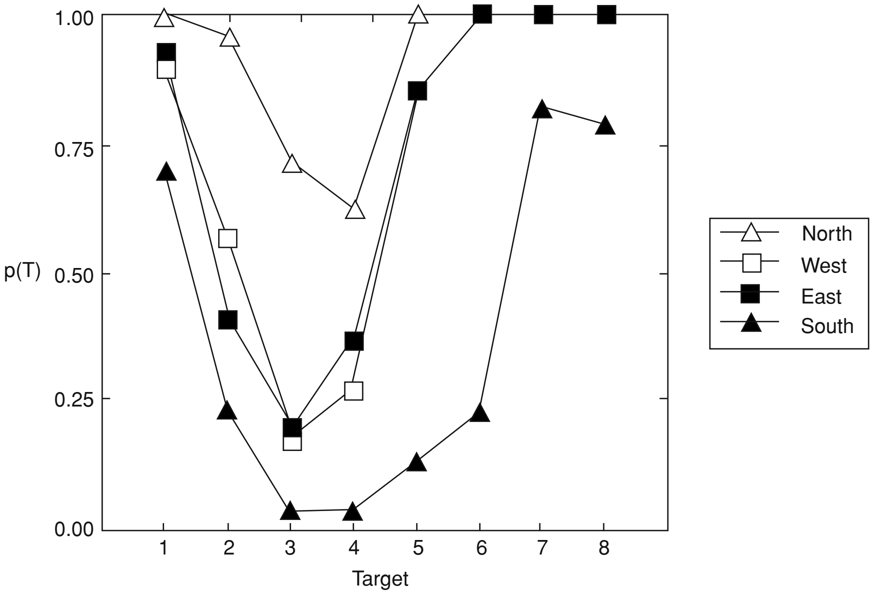


FIGURE 10. Probability, p(T), of grasping the bar with the thumb toward the pointer. From Rosenbaum, D. A., Vaughan, J., Barnes, H. J., & Jorgensen, M. J. (1992).

are suppressed here for the sake of brevity but can be found in Rosenbaum, Meulenbroek, Vaughan, & Jansen (2001). The model is meant to provide a general account of motor planning, not just an account of the planning of grasps. However, we focus below on the model's account of grasping given the focus of this chapter. The model only concerns kinematics, although in principle it could be extended to kinetics. The main claims of the model, along with some supporting evidence for them, are as follows.

1. Movements are planned by first specifying goal postures and then planning trajectories from the start postures to the goal postures. The notion that goal postures are planned before movements are planned fits with the observation that participants in the study of Rosenbaum, Vaughan, Barnes, and Jorgensen (1992) appeared to know what grasps they would end up with even before starting to move. In addition, this claim accords with other data indicating that initial hand speed anticipates the distance to be covered (Atkeson & Hollerbach, 1985; Gordon, Ghilardi & Ghez, 1992). Neither of these findings requires one to conclude that goal postures are planned before movements are planned; they are merely consistent with this idea. However, they do indicate that goal states are known before movements begin, at least for the kinds of movements under consideration. Additional evidence for the hypothesis that goal postures are normally planned before movements comes from neurophysiological evidence that prolonged microstimulation of specific areas in the primary and premotor cortex of monkeys leads to adoption of characteristic postures regardless of the monkey's initial posture (Graziano, Taylor & Moore, 2002). The discovery of such "posture neurons" is consistent with the view that there is a way to specify body positions prior to the initiation of motion, a concept that originates with the equilibrium-point hypothesis of motor control (Asatryan & Feldman, 1965).

2. Goal postures and movement trajectories are chosen with respect to a constraint hierarchy—a prioritized list of constraints whose rank order (most important constraint down to least important constraint) defines the task to be performed. A typical constraint is generating movements that entail acceptable levels of effort, where the acceptable levels depend on the task (e.g., weight lifting can entail more effort than feather dusting). Another typical constraint is generating movements that ensure adequate clearance around obstacles. The amount of clearance also depends on the task. Large clearances are needed if

dangerous objects must be avoided, whereas low or no clearances can be used when objects should be touched.

3. Movements are assumed to have bell-shaped tangential velocity profiles and to be straight lines through joint space from the starting posture to the goal posture unless different trajectories are needed. The assumption that movements have bell-shaped tangential velocity profiles has been supported in many studies (Hogan, 1984; Morasso, 1981). The assumption that movements are, by default, straight-line paths through joint space is motivated by the idea that goal postures are specified before movements, so movements are viewed in the theory as being, in effect, interpolations from start to goal postures. Straight-line motions through joint space have been observed (Soechting & Lacquaniti, 1981), although straight-line movements through extrinsic space have been observed more often (Abend, Bizzi & Morasso, 1982). Because movement trajectories can be shaped in the theory (see item 5 below), it is possible to deliberately generate straight-line movements through extrinsic space using the theory's computations.

4. Movements are evaluated via forward kinematics before being performed to determine if their default forms need to be changed. Reliance on feedforward modeling is well established for movement control (see e.g. Wolpert & Flanagan, 2001). A default movement may be judged unacceptable if it would result in a collision or if the shape differs from a desired shape, as in writing or dancing.

5. If a default movement is rejected, it is combined with another movement to make an acceptable *compound* movement. The movement with which the main movement is combined is assumed to be a back-and-forth movement that goes from the starting posture to a "bounce posture" and back to the starting posture. The bounce posture is selected by using a constraint hierarchy, just as the goal posture is (Vaughan, Rosenbaum, & Meulenbroek, 2001). The direction and distance of the bounce posture from the starting posture affects the curvature of the compound movement. The main movement and the back-and-forth movement are assumed to start and end together. Combining movements is a well established capability in the study of motor control (Pigeon, Yahia, Mitnitski, & Feldman, 2000).

6. Goal postures are assumed to be selected through a two-stage process. The first stage consists of determining which stored posture—the last *m* adopted goal postures are assumed to be stored—is most promising for the task at hand, as defined with respect to the constraint hierarchy. The second stage consists of "tweaking" that most promising stored posture via a diffusion process (i.e., generating candidate goal postures similar to the most promising stored posture). This aspect of the theory was supported by Rosenbaum and Jorgenson's (1992) and Cohen and Rosenbaum's (2004) discovery of sequential effects in the postures chosen for transport tasks. Of all the postures that were candidate goal postures, the one that survives the deepest cuts down the constraint hierarchy becomes the goal posture. According to this claim, recently adopted goal postures can be most useful if they are quite similar to goal postures that need to be adopted for the present task. Thus, some of the benefit of "warming up" is explained by appealing to the prevalence of stored goal postures that may be useful for a particular task. Having stored goal postures that satisfy many constraints for the task reduces the duration and/or depth of the diffusion around the most promising stored posture. The theory does not assume that movements per se are learned, because such an assumption would be unnecessary. Consistent with this claim, it is well known that end positions of movements are remembered better than movements themselves (see Smyth, 1984, for review, and Rosenbaum and Dawson, 2004, for recent discussion).

7. Regarding prehension, no special assumptions are required. Hand and arm positions are treated like any other kind of postures. The one exception is that in the simulations of reach and grasp movements reported by Rosenbaum, Meulenbroek, Vaughan, and Jansen (2001) and Meulenbroek, Rosenbaum, Jansen, Vaughan & Vogt, (2001), the hand was treated as a sub-unit of posture space. Partitioning the hand and arm this way was introduced for computational convenience only, although it is interesting that others have likewise entertained the hypothesis that the hand may be represented as a hierarchical sub-unit of the arm. This hypothesis has been advanced both in motor control (Jeannerod, 1984; Klatzky et al, 1987) and in perception (Marr, 1982; see Figure 11).

8. In grasping objects, moving directly (in joint space) from a starting posture to a goal posture that achieves a precision or power grip on the object would almost always result in a collision with the object before the grip is achieved. However, the model does not need a special mechanism for making collision-free movements to grip postures. It simply exploits the obstacle-avoiding mechanism (item 5) by which an unsatisfactory default (direct) movement is combined with another movement to make an effective compound movement (Vaughan, Rosenbaum, & Meulenbroek, 2001) to attain the grip posture without

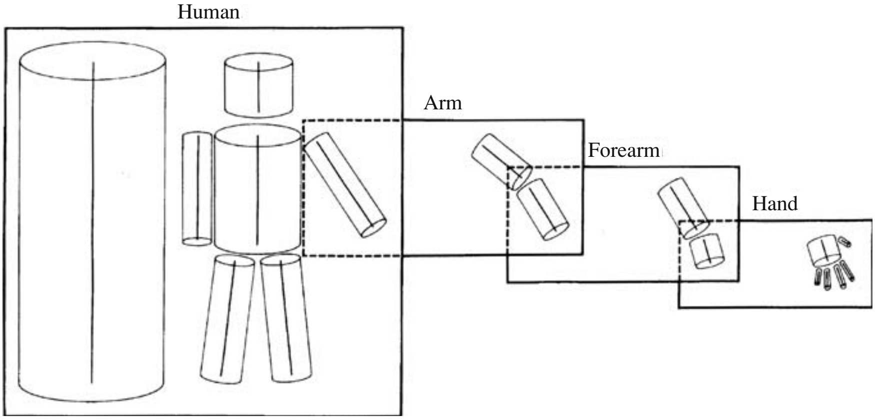


FIGURE 11. Hierarchical composition of the human body thought to be used in perceptual analysis of body forms. From Marr, D. (1982). *Vision.* San Francisco: W. H. Freeman.

colliding. Thus, no additional assumptions are required for the model to accommodate the obstacle-avoiding dimension of reaching to grasp an object (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001).

How do these ideas come together in actual simulations of grasping movements? Figure 12 shows just one of the simulations generated on the basis of the model. The figure shows an artificial creature reaching out to take hold of an object. Also included in this figure is a panel showing how the wrist tangential velocity and distance between the thumb and index finger changed together over time. The two panels on the right side of the figure show angular velocity profiles for the joints involved. Altogether, the movement is realistic, both at the level of informal observation of the animation and at the level of more detailed, quantitative examination. Indeed, the features of prehension listed above in the section called **Grasping Based on Perception** are all accounted for with the model. For detailed expositions of the accounts, see Rosenbaum, Meulenbroek, Vaughan, and Jansen (2001) and Meulenbroek, Rosenbaum, Jansen, Vaughan, and Vogt (2001). For extensions of the model to the understanding of grasping in the context of spasticity, see Meulenbroek, Rosenbaum, and Vaughan (2001). The article by Rosenbaum, Meulenbroek, Vaughan, and Jansen (2001) also covers other aspects of motor performance, not specifically tied to grasping, which the model handles. Among these aspects are immediate compensation for changes in joint mobility, changes in the relative contributions of the joints depending on the required speed of movement, and the importance of accurate information about one's starting position.

Conclusions

Through the lens of prehension research, we have considered how motor planning is influenced by perceptions of the environment and by intentions of the actor. We reviewed some noteworthy prehension phenomena, including a number of studies from our own labs. In particular, three lines of research from our labs were especially relevant: (1) the phenomenon we call "end-state comfort"; (2) the discovery of sequential effects in motor planning; and (3) the finding that postural end states are known before movements begin. The existence of these phenomena highlights the important role that mental representation plays in motor control above the most basic level. We outlined a model of motor control that can account for both perception-related and intention-related features of motor planning.

Regarding the theory, we also allow for the possibility that the planning of movements can be bi-directional: choice of movement can reciprocally influence the choice of goal posture (Kawato, 1996). So far, we have applied the theory *quantitatively* to 2-dimensional aspects of prehension and only *qualitatively* to 3-dimensional aspects. We would like to extend the model to account for 3-dimensional moves. We also hope to extend the theory to include kinetics, not just kinematics. Here it is relevant that even babies learn to anticipate the forces required to lift objects based on their experience with the object's weight in

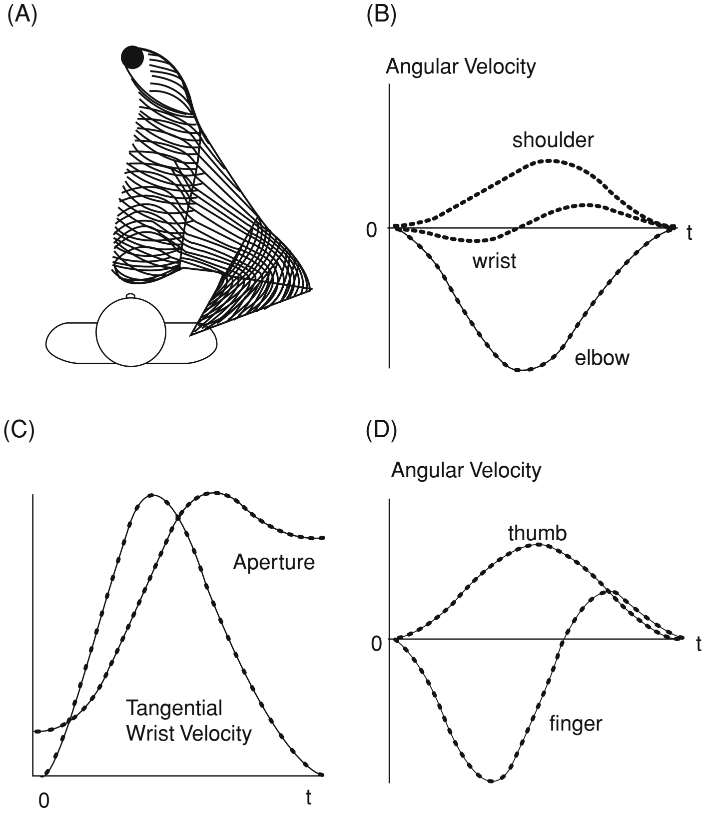


FIGURE 12. Simulated reach and grasp based on the posture-based motion planning model. (A) Stick figure animation. (B) Shoulder, elbow, and wrist angular velocity profiles. (C) Wrist tangential velocity and thumb-index finger aperture profiles. (D) Thumb and index finger angular velocity profiles. From Rosenbaum, Meulenbroek, Vaughan, & Jansen (2001).

repeated lifts. If the weight of the object is suddenly changed, the baby will lift it "too hard" (Gachoud, Mounoud, Hauert, & Viviani, 1983).

Our theory has been criticized for its computational complexity (Smeets & Brenner, 2002), but there is a tradeoff between complexity and number (or range) of phenomena accounted for. We believe that the large number and variety of phenomena successfully accounted for by our theory justify its relative complexity. To our knowledge, no simpler model exists that accounts for the phenomena described here. If others develop such a model, that would be a welcome contribution to progress in motor control.

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