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Although psychology is the science of mental life and behavior, little attention has been paid to the means by which mental life is translated into behavior. One domain in which links between cognition and action have been explored is the manipulation of objects. This article reviews psychological research on this topic, with special emphasis on the tendency to grasp objects differently depending on what one plans to do with the objects. Such differential grasping has been demonstrated in a wide range of object manipulation tasks, including grasping an object in a way that reveals anticipation of the object's future orientation, height, and required placement precision. Differential grasping has also been demonstrated in a wide range of behaviors, including 1-hand grasps, 2-hand grasps, walking, and transferring objects from place to place as well as from person to person. The populations in which the tendency has been shown are also diverse, including nonhuman primates as well as human adults, children, and babies. The tendency is compromised in a variety of clinical populations and in children of a surprisingly advanced age. Verbal working memory is compromised as well if words are memorized while object manipulation tasks are performed; the recency portion of the serial position curve is reduced in this circumstance. In general, the research reviewed here points to rich connections between cognition and action as revealed through the study of object manipulation. Other implications concern affordances, Donders' law, naturalistic observation, and the teaching of psychology.

Keywords: action, cognition, motor control, object manipulation, reaching

This article concerns the behavioral changes associated with object manipulation. The question is how individuals take hold of and manipulate objects. Our interest in this problem is motivated by practical and theoretical concerns. Practically, understanding how individuals interact with objects can benefit clinical applications, human factors, and robotics. Theoretically, the way objects are handled can indicate an actor's understanding of what the objects afford. If someone understands what an object enables him or her to do, he or she may physically grasp the object in a way that promotes its efficient transport. For example, he or she may pick up a wooden board near its center if it is heavy or long, but if the board is too heavy or too long to be picked up by one person alone, he or she may ask someone else to help. If someone appreciates what an object affords in terms of its functional properties, he or she may pick up the object in a way that reflects his or her understanding of its purpose as well as its physical composition. Thus, someone who knows that a spoon is for eating may pick up the spoon by its handle rather than by its bowl, at least if sanitation or etiquette are concerns.

Analyzing object manipulation provides a window into motor control, a surprisingly understudied topic in psychology. The dearth of attention to motor control in psychology textbooks and psychology journals is ironic, considering that psychology is the study of mental life and behavior. Motor control is the study of the means by which mental life is translated into behavior (Rosenbaum, 2010). Why motor control has received

so little attention in psychology has been addressed elsewhere (Heuer, 2003; Rosenbaum, 2005). One reason for this neglect is the belief among many psychologists that it is difficult to make progress in the study of motor control by pursuing a psychological approach to it and, likewise, that it is difficult to make progress in the study of psychology by studying motor control. An aim in this review is to show that it is actually easy to do psychological research on motor control by studying object manipulation. Observing how people (and animals) interact with objects can help psychologists contribute to motor-control research and better understand the psychological control of behavior. Among other topics, one that may be advanced through this line of research is the understanding of embodied cognition (Barsalou, 2008; Glenberg, 1997; Proffitt, 2006; Wilson, 2002).

The logic of the approach to be reviewed here is straightforward: If the same object is handled differently depending on a performer's mental state, then his or her mental state can be inferred from the way he or she handles the object. In this context, it helps to introduce the concept of orders of planning for object manipulation. This article is the first, as far as we know, where this concept is used.

First-order planning entails shaping one's object manipulation behavior according to immediate task demands, as in turning one's hand according to the orientation of an object to be grasped or opening one's fingers wider for a wide object than for a narrow object. Second-order planning for object manipulation entails altering one's object manipulation behavior not just on the basis of immediate task demands but also on the basis of the next task to be performed. The paradigmatic example, which forms the basis for this review, is the observation that people generally take hold of an object to be inverted with the thumb pointing down rather than up; the inverted grasp permits a thumb-up orientation at the end of the rotation (Rosenbaum et al., 1990).

Orders of planning for object manipulation are possible beyond the second order. In general, it is possible to say that nth order planning for object manipulation is evident if one finds a reliable change in object manipulation in task n as a function of task $n + j, j > 0$. The order of planning is given by $j + 1$. Thus, one can look for changes in object manipulation in task n not just as a function of task $n + 0$ (first-order planning) or as a function of task $n + 1$ (second-order planning) but as a function of task $n + 2$ (third-order planning), and so on.

As cognitive psychologists, we are especially interested in second- and higher order planning for object manipulation. The bulk of this review concerns second-order planning. Less space is devoted to third- and higher order planning because less research has been done on this topic. In fact, we know of only two relevant studies (Haggard, 1998; Rosenbaum et al., 1990), the results of which are discussed in the Task Extensions section.

There have been, by contrast, many studies of first-order planning. Such studies have been motivated by the desire to understand the rudiments of perceptual–motor coupling. Not surprisingly, a great deal of this research has been done with babies. Representative aims of this research have been to determine when babies adjust their hand locations, hand orientations, and finger spreads based on features of objects they see or have just seen. Reviews of this research have appeared elsewhere (e.g., Elliott et al., 2010; Keen, 2011; Rosenbaum,

2010). First-order planning for object manipulation has also been studied in older children and adolescents, in neurologically typical (healthy) as well as neurologically atypical adults, and in nonhuman animals. These lines of research have been reviewed elsewhere (e.g., Milner & Goodale, 1995; Rosenbaum, 2010; Shumway-Cook & Woollacott, 2006). Given the availability of these other reviews, we limit ourselves in this article to research on second- and higher order planning for object manipulation.

The plan for the article is as follows. First, we introduce the main tasks in which the paradigmatic second-order planning effect for object manipulation has been demonstrated. Then we discuss the phenomenon of interest as it appears or fails to appear in populations other than university students and staff, those people being the ones in whom the effect was first studied. The populations of interest in this next part of the article are nonhuman animals, children, and clinical groups. In the next part of the article, we review extensions of the effect of interest to tasks beyond those in which the effect was first studied. Here, we look at object manipulation carried out in the contexts of memorizing, social motor control, and locomotion. The last part of the article is concerned with theoretical conclusions that this body of research affords, as well as remaining challenges.

Several core questions run through all the sections of this review: (a) How far in advance is object manipulation planned? (b) What factors account for the specific anticipatory changes that are observed? (c) What cognitive and psychological capabilities affect object manipulation and are in turn affected by object manipulation? (d) What are the implications of this work for the understanding of tool use? (e) How do anticipatory effects in object manipulation differ from anticipatory effects in language production, as reflected in phenomena such as coarticulation effects (e.g., Fowler, 2007) and speech errors (e.g., Dell, 1986)? (f) What practical implications can be drawn from research in this area for domains ranging from human factors to clinical medicine and rehabilitation? We do not attempt to answer all of these questions here. We offer the questions for readers to keep in mind as they read the review, considering answers or possible leads to answers based on their interests.

A last word before we turn to the research itself concerns our focus on object manipulation. Why use object manipulation to study cognition and action? Objects are interesting for psychology because of their varying affordances (Gibson, 1977, 1979). Regardless of whether objects are natural or artificial, they can be physically moved or transformed in ways that depend on their perceived opportunities for action. A camera may be used for taking pictures or for digging for water in the desert. A belt may be used for tying or for hanging. A pencil may be used for drawing or for poking. Understanding how affordances are formed may be advanced by studying affordance-based behaviors. Psychologists have long been interested in objects from the point of view of how they are visually perceived (Marr, 1982), how they are haptically perceived (e.g., Klatzky, Pellegrino, McCloskey, & Lederman, 1993; Turvey, 1996), and how they attract attention (e.g., Tipper, Lortie, & Baylis, 1992; Welsh & Elliott, 2004). Studying how objects are manipulated may shed light on these topics.

Tasks Demonstrating the Paradigmatic Effect

Initial Studies

The first studies were prompted by a chance observation. The first author (David A. Rosenbaum) was eating at a restaurant where he noticed a waiter filling glasses with water. Each glass stood upside down. To prepare each glass for pouring, the waiter took hold of the glass with his thumb down—that is, with his palm facing away from his midsagittal plane. The waiter picked up each glass, turned it 180 degrees, filled it with water, and then set it down on the table with his thumb up—that is, with his palm facing toward his midsagittal plane. What struck the first author was that this behavior made sense from a functional perspective. Had the waiter picked up any of the glasses with his thumb up, he would have found himself in an awkward situation when he then tried to fill the glass with water. He would have had to hold the glass with his thumb down when he filled the glass with water and then when he set the glass back on the table. Apparently, the waiter had learned to tolerate an initially awkward posture for the sake of a less awkward final posture.

Rosenbaum et al. (1990) brought this observation to the laboratory. They used a wooden dowel that lay flat on two cradles, high enough above a table to allow participants to grasp the dowel with a palm-up or a palm-down hand posture. To either side of each cradle and closer to the participant were two circular targets lying flat on the table. Participants were asked to reach out and take hold of the dowel in order to place the left end of the dowel on the left or right target or to place the right end of the dowel on the left or right target. The order in which the four conditions were tested was random for each participant. The participants were university students and staff.

All the participants grasped the dowel in a way that was consistent with the waiter's performance. They adopted an initially awkward posture for the sake of a less awkward posture at the end of the object transfer task. Thus, when the participants, all of whom used their right hand, planned to place the right end of the dowel onto either target, they grasped the dowel with a palm-down hand posture, but when they planned to place the left end of the dowel onto either target, they grasped the dowel with a palm-up hand posture. The common feature of the two initial grasps was that they afforded a thumb-up posture when the dowel was placed on the target. This final posture was more comfortable than the initial posture, at least by hypothesis. Accordingly, Rosenbaum et al. (1990) called this the *end-state comfort* effect.[1]

Confirmation Via Reversal

Were participants striving for end-state comfort in the foregoing demonstration, or were they simply showing a bias to avoid thumb-down postures for the vertically oriented dowel? This possibility could not be ruled out because the experiment described above always had the horizontal position first and the vertical position second. To explore this issue, Rosenbaum et al. (1990) asked another group of participants to perform a wider range of object-transfer tasks. Some of the tasks were the opposite of the one used in the first experiment. Now the dowel stood upright on the flat target at the start of the trial and was to be transported to the cradle and laid on the cradle with a prescribed orientation.

When the downward end of the dowel was supposed to be brought to the left end of the cradle with the right hand (the preferred hand for all participants), most participants grasped the dowel with a thumb-down posture, the posture they avoided when they brought the dowel from the cradle to the target at that orientation. The same outcome was obtained in the other, corresponding, condition, so the posture that was avoided if it was the terminal posture was adopted if it was the initial posture.

The latter outcome, coupled with the fact that participants avoided the thumb-down posture when bringing the dowel from the horizontal position to the upright position in the first experiment, confirmed that participants did not simply avoid thumb-down hand postures whenever they held vertically oriented objects. Instead, they avoided thumb-down hand postures in favor of thumb-up postures when the thumb-up postures could be adopted at the end of the object placement tasks. The bottom line, then, was that ending comfortably seemed to be the main determinant of participants' grasp choices.

Comfort Ratings

Was comfort actually considered in these tasks? If so, ratings of comfort should have borne this out. To check, Rosenbaum et al. (1990) asked each participant in the experiment just described to hold the dowel with each of the two possible hand orientations at each of the possible dowel positions. While holding the hand in each posture, the participant was asked to indicate how comfortable or uncomfortable the hand posture was, on a 5-point scale. 1 meant "completely comfortable," 5 meant "completely uncomfortable," and intermediate numbers were assigned intermediate comfort levels. The conditions were administered in a random order for each participant, who was asked to give comfort ratings for each test position twice, going through all the test positions once and then going through them again, in the same order per participant. Participants were told to use the entire 5-point scale and not to feel constrained to give the same ratings for the test positions the second time through. Participants were told the first round would give them a sense of the range of comforts. Only the second-round comfort ratings were analyzed.[2]

The comfort ratings revealed that participants strove to maximize end-state comfort. The choice ratings and corresponding grasp preferences were sufficiently stereotyped that Rosenbaum et al. (1990) could conclude that end-state comfort won out over two other possible choice rules: "maximize initial-state comfort" or "maximize total (or average) comfort." The only choice rule that was unambiguously supported was "maximize end-state comfort."

Elastic Energy

Saying that end-state comfort is explained by a preference for comfort at the end is circular. How can one get around this? One

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[1] Later research, reviewed here, revealed that end-state comfort is not always the sine qua non of grasp selection for object manipulation. The name stuck, however, and many articles have referred to the end-state comfort effect.

[2] We provide details about the procedure because physical comfort ratings have rarely been used in psychological research on motor control. The only other studies that have used them, as far as we know, were conducted by Parsons (1994) and Johnson (2000).

way is to consider alternative hypotheses. One such that was considered by Rosenbaum and Jorgensen (1992) was that maximizing end-state comfort is not an end in itself but instead is a by-product of a strategy involving exploitation of elastic energy. According to the elastic energy hypothesis, people bring their arms to extreme positions so they can stretch their muscles and tendons in preparation for subsequent moves. An analogous strategy is used for jumping. Jumpers lower themselves before leaping. The same strategy is used for throwing. Throwers retract their arms before tossing. Is a similar strategy used when people prepare to turn objects?

Rosenbaum and Jorgensen (1992) tested the elastic-energy hypothesis by reasoning as follows. If elastic energy is used, the preference for end-state comfort should be seen only when reliance on the elastic-energy strategy is possible. They assumed that the elastic energy strategy would not be exploited for lifting objects high over the shoulders, for the elastic energy stored up by twisting the arm before hoisting would be insufficient to help the heft. Given that assumption, the preference for end-state comfort would not be seen for high lifts, at least if the preference for end-state comfort was a consequence of elastic-energy usage.

To test this prediction, Rosenbaum and Jorgensen (1992) placed the cradle (the same as the one used in previous studies) on a platform attached to a tall bookshelf. On each trial, the participant was asked to reach out, take hold of the dowel (the same as used before) as it lay on the cradle, and bring its left or right end up against a large numbered dot on the edge of one of 14 shelves on the same bookshelf. The dots were numbered 1 for the top shelf, located at or near participants' maximum upward reach, to 14, located near the floor. After placing the named end of the dowel against the named dot, the participant was supposed to return the dowel to the cradle in its original orientation and then let go, returning his or her hand to his or her side. A typical instruction was "Black to 7," which meant, bring the black (left) end of the dowel to target 7.

The results contravened the elastic-energy hypothesis. Postures that afforded end-state comfort were observed for all target shelves. When the dowel was brought to the highest shelves, participants grasped the dowel so the dowel would be held with the thumb away from those shelves. When the dowel was brought to the lowest shelves, participants grasped the dowel so the dowel would be held with the thumb toward those low shelves. This outcome was consistent with the hypothesis that participants sought to maximize end-state comfort per se. By contrast, the result was inconsistent with the hypothesis that participants exploited elastic energy only when they could do so.

Hysteresis

Another finding from the experiment of Rosenbaum and Jorgensen (1992) concerned hysteresis—a change in the point at which a system switches outputs from one value to another depending on history. An example from a domain outside of object manipulation concerns the control of a furnace. The critical temperature for a furnace to turn on is usually lower than the critical temperature for the furnace to turn off. This change is built in to the furnace control system. Biological control systems, including the human motor system, exhibit similar tendencies.

A well-known example of hysteresis in human motor control pertains to coordination of bimanual oscillation. The critical frequency at which people switch from in-phase to anti-phase oscillation of the extended index fingers is different if the driving frequency ascends or descends (Kelso, 1984). Kelso, Buchanan, and Murata (1994) demonstrated hysteresis in a grasping task in which participants reached out to grasp a dowel oriented in different ways. The orientation at which participants switched from a palm-up to a palm-down grasp or vice versa was found to depend on the order in which the dowel orientations were tested. There was no subsequent manipulation required in this task, so this is an example of first-order planning.

Rosenbaum and Jorgensen (1992) tested for hysteresis in their dowel-to-shelves task by having participants reach with the dowel for target heights that successively increased or decreased. When the targets were tested in ascending order, participants switched from grasps that brought the thumb toward the shelf (low targets) to grasps that brought the thumb away from the shelf (high targets) at higher locations than when the targets were tested in descending order. Hysteresis results like these were subsequently reported by Short and Cauraugh (1997); Weigelt, Rosenbaum, Huelshorst, and Schack (2009); Weiss and Wark (2009); and Schütz, Weigelt, Odekerken, Klein-Soetebier, and Schack (2011).

Control Rather Than Comfort

So far in this review we have said that when people grasp objects with an awkward hand posture prior to turning the objects, they do so because they have a preference for end-state comfort. Still, the reason for this preference has not been provided. It may be that ending comfortably mainly contributes to better control at the end of the movement. This explanation is not just important for rationalizing the end-state comfort preference; it also leads to the important idea that end positions per se may not always be most important for determining initial grasps. Rather, initial grasps and, for that matter, other aspects of object manipulation might reflect a concern for control when and where it is most needed.

Short and Cauraugh (1999) pursued this possibility with a task similar to the one used in the dowel-to-shelf task of Rosenbaum and Jorgensen (1992). Short and Cauraugh asked participants to bring the end of a dowel to targets at different heights, as in the experiment of Rosenbaum and Jorgensen, but Short and Cauraugh used targets that were narrow as well as wide. Rosenbaum and Jorgensen used only narrow targets. Short and Cauraugh found that the probability of adopting awkward initial grasps prior to object rotations was greater for narrow targets than for wide targets. Because the final postures adopted for the narrow and wide targets were the same, Short and Cauraugh inferred that the desire for greater targeting control, as required for narrow targets, accounted for the grasp choices they observed.

Further evidence for this conclusion came from a task in which participants rotated a handle from an initial orientation to a final orientation (Rosenbaum, Vaughan, Jorgensen, Barnes, & Stewart, 1993). The handle rotation device consisted of a large disk with a handle at its center. The handle was mounted on two rigid extensions that were far enough from the middle of the handle that participants could grasp the handle with an underhand grasp or an overhand grasp, as in the studies described earlier. Turning the handle caused the disk to rotate. A tab protruding from the edge of

the disk obscured one of eight numbered targets positioned below the disk surface and at equal angular intervals around the disk's perimeter. Participants reached out and turned the handle to bring the tab to a named target (i.e., to cause the tab to cover the target with the named number). Because the disk had very low friction, it took little torque to turn the disk. Participants had to carefully center the tab on the target, owing again to the low friction. All the required tab rotations covered 180 degrees.

The main finding was that the probability, p(T), of taking hold of the handle with the thumb toward the tab varied as a function of the final required handle orientation. For those participants who performed the task with the right hand (as per instruction), p(T) was lowest when the tab had to be brought to a position near 4 o'clock. For those participants who performed the task with the left hand (again, as per instruction), p(T) was lowest when the tab had to be brought to a position near 7 o'clock. Participants therefore grasped the handle in a way that ensured avoidance of awkward final postures.

Why did participants avoid awkward postures at the final handle positions? The answer offered by Rosenbaum, Vaughan, et al. (1993) was that having the limb at midrange positions rather than at extreme positions made it possible to maximize control while homing in on the target. The idea was that the initial phase of the handle rotations could be completed quickly, whereas the final phase had to be completed more slowly. Slow, precise positioning at or near the target was hypothesized to be easier at midrange arm postures than at extreme arm postures.

The idea that aiming movements have a quick phase followed by a slow phase has a long history in research on perceptual–motor control. The distinction was drawn by Woodworth (1899), who is best known in behavioral science for his reviews of experimental psychology (Woodworth, 1938; Woodworth & Schlosberg, 1954). However, for his doctoral dissertation, completed at Columbia University, Woodworth (1899) showed that in visually guided aiming, the hand exhibits an initial ballistic phase followed by a later homing-in phase. Excellent reviews of this work have been prepared by Digby Elliott and his colleagues (Elliott et al., 2010; Elliott, Helsen, & Chua, 2001). Woodworth's two-stage model holds both for linear aiming tasks, as studied by Woodworth himself, and for rotary aiming tasks, where a handle is turned to bring a pointer to a target (e.g., Wright & Meyer, 1983). The study of Rosenbaum, Vaughan, et al. (1993) was the first rotary aiming task we know of in which participants could freely adopt different grasp orientations.

Although Rosenbaum, Vaughan, et al. (1993) hypothesized that the grasp orientations chosen by their participants ensured greatest control when greatest precision was required, it was important to test that claim directly. Such a test was provided by Rosenbaum, van Heugten, and Caldwell (1996), who used a handle rotation task that required very little control in the termination phase of the rotation. To have such a task, Rosenbaum et al. (1996) modified the apparatus of Rosenbaum, Vaughan, et al. (1993). They added a spring-loaded bolt to the edge of the disk and made other modifications that permitted the disk to stop by itself when the tab reached the target. Participants merely had to "fling" the disk toward the target. Rosenbaum et al. (1996) reasoned that if participants chose initial postures that maximized terminal control at the target, those postures would not be chosen reliably when little end-state control was required.

The data obtained by Rosenbaum et al. (1996) corroborated this hypothesis. For the first time in any study of grasp choices involving object turns, an appreciable number of participants adopted comfortable initial grasps. Half the participants consistently grasped the handle with a midrange arm posture rather than an extreme arm posture; this led to their adopting extreme arm postures at the end of the rotation, something that was rarely seen before. The other participants still showed the awkward-at-first effect, perhaps because that was their general habit. The fact that the usual anticipation effect could be eliminated in a large number of participants by removing the need for end-state precision fit with the hypothesis that planning for precision at the end of object displacements was a key determinant of participants' grasp choices.

Rosenbaum et al. (1996) added a further check of the hypothesis that controlling the handle was easier at or near the middle of the arm's range of motion (along the pronation-supination axis) than at or near an extreme position. In another experiment, they asked participants to oscillate a handle as quickly as possible. In one condition, participants were supposed to keep the forearm as pronated as possible during the oscillation. In another condition, the participants were supposed to keep the forearm as supinated as possible during the oscillation. In a third condition, the participants were supposed to keep the forearm at or near the center of the pronation–supination range. The result was that oscillation rates were dramatically higher at the middle of the range of motion than at either end of the range, a result that fits with known facts about the power of the forearm at various portions of the pronation–supination axis (Winters & Kleweno, 1993). Finding that the highest oscillation rates were possible in the part of the range of motion that people preferred for aiming accords with the hypothesis that participants chose grasps that permitted greatest control in the phase of the movement when greatest control was required. All in all, then, the results reviewed in this section indicate that control rather than comfort was likely to be the primary determinant of participants' grasp choices.

The Grasp Height Effect

If control rather than comfort is the main determinant of grasps for object manipulation, one should see evidence for this principle in measures of where objects are grasped as well as how objects are grasped. This expectation was confirmed in the discovery of the *grasp height* effect (Cohen & Rosenbaum, 2004).

As was the case for the phenomenon that was initially called the end-state comfort effect, the grasp height effect was discovered via naturalistic observation. The first author (D. A. Rosenbaum) needed to use a toilet plunger in his home bathroom. Later, when he put away this "plumber's helper," he noticed that he took hold of the plunger shaft high before setting it down on the floor. Noticing this, he thought he might have grasped it high because he was planning to move it low. Had he grasped the plunger at its midrange position, he reasoned, he would have had to adopt an awkward posture at the end of the low plunger placement. Informal testing at home suggested that the lower the planned placement of the plunger, the higher the grasp height. In addition, the higher the planned placement of the plunger, the lower the grasp height.

Cohen and Rosenbaum (2004) brought this naturalistic observation into the laboratory. They asked participants to stand before

an empty bookshelf. While facing the shelf, each participant saw a platform protruding from the middle of the shelf, on which stood another bathroom plunger (one that had never been used for its intended purpose). This object was a convenient manipulandum because it could be easily picked up and set down at another spot. To the right of the platform stood another platform that protruded from the shelf at different heights in different conditions. The participant was asked to stand in front of the setup, midway between the platform on the left and the platform on the right. When the experimenter said "Go ahead," the participant grasped the plunger with the right hand (the preferred hand for all participants), moved the plunger from the occupied platform to the unoccupied platform, and then lowered his or her hand. When the experimenter again said "Go ahead," the participant reached out for the plunger, returned it to the home platform, and then lowered his or her hand once again. The same procedure was repeated, whereupon the participant was given a short break during which the experimenter changed the height of the target platform, keeping the height of the home platform constant. Participants were videotaped as they did the task. They were invited to perform in a leisurely way.

Cohen and Rosenbaum (2004) found, as the first author had found on his own, that the higher the target to which the plunger was brought, the lower the height at which the plunger was grasped. Similarly, or saying the same thing in a different way, the lower the target to which the plunger was brought, the higher the height at which the plunger was grasped. Over the range of target heights tested, Cohen and Rosenbaum found an inverse linear relation between target height and the grasp height.

In a later experiment, Rosenbaum, Halloran, and Cohen (2006) asked whether the grasp height effect would be modulated by concern for control rather than comfort. They followed logic like that of Short and Cauraugh (1999), who varied precision requirements while keeping postural requirements the same. Recall that in the task of Short and Cauraugh, grasp orientation rather than grasp height was the dependent variable. Rosenbaum et al. (2006), in contrast to Cohen and Rosenbaum (2004), varied the precision requirements of lifting the plunger from its home position and of placing the plunger in its target position. They did so by adding rings of varying diameter to the home platform and to the target platform. The rings, which were made of Styrofoam and were 5 cm high, had interiors that were either slightly wider (14 cm) or considerably wider (20 cm) than the 13-cm plunger base. When the home platform's inner ring was wide, the precision requirement of lifting the plunger was low, but when the home platform's inner ring was narrow, the precision requirement of lifting the plunger was high. Similarly, when the target platform's inner ring was wide, the precision requirement of placing the plunger was low, but when the target platform's inner ring was narrow, the precision requirement of placing the plunger was high. The question was how and whether the grasp height effect would depend on the precision required for lifting and placing. The prediction based on the control rather than the comfort hypothesis was that the grasp height effect would be attenuated whenever required precision requirement was high. The rationale was that the range of grasp heights would be reduced, and low grasps, in particular, would be expected when high precision was needed because a low grasp height would allow for better control of the plunger base. Said another way, grasping the plunger high would lengthen the lever

arm, causing unintended hand motions to be magnified at the base of the plunger. High grasps would be avoided then, in general, when high precision was needed.

The results confirmed this prediction. The grasp height effect was replicated, but the slope of the function relating grasp height to target height was lower and the arithmetic mean of the grasp heights was lower when required precision was high than when required precision was low. Whenever the precision requirements increased—either by requiring a lift of the plunger from a narrow rather than a wide base or by requiring a placement of the plunger into a narrow rather than a wide base—the grasp height effect was reduced and the grasp heights were lowered. This outcome fits with the precision account of the grasp height effect. Where the object was grasped (at which height) was apparently chosen to promote control and not just comfort, just as how the object was grasped (with which hand orientation) was chosen to promote control and not just comfort.

Influence of Repositioning on the Grasp Height Effect

While investigating the grasp height effect, Cohen and Rosenbaum (2004) noticed something unexpected. When their participants returned the plunger to the home position from the target position, the participants did not display the full-fledged grasp height effect. Instead, they grasped the plunger close to where they had grasped it to carry it from the home site to the target site.

To understand the significance of this outcome, consider what would have happened if participants had shown the grasp height effect when they returned the plunger from the target platform to the home platform. Because the home platform had a single, fixed height, participants would have grasped the plunger at the same height on the plunger no matter which target platform it occupied. This is not what happened, however. Instead, participants grasped the plunger at a height along the plunger shaft close to where they had just grasped it when they brought the plunger from the home position to the target position. The return grasp positions were not always exactly where they were before, but they were skewed toward the grasp heights adopted when the plunger was brought from the home to the target.

How can one explain this result? Possibly it could be ascribed to an effect of regression to the mean. Perhaps participants grasped the plunger for return moves at positions that tended to congregate toward the mean of the grasp heights adopted before. This hypothesis was called into question in an experiment in which the height of the home position was varied and the height of the target position was fixed. This was the opposite of the situation used in the first experiment of Cohen and Rosenbaum (2004), where the height of the home position was fixed and the height of the target position was varied. In this new situation, the grasp heights for the return moves were close to what they had been for the home-to-target moves. Therefore, the return-move grasp heights diverged from the mean grasp height and did not converge toward the mean grasp height—just the opposite of what would have happened if the return-move grasp heights had reflected regression to the mean.

What does this pattern of results add to the understanding of grasp-position choices in object manipulation? Evidently, grasp-position choices do not just reflect considerations of control for precision, as discussed in the last section; they also reflect effects of memory. Relying on memory to choose grasp heights for return

moves can obviate "figuring out" which grasp heights to use. Said another way, relying on recall rather than planning may save cognitive resources. By analogy to solving math problems and the familiar idea that people use recall (e.g., remembering the proposition $12 \times 12 = 144$) to avoid carrying out computations (Lewin, 1922a, 1922b; Logan, 1988), participants in the experiment of Cohen and Rosenbaum (2004) may have relied on recall to choose grasp heights for return moves from target positions. Doing so would have assured them of getting the plunger back to the home position in a way that was at least posturally tolerable; they had, after all, just placed their hand on the plunger at the home position, so there was no doubt that hand position was possible.

Frames of Reference for Grasp Height Recall

What information did participants recall when they recalled grasp heights? Did they recall postures, or did they recall external locations? If they recalled postures (full body positions), the information they recalled would have been represented in intrinsic (body-based) coordinates. But if they recalled external locations, the information they recalled would have been represented in extrinsic (allocentric) coordinates. Distinguishing between these hypotheses was theoretically important, not just for finding out more about the source of the grasp height recall effect but also, more generally, for finding out what information is used in the guidance of physical actions.

Data bearing on the posture-recall hypothesis versus location-recall hypothesis were provided by Weigelt, Cohen, and Rosenbaum (2007). Their participants moved a plunger from a home location to a target location. Then the participants lowered the hand and then raised the hand again to move the plunger back to the home location. The important difference between the task used by Weigelt et al. and the task used earlier by Cohen and Rosenbaum (2004) was that Weigelt et al. had their participants take a sideways step between the first plunger move and the second. In this interim step, the participants stepped up onto a platform, down from a platform, or, in the control condition, horizontally. These manipulations allowed Weigelt et al. to find out whether the grasps for the return moves were better predicted by intrinsic or extrinsic coordinates. If participants recalled the grasp in intrinsic coordinates, they would have reached for the plunger with the same posture as before—at or near the point where they grasped it earlier relative to some body location (their feet, say) and not relative to some external location (the base of the plunger, say). Conversely, if participants recalled the grasp in extrinsic coordinates, they would have reached for the plunger at the same point as where they grasped it relative to an external location (e.g., the base of the plunger), not relative to some body location (e.g., their feet).

The results supported the extrinsic hypothesis rather than the intrinsic hypothesis. Participants grasped the plunger close to where they had grasped it before relative to the base of the plunger, not relative to their feet. This was true even if it meant adopting radically different postures between grasps, especially before and after stepping up or down. Because the grasp heights for the return-to-home moves were well predicted by the distance of the grasp from the base of the plunger rather than from participants' feet, Weigelt et al. (2007) concluded that participants recalled

extrinsic (allocentric) coordinates rather than intrinsic (postural) coordinates.[3]

Combining Grasp Height and Hand Orientation

As discussed above, choosing grasp heights and choosing hand orientations reflect similar principles of motor planning. Therefore, it is reasonable to expect these two phenomena to co-occur. When an object must be turned as well as lifted or lowered, one could expect the grasp height effect and the hand-orientation effect to appear together. If these two effects were thought to reflect the operations of two independent information-processing channels or were thought to reflect the operation of a single integrated information-processing channel, one could expect both phenomena to appear when they are tested together. Conversely, if the two effects were thought to reflect the operations of two dependent information-processing channels, one could expect one or both of the phenomena to appear in weakened or, conceivably, in strengthened form if tested with the other (Sternberg, 1969).

Cohen and Rosenbaum (2011) tested these hypotheses in a study in which participants chose grasp heights and grasp orientations. At the start of each trial, the participant saw a plunger lying across two cradles. The participant could grasp the plunger with an overhand grasp or with an underhand grasp to carry it to a platform at some height to the right of the pickup site. The base of the plunger was either to the left or to the right at the time of the pickup, which meant that picking up the plunger with a right-hand overhand grasp would be problematic if the base of the plunger was to the left, and picking up the plunger with a right-hand underhand grasp would be problematic if the base of the plunger was to the right. (All the participants spontaneously performed the task with the right hand.) Meanwhile, the length of the plunger shaft was long enough that participants could take hold of the plunger shaft at different places along its length. In the studies reviewed earlier, where the grasp orientation was the principal measure, the dowel was much shorter and grasp positions were not recorded.

Cohen and Rosenbaum (2011) found that the participants (university students) grasped the plunger with a grasp orientation that afforded a comfortable (thumb-up) final position. They also grasped the plunger along its length at a place that allowed the final hand position to be near the middle of the range of motion rather than at an extreme position, as in previous demonstrations of the grasp height effect. There was no indication that the grasp height effect or hand-orientation effect was weaker than in the tasks used before.

Taking stock of these results, Cohen and Rosenbaum (2011) suggested that their data were consistent with the view that the

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[3] Remembering a location on an object may require less memory than remembering an entire posture. The number of variables (degrees of freedom) to be stored in remembering a location is less than the number of variables to be stored in remembering a configuration of the human body. This fact is related to the degrees-of-freedom problem for motor control, the mapping of many extraneous degrees of freedom onto fewer degrees of freedom, as in determining which posture to adopt to bring the hand to a point in 3D space (Bernstein, 1967). For a review of psychologically related research devoted to this problem, written primarily for psychologists, see Rosenbaum (2010).

grasp height effect and the hand-orientation effect either reflected the operation of two independent channels (one for grasp height and one for grasp orientation) or the operation of a single integrated channel for these two response features. They suggested that the integrated-channel account was preferable because the same neuromuscular control system is required both for raising and for rotating the arm. Indeed, if one subscribes to the view that the actions of raising and rotating the arm bring the arm to a goal posture (Butz, Herbort, & Hoffmann, 2007; Morasso & Sanguineti, 1995; Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Rosenbaum, Vaughan, et al., 1993), the integrated-channel account makes a great deal of sense.

Choosing Forthcoming Grasps

When do people decide which grasps to use for manipulating objects? Two lines of research, summarized next, suggest that they decide very soon after seeing objects to be manipulated, often before starting to move the hand.

One line of research relied on the times to choose forthcoming grasps. Rosenbaum, Vaughan, Barnes, and Jorgensen (1992) had participants reach out to move a dowel from one location to another, with several different start locations and target locations possible. Only when one of several possible target lights came on did participants know where to move the dowel from its start location. The grasp to be used—thumb toward one end or the other of the dowel—was for the participants to choose. The participants' reaction times suggested that even before they moved their hands from the start position, they selected the grasps they would use. The reaction times differed for the identical start and target position of the dowel when participants would grasp the dowel one way or the other, though again those grasps were generally more awkward when the dowel was grasped than when it was placed. By and large, it was when this rule was not followed that longer reaction times were seen for starting to move the hand toward the dowel.

Further support for the idea that forthcoming grasp choices are made very early came from a study of knob turning. In this study, conducted by Herbort and Butz (2010), participants adjusted their initial forearm position and hand orientation based on the direction they would rotate the knob. When the participants were given advance information about the forthcoming rotation direction, their reaction times for grasping the knob differed as a function of the rotation direction. Herbort and Butz concluded, as did Rosenbaum et al. (1992), that participants chose postures based on action demands before the onsets of the actions itself. Chang, Klatzky, and Pollard (2010) arrived at the same general conclusion in another study of manual lifting behavior, as did Lippa and Adam (2001) and Zimmerman, Meulenbroek, and de Lange (2011) in studies concerned with stimulus–response compatibility.

If people mentally represent forthcoming grasp postures, one would expect them to make similar action choices when they can actually reach out and grasp objects and when they can only indicate how they would do so if they could. The latter hypothesis was explored in a study in which participants could either reach out to grasp a dowel oriented in different ways in real space or only indicate via verbal responses how they would grasp that dowel oriented in the same ways as a dowel shown in a virtual, pictured,

space (Johnson, 2000). This comparison of grasp choices using real or pictured objects yielded the second line of evidence for the hypothesis that people can decide even before actually moving how they will complete the move to grasp an object one way or another.

In the real-space condition of Johnson's (2000) experiment, participants reached out and grasped the dowel without having to move it anywhere afterward. By contrast, in the virtual-space condition, participants saw pictures of the dowel in each of the same orientations as in the real-space condition and announced which end of the dowel they would grasp, using the thumb as a reference. Johnson addressed two questions. One was whether the names the participants called out in the virtual grasp conditions would map onto the ends toward which their thumbs would point in the real grasp conditions. The other question was whether the reaction times would vary with dowel orientation in comparable ways in the real and virtual conditions. The answer to both questions was Yes. Participants called out the same names in the virtual grasp conditions as they had in the real grasp conditions, replicating an earlier finding by the same author (Johnson, 1998). Reaction times also varied with dowel orientation in comparable ways in the real and virtual conditions. Altogether, Johnson's (2000) study led to a conclusion that agreed with the main conclusion of the earlier studies reviewed in this section: Mental representations of forthcoming grasp postures are available very quickly, even before movements are under way.

Bimanual Grasp Selection

People do not manipulate objects with only one hand. Sometimes they use two. Do they show similar planning for bimanual object manipulation as for unimanual object manipulation? The question is theoretically interesting because, for bimanual movements, there is a strong tendency to move the hands symmetrically (Diedrichsen, Hazeltine, Kennerley, & Ivry, 2001; Franz, Zelaznik, & McCabe, 1991; Ivry, Diedrichsen, Spencer, Hazeltine, & Semjen, 2004; Kelso, Southard, & Goodman, 1979; Kunde & Weigelt, 2005; Weigelt, 2007). In some circumstances, therefore, there can be a conflict between moving the hands symmetrically and ending in a comfortable or easily controlled posture. When such a conflict exists, which tendency wins? Is there always a clear winner, as might be expected if there were a rigid constraint hierarchy, or does the identity of the winner change depending on the context in which performance is tested?

A study on this topic was done by Weigelt, Kunde, and Prinz (2006). This trio asked participants to grasp and reposition two dowels from a pair of start locations to a pair of target locations. The dowels were positioned horizontally in front of the participants, as in the original dowel placement task of Rosenbaum et al. (1990). As in that original study, each dowel sat on raised cradles so it could be picked up either with an overhand grasp or with an underhand grasp. Participants in the study of Weigelt et al. were asked to grasp the two dowels at the same time and to move the two dowels' black or white ends to black or white targets, respectively, depending on the instruction. "Black" always meant "put both black ends down on the black targets." "White" always meant "put both white ends down on the white targets."

Because the initial orientations of the dowels changed over trials, achieving thumb-up postures for both hands as their end

state required participants to adopt different combinations of overhand and underhand grasps in different conditions. In congruent conditions, when the dowels were oriented the same way at their horizontal start positions, participants could adopt the same grasp with each hand and make symmetric left- and right-hand movements while also ending with thumb-up postures. In incongruent conditions, participants could not make symmetric left- and right-hand movements and also achieve thumb-up postures with both hands. Consequently, they had to achieve bimanual symmetry and fail to achieve a final posture with two thumbs up, or they had to achieve a final posture with two thumbs up and fail to achieve bimanual symmetry.

Weigelt et al. (2006) found that their participants almost always achieved a final posture with two thumbs up regardless of congruency. Thus, the participants adopted symmetrical grasps that allowed for the final two-thumbs-up posture in the congruent conditions (also see Fischman, Stodden, and Lehman, 2003, for similar results), but the same participants did not grasp symmetrically in the incongruent conditions; instead, participants grasped asymmetrically in order to bring both hands to thumb-up postures at the ends of their respective movements. Weigelt et al. concluded that achieving desired final postures took priority over moving symmetrically.

Hughes and Franz (2008) performed a similar study, except that instead of varying the initial orientations of the objects to be moved while keeping the end orientations constant, as done by Weigelt et al. (2006), Hughes and Franz varied the objects' end orientations while keeping the objects' initial orientations fixed. By using this experimental manipulation, Hughes and Franz could conduct another check of the relative importance of end-state posture versus movement symmetry in bimanual grasp planning. To do so, they had their participants reach out and grasp two dowels, each of which had distinctly colored ends, and transport the dowels simultaneously and as quickly as possible to two target locations. The two dowels stood vertically and had one color (the same color) on their tops and another color (the same color) on their bottoms. The two targets to which the dowels were brought stood on a platform above the dowels' start positions. Participants had to either put the same colors on the two targets or put different colors on the two targets. Thus, as in the study of Weigelt et al., the initial grasps the participants had to adopt to achieve final thumb-up postures either matched (in the congruent conditions) or mismatched (in the incongruent conditions).

The result was that participants grasped the dowels in ways that afforded bimanual thumb-up postures in 99% of the congruent trials not requiring object rotation and in 72% of the congruent trials requiring object rotation; in the incongruent trials, they did so in 58% of the incongruent trials requiring rotation of the left hand dowel and in 71% of the incongruent trials requiring rotation of the right hand dowel. Thus, participants did not always achieve bimanual thumb-up postures, contrary to what was observed, or nearly observed, by Weigelt et al. (2006).

Another study combined the manipulations of start and end orientations to examine the effects of these variables on final postural symmetry versus movement symmetry. Janssen, Beuting, Meulenbroek, and Steenbergen (2009) asked right-handed participants to grasp two compact disc cases and transport them to two compact disc racks. Each rack had a horizontal slide and a vertical slide. The compact disc could be put into each rack either in a horizontal or a vertical orientation. The required end orientation as well as the initial orientation of each compact disc at the start locations varied between trials. Janssen et al. (2009) found that the tendency to end in thumb-up or thumb-in (toward the midsagittal plane) postures with the two hands did not depend on whether the movements of the two hands were symmetric. Thus, this result replicated what was found by Weigelt et al. (2006). In another study, Janssen, Crajé, Weigelt, and Steenbergen (2010) reached the same conclusion. Hence, of the four studies reviewed here that juxtaposed movement symmetry and end-state posture, three studies (Janssen et al., 2009, 2010; Weigelt et al., 2006) found that end-state posture won out over movement symmetry.

The final study reviewed in this section on bimanual grasp selection joined interest in bimanual object manipulation with the grasp height effect. The question was whether the two hands would both show the grasp height effect when bimanual object transports were required. Would the grasp height effect be attenuated in the case of two-hand performance? If so, what factor or factors would contribute to attenuation of the grasp height effect?

Van der Wel and Rosenbaum (2010) pursued this question by asking participants to grasp two plungers, one with each hand, from two fixed start locations of equal height to move the plungers to targets of varying heights. As in the previous studies of bimanual grasp selection, the question of interest was whether participants would favor bimanual symmetry or would select grasp heights based on the location of the target, even if this meant they sometimes violated bimanual symmetry. Van der Wel and Rosenbaum found that, regardless of whether the target heights differed, participants adopted similar grasps on the two objects. Thus, they started the object transports in symmetrical body postures. Importantly, this tendency for symmetric grasping implied that participants did not show the grasp height effect in the context of bimanual transport. When the objects to be moved had different weights, however, participants abandoned the symmetrical grasping postures in favor of postures that anticipated the location of the targets. Van der Wel and Rosenbaum concluded that bimanual object manipulation relies on a flexible, context-dependent prioritization of constraints. Neither considerations of symmetry nor ending with the hands toward the middle of the range of motion (i.e., ending comfortably) was always the most important constraint for bimanual object manipulation. Instead, people flexibly took these constraints into account when they performed their two-hand object manipulations.

Populations

All the studies described so far concerned performance by neurologically normal young adults or, more specifically, university students and staff. Other studies have concerned nonhuman animals, children, and clinical populations.

Nonhuman Animals

Although fewer studies have concerned second-order motor planning effects in animals than in humans, enough studies have been done with nonhuman animals to provide a critical mass of evidence on this topic. Why study nonhuman animals in this context? The basic-science reason is to draw inferences about when in evolution such effects may have emerged. The idea is to

look for those planning effects in species whose lineage is known relative to humans. If that species shows second- or higher order planning, then it is possible to infer that such planning or its underlying competencies arose at or before the branch point for that species vis-à-vis the line of phylogeny that led more directly to *Homo sapiens* (Hodos & Campbell, 1990).

Weiss, Wark, and Rosenbaum (2007) conducted the first study of second-order motor planning effects in animals. They investigated the effect in cotton-top tamarins (*Saguinus oedipus*). These small, arboreal, New World monkeys are interesting to study in connection with second-order planning for object manipulation because they are believed not to use tools in the wild, although they still seem to have some understanding of means–end relationships (Hauser, 1997; Santos, Pearson, Spaepen, Tsao, & Hauser, 2006). If the cognitive capacities underlying second-order planning effects are sufficient for feral tool use, as suggested by Johnson-Frey (2004), one would not expect cotton-top tamarins to display such effects. Conversely, if the cognitive capacities underlying second-order planning effects are insufficient for tool use in the wild, one might expect to find that cotton-top tamarins display those effects despite their apparent non-tool use in their native habitat. Behind the latter statement is the idea that in some species of non-tool users, second-order planning may be seen, whereas in other species of non-tool users, second-order planning may not be seen. Non-tool-using animals that do show second-order planning may be said to be farther along on the evolutionary path to tool use than non-tool-using animals that do not show second-order planning. The latter distinction makes sense only if one assumes that second-order planning is insufficient for tool use, an assumption that is still debated (Arbib, Bonaiuto, Jacobs, & Frey, 2009; Baber, 2003).

Weiss et al. (2007) tested for second-order motor planning in cotton-top tamarins using a variant of the original dowel transfer procedure of Rosenbaum et al. (1990). First, during a familiarization phase, the researchers presented each individually tested tamarin with a small plastic cup (a transparent plastic champagne glass with a stem whose base was removed). Inside the cup was one of the tamarin's favorite treats—a bit of marshmallow. The cup was presented in various orientations, and the tamarin was free to remove the food however it wished. Once it demonstrated sufficient familiarity with this task, it graduated to the test phase. Here, the cup was suspended, in either an upright or an inverted orientation, with its open end up against a flat surface that prevented the tamarin from reaching into the cup to get hold of the marshmallow within it. To get the food, which was clearly visible in the cup, the tamarin had to slide the cup out of the apparatus, grasping the cup's stem and pulling the cup toward its body. The question was which grasp it would use to pull the cup. When the cup was upright, would it grasp the stem with the thumb up? When the cup was inverted, would it grasp the stem with the thumb down? The answers to both questions were affirmative. When the cup was upright, the tamarin grasped the stem of the cup with the thumb up. When the cup was inverted, it grasped the stem of the cup with the thumb down. The latter result was striking because tamarins rarely grasp objects with their thumbs down (i.e., with extreme pronation). Their doing so in this experiment signaled their appreciation of the need to adopt an initially unusual posture for the sake of later control.

Tamarins are believed to have diverged from the hominid line about 40 million years ago, so the cognitive capabilities underlying their second-order planning ability can be said to have taken hold at least that long ago. Chapman, Weiss, and Rosenbaum (2010) asked whether the capabilities supporting the second-order planning effect may have arisen even earlier in primate evolution. To do so, Chapman et al. looked for the same effect in lemurs. Lemurs are prosimian primates that are even more evolutionarily remote from humans than tamarins are. Lemurs are believed to have diverged about 65 million years ago, or roughly 25 million years before the divergence of New World monkeys (including tamarins) and hominids (Horvath et al., 2008). If lemurs show a second-order planning effect, that would push back the emergence of the associated abilities by about 25 million years.

Chapman et al. (2010) offered lemurs the same type of transparent plastic champagne glass as used in the tamarin study of Weiss et al. (2007). The lemurs were shown the cups in either an upright or an inverted orientation, as in the earlier study, and the result was again positive. The lemurs used thumb-up grasps when the cup was upright but thumb-down grasps when the cup was inverted. Remarkably, the lemurs often displayed the inverted hand grasp in their first test trial with the inverted cup. Finding a second-order motor planning effect in lemurs, the most distant living primate relatives of humans, suggests that the cognitive ability that allows for this planning effect was characteristic of one or more species ancestral to primates.

If the latter suggestion is correct, one would expect second-order motor planning effects to hold in great apes (e.g., chimpanzees and gorillas) and Old World monkeys (e.g., macaques and baboons), not just in New World monkeys (e.g., tamarins and capuchins) and prosimians (e.g. lemurs). To the best of our knowledge, great apes and Old World monkeys have not yet been tested on second-order motor planning tasks. However, a recent study that tested the motor planning abilities of rhesus monkeys (*Macaca mulatta*, a species of Old World monkey) yielded results suggesting that such an effect would appear in these species.

Nelson, Berthier, Metevier, and Novak (2011) tested seven adult rhesus monkeys on a spoon-reaching task adapted from earlier work with human infants (McCarty, Clifton, & Collard, 1999). The rhesus monkeys had no prior experience manipulating spoons. Each monkey was presented with a food-laden spoon resting on a holder designed to encourage grasping of the spoon's handle. Individual monkeys mastered efficient spoon transport at a much faster rate than was observed in a comparable task with human infants (McCarty et al., 1999). Three of the monkeys alternated their reaching hand to bring the bowl of the spoon to their mouth efficiently, using the same strategy as 19-month-old human infants in a similar paradigm. Three other monkeys did not alternate hands but instead used a preferred hand to grasp the spoon, changing their posture and reaching from an initially awkward oblique angle that allowed for an efficient grasp with the preferred hand. This strategy, in our view, can be regarded as consistent with grasping with an awkward posture for the sake of a posture that affords more control when it is most needed.

The final study reviewed in this section addressed the question of whether another feature of motor planning—the tendency to persevere with whatever motor plan was recently used—would be seen in nonhuman species. Recall that Rosenbaum and Jorgensen (1992) observed this tendency in human participants and that the

same hysteresis effect was replicated (again with human participants) by others, as reviewed above. To determine whether the same phenomenon exists in a species of nonhuman animals, Weiss and Wark (2009) presented cotton-top tamarins (the same individuals tested by Weiss et al., 2007) with a piece of food that could be reached with one hand or the other. On subsequent trials, the position of the food was changed, being presented in a series of locations that went either clockwise or counterclockwise in an imaginary arc in front of each participant. Weiss and Wark measured the radial position at which the participants switched the hand they used to grasp the food. The grasps were made through a hole in a transparent Plexiglas barrier. Consistent with the hysteresis prediction, Weiss and Wark found that the transition point for the left or right hand differed for the clockwise and counterclockwise directions. The switch point was delayed to favor the hand that had been used previously. Although this finding was not a further demonstration of a second-order motor planning effect per se, it accords with the more general idea that the nature of motor planning is similar in human and nonhuman primates.

Children

Just as it is useful to study planning for object manipulation phylogenetically, as discussed in the last section, it is also useful to study this topic ontogenetically, as discussed in this section. Does second-order planning for object manipulation appear in children? If so, at what age?

The first study of this topic that we know of came from Hughes (1996), who tested normally developing children as well as children with autism and children with moderate learning disabilities. Using the dowel-placing task of Rosenbaum et al. (1990), Hughes found that neither children with autism nor children with moderate learning disabilities consistently strove for terminal thumb-up hand postures. By contrast, for the normally developing children she tested, 71% of 4-year-olds showed the effect but only 14% of 3-year-olds did.

Other investigators had difficulty replicating all of Hughes' (1996) results, however. Smyth and Mason (1997) used the dowel placement task to investigate motor planning skills in normally developing children and in children with developmental coordination disorder. Smyth and Mason found that children with developmental coordination disorder did not consistently end with thumb-up postures, but neither did a majority of children in the control group that these investigators studied—namely, normally developing children ranging in age from 4 to 8 years. In none of the age ranges tested by Smyth and Mason was there a statistically significant tendency to end the object transports with thumb-up postures.

Why did Smyth and Mason (1997) not observe this tendency in the normally developing children they studied? One possibility is that they asked their participants simply to hold the dowel briefly on the target before returning it to the initial location. It could be that holding the dowel briefly at the target location caused the participants to think of that location as an intermediate rather than an end position. By contrast, Hughes (1996) had her participants insert one end of the dowel into a hole, perhaps causing her participants to think of the corresponding position as an end site. Regardless of how the participants in the two groups mentally represented the tasks, the results of Smyth and Mason suggest, at the very least, that the tendency to plan for thumb-up final postures is less robust in children than in adults.

This impression finds further support in a study by Manoel and Moreira (2005). They tested 3- to 6-year-old typically developing children with a variant of the dowel-placing task. Manoel and Moreira explored two precision requirements, one allowing easy placement of the dowel, the other requiring more precise placement of the dowel. These authors hypothesized that greater precision requirements might bring out planning for the thumb-up final posture in young children. Their results provided little evidence for this hypothesis, however, in the children of any of their age groups. Still, Manoel and Moreira tested few participants, certainly far fewer than did Hughes, who found thumb-up postures in the children she tested. Hughes (1996) tested 14 children in her 3-year-old group and 14 children in her 4-year-old group. Manoel and Moreira tested just six children in each of their four groups, who ranged in age from 3 to 6 years.

Just as Smyth and Mason (1997) and Manoel and Moreira (2005) found little evidence of thumb-up final postures in young children using the dowel-placing task of Rosenbaum et al. (1990), another group of investigators, not mentioned before in this review (van Swieten et al., 2010), found little evidence of the effect in children as tested with the handle rotation task of Rosenbaum, Vaughan, et al. (1993). Van Swieten et al. tested typically developing children, children with developmental coordination disorder, and children with autism. These researchers asked the children they tested to reach for a vertical handle and rotate it clockwise or counterclockwise to a final position. The handle rotation task could be completed in a thumb-up or thumb-down posture. Van Swieten et al. found that anticipation of the final thumb-up posture occurred in 19% of typically developing 5- to 8-year-old children and in 48% of typically developing 9- to 14-year-old children. This pattern of results suggested a developmental trend for the effect, although it also suggested incomplete acquisition of the effect in the 9- to 14-year age range.

Why didn't a greater number of older children in the study of van Swieten et al. (2010) show the final thumb-up posture? One possibility is that the precision demands were low in this task. The handle could be released instantly after a simple clockwise or counterclockwise rotation, making the task similar to the low-precision task of Rosenbaum et al. (1996). Recall that the latter group found, using their task that could be achieved by merely flinging the pointer toward the target, that only half their adult participants anticipated thumb-up postures (or postures with the thumb pointing toward the midline, given that the rotation was done with the hand hanging down). This value is very similar to the value of 48% found by van Swieten et al. for their oldest group.

More insight into the development of planning for object manipulation came from a study by Adalbjornsson, Fischman, and Rudisill (2008). These researchers asked preschool children (2–3 years old) and kindergarten children (5–6 years old) to invert an overturned glass. When the 2- to 3-year-old and the 5- to 6-year-old children performed the task, they almost always grasped the inverted glass with a thumb-up posture, leading to a thumb-down posture at the end of the inversion. Thus, as in the other studies reviewed in this section, the planning effect did not appear in these children. By contrast, adults showed the planning effect when

performing the glass inversion task (Fischman, 1997), as did the waiter in the restaurant, where the effect was first noticed.

Still more information about development was provided by Weigelt and Schack (2010), who tested a large number of participants—a total of 51 participants, with 17 in each of the three age groups, 3, 4, and 5 years—in a task requiring insertion of the left or right end of a dowel into a target disc. All the children reached for the dowel with an overhand grasp when this resulted in a thumb-up end-state. However, when the initial overhand grasp would have resulted in a thumb-down end state, 18% of the 3-year-olds, 45% of the 4-year-olds, and 67% of the 5-year-olds took hold of the dowel with an underhand grasp, thereby ensuring the final thumb-up posture. This result indicates that there was improvement in children's sensitivity to end-state posture as they made the transition from 3 to 5 years of age. However, by age 5 the planning effect was still not as strong as in adulthood.

Thibaut and Toussaint (2010) assessed the performance of 120 children, age 4, 6, 8, and 10 years, in the dowel placement task of Rosenbaum et al. (1990). As in the original task, for Thibaut and Toussaint the dowel did not have to be inserted into a target hole, so it required less final precision than in the study of Weigelt and Schack (2010). The result, nonetheless, was that initial grasps were modulated to afford final thumb-up postures in 42% of the 4-year-olds, in 66% of the 6-year-olds, in 49% of the 8-year-olds, and in 81% of the 10-year-olds. Why there was a drop in the percentage of children who showed the effect in the 8-year-old range was unclear. Thibaut and Toussaint speculated that some form of motor reorganization may take place at or around this age. Setting that issue aside, the general trend was unmistakable: Older children were more likely than younger children to choose initial grasps that afforded final grasps that presumably permitted greater control.

The motor planning of children with cerebral palsy was a focus of research by Crajé, Aarts, Nijhuis-van der Sanden, and Steenbergen (2010), who tested typically developing children as well as children with cerebral palsy in an object manipulation task. Their task combined the logic of the dowel placement task and the handle rotation task used in previous studies. Children, 3–6 years old, were invited to reach for a wooden sword and insert its blade into a slot in a wood block. The sword was presented with the blade in several orientations. In the critical conditions, for the sword to be inserted into the slot with a relatively comfortable hand posture, the sword's handle had to be grasped in a relatively uncomfortable way. Crajé et al. found a steady increase, over age, in the likelihood of ending comfortably among the normally developing children they tested. By contrast, they did not obtain evidence for a strengthening with age of the planning effect among the children with cerebral palsy. In those children, the effect was small at all ages. Even so, however, the children with cerebral palsy showed a benefit of training. After these children completed an 8-week training course, they showed a significant increase in the likelihood of grasping the sword in the awkward manner for the sake of ending in the less awkward manner.

Williams' syndrome has also been investigated through the lens of planning for object manipulation. Newman (2001) reported motor planning deficits in children with this genetic disorder, whose primary symptom is disturbed visuospatial and visuomotor performance contrasted with relatively fluent verbal ability. Newman tested children diagnosed with Williams' syndrome as well as typically developing children in two motor planning tasks—a handle-rotation task and a bar-transport task—both designed to reveal the children's sensitivity, or lack thereof, to future task demands. Newman found that typically developing children showed second-order planning on both the handle-rotation task and the bar-transport task. The rates at which the planning effect was manifested were similar in the two tasks for these typically developing children. By contrast, the children with Williams' syndrome failed to select grasps with respect to final posture in the handle-rotation task, though their performance on the bar-transport task was no different from that of typically developing children. Newman hypothesized that the children with Williams' syndrome had trouble with the handle-rotation task because of problems with visualization. This account dovetails with findings reviewed above, in the section called Choosing Forthcoming Grasps, indicating equivalent performance on tasks requiring visuomotor imagery and tasks requiring overt performance. The latter result might be taken to suggest that selection of appropriate means of overt performance relies on visuomotor imagery. Until Newman's study came along, it might have been difficult to draw that inference, but the interaction between clinical status and task reported by Newman might be used as a basis for making that claim (cf. Jeannerod, 1994).

The developmental studies reviewed here paint a fairly consistent picture of the development of second-order planning for object manipulation. In general, in normally developing children, the observed capacity for such planning increases from age 3 to 10 years, though by 10 years of age, it is still not as strong as in adulthood. The age at which the effect reaches adult strength has not yet been determined.

An exciting recent finding is that even toddlers as young as 18 months begin to exhibit the tendency to grasp objects in noncanonical ways if such behavior leads to more canonical hand postures when the final hand postures require considerable control (Jovanovic & Schwarzer, 2011). This study shifted the emphasis from the age at which the grasp planning effect is fully in place to the matter of the age at which the grasp planning effect seems to show the first signs of viability. Evidently, at least in some children it can be observed in the second year of life.

Adult Clinical Populations

So far, we have considered clinical aspects of higher order planning for object manipulation in connection with children who have autism, cerebral palsy, developmental coordination disorder, or Williams' syndrome. The research reviewed above indicated that such children were less likely than their typically developing confreres to show second-order planning for object manipulation. In the present section, we review research with adult clinical populations.

Dijkerman, McIntosh, Schindler, Nijboer, and Milner (2009) asked two adults with visual agnosia to reach out and turn a dowel. Visual agnosia is an impairment in recognizing objects attributed to a breakdown of the ventral stream for visual processing. It is a rare disorder, which is why Dijkerman et al. could publish what amounted to a two-case study. They asked their two participants to turn a dowel from various initial orientations to a fixed target orientation. Whereas healthy controls modulated their initial hand orientations (changing from a clockwise to an anticlockwise ori-

entation and vice versa) in a way that reflected sensitivity to end-state control (see Stelmach, Castiello, & Jeannerod, 1994, for related data with healthy adults), the participants with visual agnosia did not modulate their hand orientations so clearly. This outcome suggests that the ventral stream plays a role in the visual registration of object properties relevant to object manipulation, a result that might not have been expected if one thought that this neuroanatomical pathway plays little or no role in perception for action (Milner & Goodale, 1995). Dijkerman et al.'s result casts doubt on this otherwise influential hypothesis and may be viewed as being consistent with the view, offered by Glover (2002), that the ventral stream is critical for movement planning and the dorsal stream is critical for online control (but see Mendoza, Elliott, Meegan, Lyons, & Welsh, 2006).

Another series of studies that focused on second-order grasp choices for object manipulation in an adult clinical population cast doubt on another widely held view—that cerebral palsy is a deficit of motor execution rather than motor planning. Earlier in this review, we mentioned a study that suggested this outcome for children with cerebral palsy. As reported above, Crajé et al. (2010) found that children with cerebral palsy failed to show end-state grasp planning as reliably as did typically developing children. Other studies with older individuals with cerebral palsy showed the same thing vis-à-vis their age-matched, neurologically normal controls (Crajé, van der Kamp, & Steenbergen, 2009; Mutsaarts, Steenbergen, & Bekkering, 2006; Mutsaarts, Steenbergen, & Meulenbroek, 2004; Steenbergen & Gordon, 2006; Steenbergen, Hulstijn, & Dortmans, 2000; Steenbergen, Meulenbroek, & Rosenbaum, 2004). These studies, coordinated by Steenbergen, also showed that the nature and severity of motor planning deficits depend on the side of the brain in which damage is sustained. The studies showed that individuals whose cerebral palsy takes the form of right hemiparesis (following damage to the left cerebral hemisphere) tend to show more severe second-order grasp planning problems than do individuals with left hemiparesis (due to damage of the right cerebral hemisphere). Those with right hemiparesis gave little indication of second-order grasp planning when using the impaired (right) hand and showed limited second-order grasp planning at best when using the unimpaired (left) hand. By contrast, those with left hemiparesis, whose neurological damage was mainly centered in the right hemisphere, showed greater sensitivity to second-order grasp planning than did those with right hemiparesis, and this was true regardless of which hand was used by those with left hemiparesis. These studies suggest, then, that motor planning, as revealed by the strength of second-order planning for object manipulation, relies more heavily on the left cerebral hemisphere than on the right cerebral hemisphere. The latter inference is well known in neurology, where it has been known since the early twentieth century that apraxia, a high-level motor control problem, is generally more pronounced in patients with left-hemisphere damage than in patients with right-hemisphere damage. For reviews, see Freeman (1987) and Heilman and Valenstein (1985).

Hermsdörfer, Laimgruber, Kerkhoff, Mai, and Goldenberg (1999) studied second-order object manipulation in individuals with apraxia. These patients had unilateral lesions resulting from cerebrovascular accidents in either the left or the right hemisphere. The patients were asked to grasp a bar that had various initial orientations and then to place one end of the bar into a hole.

Hermsdörfer et al. contrasted performance on an unconstrained version of this task, in which either end of the bar could be placed in the hole, with a constrained version of the task in which participants were instructed to place a particular end of the bar into the hole. The latter condition was like the one studied by Rosenbaum et al. (1990). Participants with right brain damage exhibited pronounced deficits in prehension related to the spatial aspects of the task. Their performance was especially impaired in the unconstrained version of the task. Participants with left brain damage exhibited pronounced deficits in prehension related to the motor aspects of the task. Their performance was equally impaired in the constrained and unconstrained versions of the task. On the basis of these results, Hermsdörfer et al. suggested that the primary role of the right hemisphere in object manipulation is coding the spatial requirements of the task and that the primary role of the left hemisphere in object manipulation is motor planning. This suggestion echoes the classical view mentioned above.

Task Extensions

We come now to the third major part of the article, the part concerned with extensions to tasks and domains beyond those in which the planning phenomena of interest were first studied. We limit ourselves to object manipulation, though we wish to note in passing that the approach to planning described here in connection with object manipulation was recently extended to walking (Cowie, Smith, & Braddick, 2010).

Higher Order Planning

As discussed in the opening section of this article, our main interest in the study of planning for object manipulation is with planning beyond the first order—that is, planning for aspects of object manipulation that come after the first, most immediate, forthcoming task. So far, we have focused on second-order planning, postponing consideration of third- or higher order planning because of the paucity of studies on this topic. We review those few studies now.

The first study that went beyond second-order planning for object manipulation was actually reported by Rosenbaum et al. (1990). In some tasks, they asked participants to pick up a dowel and bring one end or the other to one target and then to bring that same end of the dowel or the other end of the dowel to the same or another target. The question was whether the grasp orientation would minimize awkwardness at the end of the first move or second. The data favored the first option. Participants grasped the dowel in a way that minimized awkwardness of the posture adopted at the first new position, not the second. Hence, the data confirmed that there was second-order planning but not that there was third-order planning.

Not finding evidence for third-order planning in this context suggests that the state of the body at the end of the series of tasks to be completed is not the sine qua non of planning for object manipulation. If it were, participants in this study would have planned their first grasps to minimize awkwardness at the end of the last position they would adopt. Whether with more practice they would have done so is an open question.

The second and only other study we know of on third- and higher order planning for object manipulation was reported by

Haggard (1998). He asked his participants to grasp an octagonal object and place it subsequently into two, three, or five different slots whose identities were revealed prior to the initial grasp. Haggard's participants selected different initial grasps for different slot positions two or three moves later, but not four or five moves later. This outcome suggests that planning of movement occurred up to three moves in advance in Haggard's study.

Why did Haggard's participants plan farther ahead than Rosenbaum et al.'s? One factor that distinguished Haggard's (1998) study from Rosenbaum et al.'s (1990) was that the targets used by Haggard occupied a single plane, whereas the targets used by Rosenbaum et al. occupied multiple planes. Whether this difference or some other accounted for the difference in outcomes is something that can be examined in the future.

Another possibility is that the critical difference concerned the time to complete the task. Haggard's positioning moves may have been completed more quickly than Rosenbaum et al.'s, though the actual times were not recorded in either study. Planning spans in speaking and in typewriting go well beyond two or more forthcoming gestures, and speaking and typewriting are performed much more quickly than object manipulation, at least in skilled speakers and typists. (For a review of work as pertains to the speed of speaking and of typing and to planning spans in these domains, see Rosenbaum, 2010.) This difference lends credence to the possibility that time, or some cognitive function related to time, might be relevant to the determination of planning spans. Tasks that take more time might tax working memory more than tasks that take less time. If working memory is critical for the planning of object manipulation, there should be evidence consistent with that view. As seen in the next section, there is.

Working Memory

In everyday life, physical actions are usually carried out to satisfy higher order goals; they are not usually carried out for their own sake. A waiter who inverts a glass to pour water into it does so to satisfy his job requirements, but while he pours the water into the glass, he has other things on his mind—what he'll do after work, what may be on the exam he'll take the next day when he returns to class, and so on. In the studies reviewed so far, participants carried out the tasks they did with no purpose other than performing the tasks they were asked to (aside from getting paid or receiving credit for their participation). Would the results be different if the object manipulations were done while satisfying higher level purposes?

Weigelt, Rosenbaum, Huelsthorst, and Schack (2009) explored this issue by combining an object manipulation task with a memory task. They asked university students to open each of a number of drawers in a vertical chest of drawers. Each time a participant opened a drawer, he or she lifted an upside-down cup inside the drawer, turned the cup over and looked inside it and memorized the letter in its bottom, then returned the cup to the drawer in its original inverted position, closed the drawer, and repeated this procedure for the next drawer to be checked. In one condition, participants opened the drawers from bottom to top. In another condition, the same participants opened the drawers from top to bottom. A critical feature of the drawers was that each one had a wide oval hole, allowing the participant to open the drawer with either an overhand grasp or an underhand grasp.

Having participants open the drawers in different orders—bottom to top or top to bottom—let Weigelt et al. (2009) determine whether the hysteresis effect found before would be replicated when the actions to be carried out were performed in the service of a higher order goal, in this case, memorization. Weigelt et al. found that the hysteresis effect was indeed manifested in this situation. Participants used underhand grasps for low drawers and overhand grasps for high drawers. Furthermore, the transition point from one grasp to another was at a higher drawer for ascending sequences than for descending sequences, as found earlier. Because the hysteresis effect was replicated in this context, Weigelt et al. concluded that it survived the embedding of the object manipulation task in an overarching cognitive task.

How well did participants remember the letters in the Weigelt et al. (2009) task? Normally, when people try to remember lists of items, they recall both early and late items better than intermediate items. This relation is the famous serial position curve for free recall, described in virtually all textbooks of human memory. Weigelt et al. made a surprising discovery about the serial position curve in their drawer-opening experiment. They found that the recency effect was eliminated. The last items in the list were recalled no better, statistically speaking, than the intermediate items, though the early items were recalled better than the items that followed. The overall level of recall was high enough that Weigelt et al. could dismiss the hypothesis that participants simply gave up trying to remember those letters.

Weigelt et al. (2009) interpreted the elimination of the recency effect in this context as supporting the hypothesis that motor planning takes up cognitive resources. A priori, one might not have expected this to be the case. Under the conventional view that motor control is separate from "true mental function," one might have expected verbal memory to be unaffected by object manipulation. However, the fact that verbal memory was influenced by ongoing motor planning and motor control suggests that motor planning and motor control tax at least some of the same cognitive or intellectual resources.

Beyond this inference, the memory effect discovered by Weigelt et al. (2009) may also be taken to suggest that working memory may have as one of its primary roles the planning and preparation of voluntary physical acts. There are at least two bases for this suggestion. First, the recency portion of the serial position curve is generally thought to reflect readout from working memory. The fact that the recency portion of the serial position curve was eliminated by embedding the verbal list learning task in physical tasks suggests that working memory is involved in motor planning. Second, it has long been appreciated that one component of working memory is the so-called visuospatial sketchpad (Baddeley & Hitch, 1974). This component of working memory is thought to be a station for the management of visual-spatial representations. Insofar as the management of visual-spatial representations is critical for motor planning, it is consistent with prior claims about working memory to suggest, as Weigelt et al. did, that when motor planning occurs, working memory is critically involved. What is perhaps most important about this claim vis-à-vis other literature is that working memory has not traditionally been

thought of as a system for motor planning. We do not mean to suggest that motor planning is the only or primary function of working memory, though we could imagine that a strong embodied-cognition view might lead to that interpretation. The fact that another function of working memory has long been recognized to be the maintenance of information for verbal articulation is, of course, consistent with the idea that working memory is, at least in part, a system for the organization of information for forthcoming actions.[4]

Social Factors

Object manipulation sometimes occurs in social settings. Handing someone a spoon in a way that reflects understanding of what the recipient will do with the spoon illustrates the way that social factors can interact with action planning.

Do people modulate the way they manipulate objects during joint actions such that they take into account others' action constraints? To investigate this possibility, Gonzalez, Studenka, Glazebrook, and Lyons (2011) asked participants to pick up one of three objects (a hammer, a calculator, or a stick) that was initially positioned in an upright or an upside-down orientation. In some conditions, the participants handed the object to another person (actually a confederate), who either used the object for its intended purpose or simply laid down the object. The participants were aware of what the other person would do with the object and were told to make the task as easy and efficient as possible for the recipient. The question of interest was whether the participants would hand the object to the recipient in a way that depended on this context. The results confirmed that they did. Of special interest, participants adopted awkward initial postures to end comfortably when their actions facilitated the subsequent use of the object by the person on the receiving end.

In a study similar to the one just described, Ray and Welsh (2011) asked whether people take the efficiency of a co-actor's future actions into account in a sequential object-passing task. In this task, participants handed a jug of water to a confederate, who then either placed the jug on a table or poured water from the jug. The jug could be grasped either by its body or by its handle. The question of interest was whether participants would hand the jug to the confederate with the handle available to them; doing so would, of course, ease pouring. Ray and Welsh found that participants did so almost all the time. This outcome provides further support for the idea that people can incorporate others' action needs into their own action plans.

Grasp choices are also affected by social modeling, as shown by Santamaria (2008), who recorded participants' grasp heights when they took hold of a plunger to move it either up or down from a central height. The height of the target was designated by an experimenter in different ways. When the experimenter grasped her own plunger at distinct heights to designate high or low target heights for the participants, there was a stronger effect of the compatibility of her grasp heights on the participants' grasp heights than when the same experimenter pointed to or named those same distinct heights on her own plunger. The nature of the experimenter's actions therefore affected the grasp heights that participants adopted. The more closely the experimenter's actions resembled the actions the participants would perform, the more the participants' adopted actions came to be influenced by the experimenter's behavior.

Results like these indicate that object manipulation is subject to social influences. This outcome is not surprising from the perspective of the powerful role that imitation plays in daily life. Moreover, one would expect such influences given the discovery of and avalanche of research on mirror neurons (Rizzolatti & Craighero, 2004). What is more surprising about the results just summarized is that they suggest that social influences run deeper, or to a more specific level of behavior, than might have been expected. Plainly, when people engage in actions that have clear social messages, such as holding a door for another other person, it is plausible that the door holder mentally models what the follower's physical needs will be (Santamaria & Rosenbaum, 2011). But door holding is, by nature, a communicative act, as is a waiter's handing a spoon to a customer. Where one grasps an object in a situation that is not overtly social might not be expected to be subject to social influences. That it is speaks to the tremendous power of social communication and, no less, to the permeability of motor planning to social influences. If motor planning were a function far removed from traditionally studied mental functions, one might expect it not to be shaped by social factors. That it is accords with the theme of this article that cognition and action go hand in hand.

General Discussion

We began this article by noting that psychology has paid scant attention to motor control. In this connection, it is noteworthy that *Psychological Bulletin*, the premier journal for the review of literature in psychology since its founding in 1904, has carried only two articles with the terms *motor control* or *movement control* in their titles (Keele, 1968; Nathanson, 1932) and only 33 articles with the word *motor* in their titles, one of which was about U.S. Army motor transport personnel (DeSilva, Robinson, & Frisbee, 1941). The most recent article concerned motor action in the sense used here (Klapp & Jagacinski, 2011), and another article, by Glencross (1977), focused on the control of skilled movements. It could be that there have been so few articles on motor control out of the 7,170 articles published in *Psychological Bulletin* (according to Web of Science on September 18, 2011) because motor control accounts for no more than .46% of the variance in psychologically mediated behavior—that is, .46% = 100 × (33/7,170). Unquestionably, the exact means by which body movements are made is less important than other factors in many contexts. To cite just one chilling example, if someone decides to crash a plane into the World Trade Center, the nature of his or her movements is less important (except at the very end) than are the factors that led up to the decision. This point notwithstanding, the way movements are made reflects states of mind. This point has

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[4] Logan and Fischman (2011) reported additional evidence for reduction of the recency portion of the serial position curve when an object manipulation task was added to a learn-words-followed-by-recall task. In their study, participants memorized words and then carried out physical tasks like those used by Weigelt et al. (2009). Logan and Fischman's procedure was similar to ones used in classical studies of short-term memory in which tasks are interpolated between learning and recall. There, the recency portion of the serial position curve, but not the primacy portion of the serial position curve, was found to suffer.

long been recognized in connection with facial expressions (Darwin, 1872/1965; Ekman & Friesen, 1975; Rinn, 1984). It has not been recognized to the same degree for everyday acts like manipulating objects.

We focused here on one aspect of object manipulation that reflects mental states—the tendency to grasp objects with awkward grasps if those initial, awkward, grasps promote subsequent control. In the remainder of the General Discussion, we consider the implications of the findings reviewed here and remaining challenges for this line of research. The implications of the present work fall into two broad categories. One concerns implications that have already been noted. The other concerns implications that have not.

Implications for Cognition and Action

Perhaps the single most important implication of the work reviewed here, which has already been noted, is that cognition and action are richly interwoven. The observations we have summarized indicate that people and animals grasp objects in ways that reflect intentions. Whether actors, human or nonhuman animals, grasp objects with one orientation or another depends on how they plan to orient the objects. Where along the lengths of objects they grasp the objects depends on the height to which they plan to carry the objects. How they grasp the objects depends on whether they expect to hand the object to another person and what the other person will do with the object. The same object is grasped differently, then, depending on the actor's plans. Plans can take into account a multiplicity of factors, including biomechanical efficiency and comfort, the relative importance of different kinds of costs such as the symmetry or asymmetry of bimanual movements, and considerations of others' needs.[5]

That object manipulation is a psychologically rich activity is also reflected in the fact that it does not come easily, cognitively speaking, to all people. In people with cerebral palsy, whose motor difficulties were previously thought to be uniquely related to movement execution, research on object manipulation has shown that some of their motor difficulties also relate to motor planning. Research on object manipulation has also shown that children fail to show second-order planning as readily as adults do. Furthermore, university-student participants carrying out object manipulation tasks while learning lists of words show reduced recall of those words, especially the most recent ones, consistent with the hypothesis that working memory is called upon for motor planning and control (see also Acheson & MacDonald, 2009).

Implications for Affordances

We turn next to implications that were not expressed before in this review. Three of them will be discussed. One concerns affordances. The second concerns Donders' law. The third concerns naturalistic observation and the teaching of psychology.

Affordances are actors' appreciations of what the environment enables them to do. The concept of affordances was introduced by Gibson (1977, 1979) and has had tremendous impact among perceptionists (e.g., Proffitt, 2006) and human-factors investigators (e.g., Norman, 1988).

Norman's application of the affordance concept is especially relevant here because it focused on object design. Norman (1988)

proposed that the design of objects should suggest in as direct a way as possible how those objects should be acted on. An example he praised was a knob for changing the position of a car seat. The knob was shaped like a miniature car seat and was situated to the left and below where the driver sat. According to Norman, the driver would be able to tell from the feel of the knob how to act on the felt miniseat to manipulate the real seat on which the driver sat. More broadly, Norman urged that the layout of environments on which, and in which, individuals act should reliably signal adaptive ways of acting. This same idea was emphasized earlier by Fitts and Deininger (1954) in their introduction of stimulus–response compatibility and the concept of population stereotypes for stimulus–response associations. Proctor and Reeve (1990) provided a review of work on stimulus–response compatibility, and Michaels and Stins (1996) provided a review of research aimed at recasting stimulus–response compatibility in terms of affordances.

The research summarized in this article sets limits on the extent to which one can ascribe the appreciation of affordances to direct perception—that is, to the direct pickup of information from the environment concerning the actions it affords (Michaels & Carello, 1981). The concept of direct perception is alluring. Undoubtedly, some features of the environment require little or no problem solving about what is "out there," contrary to the computational view of perception espoused by Helmholtz (1866/1962) and his disciples (e.g., Marr, 1982; Rock, 1983). However, the presence of second- and higher order planning shows that reliance on direct perception cannot, by itself, account for action. What determines the manner in which individuals interact with the environment reflects their intentional states. This implies that any extension of the ecological approach to perception and action must come to grips with intentional dynamics, as advocates of the ecological approach have appreciated (e.g., Turvey, 2007) and as more cognitively oriented investigators have long understood (e.g., Klatzky, Fikes, & Pellegrino, 1995).

Implications for Donders' Law

The second as-yet unmentioned implication of the phenomena we have discussed pertains to Donders' law, a law (one of the few in psychology) that is probably unfamiliar to most readers of *Psychological Bulletin*. Ironically, many or perhaps most readers of this journal have probably heard of Donders in connection with his use of reaction times to estimate the durations of mental operations. As those readers know, Franciscus Donders, who was a Dutch ophthalmologist (1818–1889), collected reaction times in tasks of varying complexity. He was interested in changes in the reaction time to generate the same response to the same stimulus depending on the task.

Whereas Donders' pursuit of reaction time methodology is well known among readers of *Psychological Bulletin,* his law is less so. Donders, being an ophthalmologist, was interested in the eye. His law concerned gaze angles and eye positions. He proposed that for any gaze angle, the eye occupies a unique position (Fetter, Misslisch, & Tweed, 1997; Gallistel, 1999). Donders appreciated that

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[5] Object grasps also anticipate abduction–adduction of the hand, a biomechanical variable that was not previously discussed here (Zhang & Rosenbaum, 2008).

for a given gaze angle there need not be just one ocular position. On the contrary, the eye could, in principle, occupy any of an infinite number of positions while keeping its gaze direction constant. That is, it could have an infinite number of pitch, roll, and yaw angles for a given direction of gaze. Donders proposed that for every gaze angle there is just one combination of these three angles. An interesting spin-off from this idea is that the unique orbital positions for all the possible gaze angles happen to lie in a single plane—the so-called listing plane. Reviews of this work have been provided by Howard and Templeton (1966), Gallistel (1999), and Fetter et al. (1997).

Some researchers have suggested that the arm may obey an analog of Donders' law (Gielen, Vrijenhoek, & Flash, 1997; Mitra & Turvey, 2004). The basis for this suggestion is easy to observe. If you point in a wide range of directions, keeping your elbow fully extended and, for the sake of the demonstration, keeping all of your arm fully extended as well, you can observe your hand changing orientation depending on where you point. Studies of these orientation changes have suggested that they are systematic, as if, to a first approximation, there may indeed be a unique mapping of pointing directions to arm orientations, as would be expected if Donders' law applied to the arm (Gielen et al., 1997; Mitra & Turvey, 2004). However, detailed investigations of arm orientations following different prior arm postures have shown that this invariance does not hold exactly. How the arm is oriented for a given pointing direction depends in subtle ways on where it pointed before (Soechting, Buneo, Herrmann, & Flanders, 1995).

The manual planning effects reviewed here show that Donders' law is not just subtly violated for the arm. It is strongly violated when an object is grasped in transit to another destination. As has been shown here repeatedly, the arm orientations that people and animals adopt when they take hold of objects can be awkward if that awkwardness subserves later comfort or control. Furthermore, the posture adopted when holding the same object can differ dramatically depending on whether the object will be carried to another place or is brought to that place from another location. Thus, there is not a unique mapping of arm orientations to arm positions, contrary to Donders' law as applied to the arm. The application Donders' law to the arm was never suggested by Donders, by the way, at least as far as we know.[6]

Implications for Naturalistic Observation and the Teaching of Psychology

The final implication of the grasp planning effects that was not previously mentioned concerns naturalistic observation and the teaching of psychology. As was mentioned here, the tendency to grasp objects with different hand orientations depending on the later placement of the objects was discovered through naturalistic observation, as was the tendency to grasp objects at different positions along their lengths. Naturalistic observation has not received much attention in modern scientific psychology, though it is, or potentially could be, a wellspring of psychological research.

A happy implication of the history of the discoveries underlying the present body of research is that it is indeed possible to make new discoveries about psychology by simply keeping one's eyes and ears open to potentially interesting phenomena. It may be instructive for students to be made aware of the fact that the effects covered here were discovered simply by noticing everyday behav-

iors. This feature of the effects, coupled with the general "low-tech" nature of the experiments done to explore them, was brought to the attention of students in a recent textbook (Lee, 2011).[7]

Remaining Challenges

For whatever new things have been learned about cognition, action, and object manipulation through the studies reviewed here, challenges remain. One is to better understand the development of the planning effects in children. The willingness to adopt awkward initial postures for the sake of less awkward later postures does not appear to take hold reliably until after age 12, at least judging from the data reviewed here. This is surprising considering that by age 10, children are capable of advanced cognitive operations, as shown, for example, by the fact that youngsters 6, 8, and 10 years of age can solve the Tower of Hanoi problem at a level involving six moves (Borys, Spitz, & Dorans, 1982). The latter result implies that children in this age range can achieve complex means–ends problem solving, making it unclear why children within this age range do not demonstrate second-order planning for object manipulation to the same degree as older people.

One possibility is that older children, like their younger counterparts but unlike adults, have difficulty learning novel perceptual-motor skills. Vasudevan, Torres-Oviedo, Morton, Yang, and Bastian (2011) recently reported that older children cannot learn to walk on two treadmills at once, at least when the two feet must walk at different speeds. Adults can learn this task, however. Perhaps reaching for objects in highly skilled ways also takes longer to learn than one might expect.

Another possibility, not mutually exclusive with the first, is that children have difficulty exercising self-control (Casey, Jones, & Hare, 2008). Grasping an object in an uncomfortable way entails delaying gratification, albeit of a limited kind. Lack of inhibitory control in this context might be especially worth pursuing because it does not depend on verbally mediated understanding.

Other populations would also be of interest. At the other end of the developmental spectrum, would elderly individuals show a diminution of the planning effects? If so, would this be due to reduced physical mobility or to cognitive changes? Insofar as the effects are largely cognitive, though they are expressed motorically, it would be useful to find out whether individuals with Alzheimer's disease, say, or other forms of dementia, still show the effects. Do motor planning abilities last longer than other, more intellectual abilities, for example?

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[6] It turns out that Donders' law is violated for the eye as well, and in a psychologically mediated way. Pashler, Ramachandran, and Becker (2006) found that participants' eyeball torsion angles changed as a function of attentional set as they looked at tilted or nontilted words centered at the same place in the visual field. Pashler et al. made no mention of Donders' law, perhaps indicating that this law is unknown to psychologists, including some of the most esteemed psychologists in the world.

[7] Another phenomenon of perceptual–motor control that was recently discovered by naturalistic observation was the tendency of people walking down staircases to make their last looks down onto the staircase about three or four steps from the bottom. This behavior was ascribed to triggering of the last downward look by the disappearance of the stairs from the bottom of the field of view and then to reliance on memory updating as the stair descenders monitored where they were as they "walked down memory lane" (Rosenbaum, 2009).

In much the same spirit and returning to the young end of the aging spectrum, do children with language difficulties show a reduction of the grasp planning effects? If language function draws on or interfaces with other sequencing processes, including those involved in motor sequencing (Iverson, 2010), one might expect such children to do worse on object manipulation tasks than do their normally developing peers. An intriguing possibility, both for children and adults, is that training on the object manipulation tasks discussed here could promote cognitive or other self-control capabilities. This would turn the effects described here from phenomena to be explored ex post facto to ones that can be exploited for training purposes. A useful start has already begun along this line, as reviewed earlier in connection with the work by Crajé et al (2010); see the Children section.

Another remaining challenge is to learn more about planning for object manipulation in animals. Given the recent explosion of research on animal cognition (e.g., Shettleworth, 2010; Wasserman, 1993), it would be interesting to test for second- and higher order planning in other species besides those already tested. Of interest here would be studies bearing on the question of how much earlier in evolution one can presume that the cognitive machinery for future planning took hold. Relying on the same logic as used in the animal studies reported here—testing existing species whose evolutionary lineage is reasonably well known—it would be interesting to see whether the planning effects summarized here hold in nonprimate mammals, reptiles, amphibians, birds, and even in fish and insects. A broader conception of "manipulation" might be required for some of these species, of course, but the functional question would be the same: How far in advance of forthcoming tasks do animals change their behavior on the task being performed?

New tasks, analogous to the ones studied so far, could also be pursued. There are clear extensions of the basic tasks that are worth considering. Earlier, we mentioned an extension to walking (Cowie et al., 2010). Within the domain of object manipulation, many other tasks could be imagined as well. One is very close to the tasks reviewed here and should be mentioned because it hasn't been pursued. It involves simply varying the masses and mass distributions of objects to be moved. Lifting a very heavy bar is much easier with elbow flexion than with elbow extension or straight-arm lifting, so an underhand grasp might be strongly preferred over an overhand grasp if a very heavy bar or dowel were used in the basic dowel transport task of Rosenbaum et al. (1990). How would this affect participants' grasp choices?

Another task extension that comprises a farther reach from the tasks used so far is interacting with moving objects (e.g., catching them). In all the tasks described so far, the objects to be manipulated were stationary. How would object grasps change when the objects to be grasped are in motion?

It would also be interesting to investigate transfers of series of objects rather than transfers of just one object. Here hysteresis and other sequential effects could be studied. An initial investigation was made of this topic by Rosenbaum, Coelho, Rhode, and Santamaria (2010). They found that the strategies that individual participants used to walk along and stack plastic Tupperware containers were stable and distinct. Some individuals stacked the containers using a two-hand strategy, dropping the growing pile of containers held in the two hands into the next container on the table and, finally, bringing the completed stack to the final container at the target location. Other individuals used a one-hand strategy, picking up each container with one hand and adding it to the growing pile of containers they held with the other hand, finally bringing the completed stack to the target container. For both groups, where participants decided to stand at the start of the stacking task showed that they were willing to lean over and stretch quite a bit early in the task for the sake of minimal leaning and stretching at the end of the series of transfers. So there was a manifestation of the same sort of planning effect as described here but at the level of entire body postures rather than just at the level of hand and arm postures. Being able to "picture" entire body postures presumably also allowed participants in the walking study of Cowie et al. (2010) to behave as they did.

Yet another task extension would be to investigate hand choice in object manipulation tasks. The question is straightforward, though no test of it, to our knowledge, has been published. When someone needs to reach out and move an object from one position to another, which hand does he or she use? Choice of hand was never available to human participants in any of the laboratory tests reviewed here. Instead, the human participants in all the tests we discussed were told which hand to use, presumably because the experimenters believed the freedom to use whichever hand a participant wanted would cause him or her to minimize awkwardness both at the start and at the end of the object transfer. That expectation has not been submitted to experimental test yet, or at least no such test has yet been published. If it turned out that participants chose to use their nonpreferred hand rather than adopt an awkward posture ever, that outcome would support the hypothesis that maximizing postural control is more important than using the preferred hand.[8]

Two other remaining challenges can be named before we end this review. One is to pursue the neural basis of the anticipatory phenomena of interest. Despite the abundance of studies in neuroscience lately, including a large amount of neuroscientific data (both recent and vintage) on first-order planning of object manipulation, relatively little is known about the planning of extended action sequences carried out in the service of object manipulation (or other tasks). Little is known, for example, about where and when within the brain one can see activation related to forthcoming overhand versus underhand grasps. Recently, it was shown that area V6A, a structure in the dorsomedial frontoparietal circuit, has neurons whose activations depend on manual grasp orientations (Fattori et al., 2009). Such hand-orientation selectivity is apparent during the preparation as well as the execution of grasps. However, this was a study of first-order planning only. The setup used in this study could prove useful for exploring the neural underpinnings of second-order object-manipulation planning. Other brain regions could also be studied, of course.

An exciting advance on the neural control of object manipulation was recently described by Zimmerman et al. (2011). They had human adults perform the original dowel displacement task of Rosenbaum et al. (1990) but with two added twists. One was to have the postures of a participant's hand at the start of the trials be either congruent or incongruent with the hand's expected final

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[8] Preliminary data support this hypothesis (Coelho, Rosenbaum, & Studenka, 2011).

posture. The other was that while the participants indicated how they would perform the task, their brains were scanned.

The main results were twofold. First, the times to indicate which grasp would be adopted were shorter when the start postures were congruent with the preferred final postures than when the start postures were incongruent with the preferred final postures. The preferred final postures were, in turn, the canonical, easy-to-control postures observed in previous studies. Zimmerman et al. (2011) regarded this outcome as a replication and extension of the usual planning phenomenon.

The second main result of the study by Zimmerman et al. (2011) was that the fMRI data revealed that two brain regions of interest—the intraparietal sulcus (IPS) and the extrastriate body area (EBA)—showed different responses depending on the congruency between the initial and the final posture. Of special interest, the EBA appeared to be sensitive to what the later goal posture would be. This study provided the first linkage, then, between a hand posture to be adopted in the relatively distant future (two tasks down the line) and the brain region where that future state was functionally represented.

Finally, theoretical/computational work will help integrate the findings reviewed here, raise new questions, and lead to potentially useful applications. We have not laid out a detailed theoretical model of the planning effects in this review, mainly because the effects have a general theoretical implication that is sufficiently clear, we believe, that it stands on its own: Motor performance anticipates future states, even when those future states are specified mentally (i.e., not made in response to immediate sensory cues) and even when the behavior is nonverbal. The planning effects we have discussed comprise physical manifestations of the subordination of immediate needs for later ones. As such, they are motoric expressions of the capacity for delayed gratification or means–ends analysis in contexts where, and in creatures for whom, those capabilities might not have been expected. A surprise is that the capabilities are as widespread as they are. Another surprise is that they are absent when they might be expected (i.e., in children of relatively advanced ages).

Eschewing a detailed computational model for the effects we have considered is not meant to suggest that it would be useless to have one. Clearly, it would be to beneficial to have a model that makes exact quantitative predictions of grasp probabilities, grasp heights, reaction times, and so on. We are not averse to such a model. In fact, Rosenbaum, Vaughan, et al. (1993) presented a mathematical model of the grasp choice data they presented. The model was designed to account for the grasp choices of participants performing the handle rotation task described here. The model included a term for a thumb-toward bias—that is, a constant bias to grasp the handle with the thumb toward the tab even when it was otherwise maladaptive to do so. As far as Rosenbaum, Vaughan, et al. could tell, this bias was independent of the preference to end in easy-to-control postures. They hypothesized that the thumb-toward bias was related to attention. More research is needed to test this idea.

Discovering the need for additional terms in mathematical models is one of the advantages of pursuing a computational account of one's data. Another is that a computational model can help one synthesize a working system capable of generating behavior in a manner consistent with observed behavior. The idea is to go beyond curve fitting, which is essentially what was done by Rosenbaum, Vaughan, et al. (1993), and instead to pursue the general method of analysis by synthesis, building a system from scratch in the hopes of understanding it.

Some of the ideas gleaned from the studies reviewed here informed a computational theory of motor planning pursued with this aim—the so-called posture-based motion planning theory (Jax, Rosenbaum, Vaughan, & Meulenbroek, 2003; Rosenbaum et al., 1995, 2001). The main idea of the posture-based motion planning theory is that movements are planned with respect to goal postures that are generally specified before movements are planned. Consistent with this idea is the notion that goal postures themselves are planned with respect to one another, with the most important goal postures being planned before the planning of less important goal postures. With this idea, it is possible to simulate many phenomena of motor control, including those summarized in the present article; see Jax et al. (2003) and Rosenbaum, Engelbrecht, Bushe, and Loukopoulos (1993); Rosenbaum et al., 1995, 2001). The theorizing just referred to led another group of investigators to develop a neural network theory that also relies on the idea that goal and subgoal postures have primacy over movements in motor planning (Butz et al., 2007). Independently, Morasso and Sanguineti made similar suggestions (1995).[9]

The foregoing paragraph does not provide a perfectly accurate statement of how the posture-based motion planning theory arose in relation to the discovery of the grasp planning effects reviewed here. It was not really the case that the posture-based motion planning theory just happened to accommodate those phenomena. Instead, discovering the phenomena gave rise to the posture-based motion planning theory. The discovery of the phenomena stimulated the idea that movement planning may start with the planning of goal postures rather than with the planning of movements. In this sense, the discovery of the grasp planning phenomena reviewed in this article became not an end in itself but a means to a larger understanding of cognition and action. We hope this review will lead to a deeper understanding of these and related topics, which are so fundamental to the science of mental life and behavior.

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[9] The theoretical perspective described in this paragraph does not preclude the possibility that the planning of movements can influence the planning of goal postures. Goal postures can be planned first but subsequent movement planning can feed back to the goal posture level, leading to a different goal posture if necessary. Consistent with this hypothesis, movement paths can influence choices of goal postures (Elsinger & Rosenbaum, 2003; Osiurak et al., 2008).

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