The Origins and Sources of Action

18 Acquisition, Representation, and Control of Action

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Abstract

This chapter traces the gradual emergence of action control from the experience of action-produced events. It begins by reviewing and integrating findings on the acquisition of action effects, that is, on the learning of associations between movements and perceivable outcomes in infants, children, and adults. Second, it discusses what is actually acquired by these learning processes, that is, how actions and action plans are cognitively represented. Third, it outlines how the acquired knowledge is employed in action control, that is, in the planning and production of goal-directed movement.

Keywords: action control, action-produced vents, learning, movement, acquired knowledge

"If, in voluntary action properly so-called, the act must be foreseen, it follows that no creature not endowed with divinatory power can perform an act voluntarily for the first time" (James, 1890, p. 487). There is quite a bit of information that William James wanted to communicate to the reader with this sentence. First, he incidentally introduces the probably most common definition of voluntary action by equating it with goal-directed movement. Second, he emphasizes the role of anticipation in action control, that is, the selective and directing function of predictions of action outcomes. Third, he points out that action control relies on knowledge about relationships between movements and outcomes, which, fourth, implies and presupposes the previous experience of movement–outcome relationships.

In this chapter, we trace the gradual emergence of action control from the experience of action-produced events that is suggested by this theoretical view. We do so in three steps. First, we review and integrate findings on the acquisition of action effects, that is, on the learning of associations between movements and perceivable outcomes in infants, children, and adults. Second, we discuss what is actually acquired by these learning processes, that is, how actions and action plans are cognitively represented. Third, we outline how the acquired knowledge is employed in action control, that is, in the planning and production of goal-directed movement.

Knowing What We Could Do: Acquiring Action

Although newborns are already equipped with some motor and sensory capabilities, it is widely accepted that they lack the ability to perform goal-directed actions. Nevertheless, young infants can move their bodies,

and motor control develops substantially during the first 2 years. They can also perceive sensory events, including feedback from self-performed movements: Both distal (visual or auditory) and proximal (tactile or proprioceptive) action consequences can be registered from birth (for a general overview, see Kellman & Arterberry, 1998). But how do we develop from a moving and perceiving infant to an intentional agent?

By performing actions, agents try to realize goals that they have in mind, and they do so in a variety of situational contexts and by a variety of bodily movements. Accordingly, it seems unlikely that intentional action is innate. Rather, action control has to be acquired through experience in terms of both motor execution and specifying the motor patterns suited to produce the desired effects. As mentioned already, controlling an action requires the anticipation of its intended outcome (Hommel, Müsseler, Aschersleben, & Prinz, 2001; see chapters 2 and 6). Before producing a goal-directed action, the agent has thus to build up or activate a representation of the desired effect in mind and has to use this representation to select a movement pattern that is suitable to bring about this effect—James's (1890) "ideomotor principle." This ability to anticipate the consequences of one's own actions emerges around 9 months of age (Piaget, 1952; Tomasello, 1999; Willats, 1999).

In the preceding first 8 months of life, maturation leads to a differentiation of innate behavioral patterns to increasingly coordinated and controlled movements (e.g., von Hofsten, 2004). Additionally, young infants are equipped with learning mechanisms that allow them to detect and encode contingencies between self-performed movements and environmental events, or action effects (Gergely & Watson, 1999; Piaget, 1952; Rochat, 1998; Rovee-Collier, 1987). These mechanisms

are so efficient that newborns are able to vary their sucking frequency in order to obtain a certain sensory input (e.g., hearing their mother's voice, getting a sweet liquid, or seeing certain pictures; e.g., DeCasper & Fifer, 1980; Rochat & Striano, 1999). More evidence that young infants learn action–effect contingencies comes from studies on instrumental learning: Two- to 5-month-olds are able to pick up contingencies between their own leg movements and the movements of a mobile connected to the leg (Rovee & Rovee, 1969; Watson & Ramey, 1972) or the sounds of a rattle (Rochat & Morgan, 1998), and they learn to turn their heads to obtain a milk reward (Papousek, 1967). These examples demonstrate a transition from stimulus control of behavior to action control through acquired representations of action effects (for a review, see Rovee-Collier, 1987).

Learning contingencies between self-performed movements and their to-be-expected effects increasingly enables infants to exert control over their environment. They keep practicing this control ability by reproducing pleasant effects through repeating the movement over and over again, which they typically start doing by 4 months (Piaget, 1952) or even earlier (Rovee-Collier, 1987). By 4 months, infants are also able to expect a particular outcome after having performed a well-known movement, as they smile and coo when the typical effect occurs (Lewis, Sullivan, & Brooks-Gunn, 1985; Papousek, 1969) but show distress when it does not (Watson, 1972). Around 9 months of age, infants start to act in a truly goal-oriented fashion. For example, they pull a towel to obtain an object that is out of their reach, or they remove an obstacle preventing their reach to the object (Piaget, 1952; Willats, 1999). According to Tomasello (1999), these behaviors may indicate a new level of intentional functioning, inasmuch as infants now differentiate

the goal they are pursuing from the behavioral means they employ to pursue it. Most probably, infants' exploration of the contingencies between self-performed movements and their effects helps the emergence of goal-directed actions at the end of their first year (Elsner & Aschersleben, 2003).

Action–effect learning can thus be seen as a prerequisite for goal-directed action, which led Elsner and Hommel (2001) to propose a two-stage model for the acquisition of voluntary action control. Stage 1 of the model is concerned with the acquisition of contingencies between movements and effects. If a given movement and a given sensory event co-occur repeatedly in temporal proximity, their representations are connected by a bidirectional association (Elsner & Hommel, 2004). Accordingly, activating one representation on later occasions will tend to activate the other one too so that the codes of an action effect are becoming effective retrieval cues or primes of the associated movement pattern. Stage 2 of the model refers to the use of such cues for action control, that is, to the selection of goal-directed movements by anticipating their effects (Hommel et al., 2001). Establishing a goal is assumed to activate codes of related action effects, hence to effect anticipation. Via the acquired movement–effect association, activation of effect codes will spread to the related movement pattern, which is then carried out and actually produces the expected effect. Although this model was developed to explain empirical evidence obtained in adults, its implications are meant to be valid for the emergence of intentional action control in infants as well.

Studies with adults provide strong support for the Elsner and Hommel model in general and the claim that acquired action effects play a central role in action control in particular. Indeed, novel, arbitrary action effects are spontaneously acquired and become associated with the action they ac-

company, as demonstrated by the observation that the effects become effective primes of the action: Such priming effects have been observed with auditory stimuli (Elsner & Hommel, 2001, 2004), visually presented letters (Ziessler, Nattkemper, & Frensch, 2004), and words (Hommel, Alonso, & Fuentes, 2003) and even demonstrated for the affective value of visual (Caessens, Hommel, Lammertyn, & Van der Goten, 2008) and electrocutaneous feedback (Beckers, De Houwer, & Eelen, 2002). Contingencies between actions and their effects are picked up in a variety of tasks and conditions, such as in studies of choice reactions (Hommel, 1996; Stock & Hoffmann, 2002) or of the acquisition of stimulus–response sequences (Hazeltine, 2002; Hoffmann, Sebald, & Stoecker, 2001; Ziessler & Nattkemper, 2001). Further evidence that the perception of previously acquired action effects primes the associated response comes from both reaction-time experiments (Elsner & Hommel, 2001, 2004; Flach, Osman, Dickinson, & Heyes, 2006; Hommel, 1996; Kunde, 2004; Ziessler et al., 2004) and a recent brain-imaging study (Elsner et al., 2002). In this latter study using positron emission tomography, the mere presentation of previously acquired, auditory action effects was found to activate premotor brain structures (i.e., the caudal part of the rostral supplementary motor area) that are known to be involved in voluntary action planning.

Recently, action–effect learning and the priming of movements by the perception of previously acquired action effects has also been reported for 4- to 7-year-old children (Eenshuistra, Weidema, & Hommel, 2004). In this study, the younger children had greater problems in suppressing the response that was primed by the perception of a just-acquired action effect than the older ones, a finding that is consistent with the notion that action control develops substantially during childhood (e.g.,

Dowsett & Livesey, 2000; Levy, 1980). This development is commonly attributed to the maturation of the prefrontal cortex and the frontal circuits of the corpus callosum, such as changes in synaptic density and the myelinization of neural connections (e.g., Fuster, 1989; Thompson et al., 2000). Younger children's' deficits in action control suggest that associative action–effect learning and the priming of movements by action effects may be important prerequisites for voluntary action but that further cognitive processes are required to adjust the behavior to situational constraints or to actual action goals, hence to make effective use of action–effect knowledge. We now turn to the question of how such knowledge is represented and how it is used to control one's action.

Bits and Pieces: Representing Action

Now that we have an idea how novel actions are acquired, let us turn to the question of what is actually acquired. Actions are often referred to as single units. This certainly applies to the behavioristic conceptualization of action as a response defined in terms of measurable characteristics, but it also applies to modern cognitive psychology. In fact, most psychological textbooks treat action as a mere indicator of the more interesting perceptual, memory, and thought processes, an output function that allows measuring the duration and accuracy of cognitive processes. Early systematic attempts to investigate and theorize about action in its own right acknowledged that actions can be complex and hierarchical (i.e., simple actions can be organized into larger action sequences; see Lashley, 1951; Miller, Galanter, & Pribram, 1960), but how a given action is cognitively represented, what its internal structure looks like, and how people identify a contextually appropriate action still was anathema.

Sensorimotor Units

Our discussion of how agents acquire knowledge about what they are doing and what they achieve by doing so suggests that people associate their actions with representations of action effects. In other words, people are storing not just the output signals (efferences) of their cognitive system to the motor units responsible for bringing about a movement but, rather, they store integrated sensorimotor units (efferences and reafferences). In modern cognitive psychology, a more detailed theoretical treatment of how action is represented emerged no earlier than in the late 1960s in the field of motor learning. Adams (1968, 1971) picked up the control-theoretical approach of Miller et al. (1960) and considered that learning an action must comprise of at least two components. On the one hand, there must be some representation of the actual perceptual outcome of an action, which can be matched against a representation of the goal—otherwise an unsupervised learner would have no idea whether a given action was accurate. On the other hand, there must be some motor function producing the actual outcome, and this function must be modifiable.

This distinction between a perceptual and a motor component echoes the similar distinction in the introspective analysis of Lotze (1852) and Harless (1861)—better known from James's (1890) summary of their basic ideas. These authors were concerned with the question of how we can select an appropriate motor pattern to reach a given goal. Only if one has information about the likely perceptual outcome of actions, so they argued, can one determine which motor pattern is likely to realize the intended effect. Indeed, models of decision making and action planning are typically well equipped with respect to the way in which action alternatives are weighted against each other, but they are commonly

silent with regard to the question of how people identify the possible alternatives in the first place (e.g., Kahneman & Tversky, 2000; Morris & Ward, 2005). One reason for this theoretical neglect is that, in studies of decision making and planning, the to-be-considered set of action alternatives is presented to the subject. In real life, however, selection is often rather unconstrained—just think of the different ways you can grasp a cup of coffee. Having one's action alternatives associated with the to-be-expected consequences of these actions strongly facilitates the decision: One need only specify relevant goals (e.g., holding the cup, optimizing speed, saving energy, or avoiding heat), which then will prime the alternatives to the degree that their expected consequences are matching those goals (Hommel et al., 2001; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). Thus, representing actions through sensorimotor units allows for a rather smooth and automatic transition from goal specification to decision making and the ultimate selection of an action, at least in principle.

Distributed Representation

After having (re)introduced the distinction between motor (efferent) and perceptual (reafferent) components of action representations, action theorists have analyzed the motor component somewhat further. Keele's (1968) initial definition of motor programs as feedback-independent structures of muscle-specific commands, obviously reflecting the increasing impact of computer logic on psychological theorizing, soon turned out to be unrealistically inflexible. In particular, the idea that actions may be represented in terms of muscle-specific codes faces at least two serious problems: the storage problem and the novelty problem (Schmidt, 1975). The former results from the fact that each single change in a movement, be it the pressure

exerted with one finger or its end position, would require the creation of a new program, which would imply the need to store an almost infinite and therefore unrealistically large number of programs. The latter refers to the inability of the muscle-specific account to explain (in a realistic fashion) how existing skills can be modified and extended to accommodate varying situations, such as changing winds in a tennis match. According to Schmidt (1975), the storage problem and the novelty problem can be solved by assuming that action is represented in terms of schemas that contain information about the fixed features of an action but leave open slots for variable parameters, such as the width of a reaching movement. This idea was revived only recently by Glover (2004).

The concept of action representations as assemblies of codes that refer to the different features of the action is fully consistent with what we know about action representations in the primate brain. Indeed, primate brains have a preference for the distributed, feature-based coding of events, and planned actions are no exception. For instance, separate networks have been found to code the direction (Bonnet & MacKay, 1989; Georgopoulos, 1990), force (Kalaska & Hyde, 1985; Kutas & Donchin, 1980), and distance (Riehle & Requin, 1989; Vidal, Bonnet, & Macar, 1991) of arm movements. This suggests that action plans are composites of codes of separately specified action features. Such a conclusion receives further support from behavioral studies. For instance, numerous studies (e.g., Lépine, Glencross, & Requin, 1989; Rosenbaum, 1980) have shown that different parameters of pointing movements can be precued through separate stimuli, with the eventual reaction time decreasing as a function of the number of precues.

If we combine the evidence that action representations are cortically represented in a distributed fashion with the assumption

that the basic functional units[1] of action representations are actually sensorimotor components, it is interesting to consider whether evidence for distributed, action-specific sensorimotor units can be found in the human brain. Indeed, recent functional magnetic resonance imaging studies of Schubotz and colleagues provide evidence of such units (Schubotz, Friederici, & von Cramon, 2000; Schubotz & von Cramon, 2001, 2002). For instance, monitoring a visual series of events for a timing, color-shape, or location oddball has been found to recruit neural circuits in the premotor cortex that are also involved in the control of actions that are specifically related to these stimulus dimensions (i.e., tapping/articulation, grasping, and reaching, respectively). Likewise, having people prepare for a grasping or reaching movement increases their perceptual sensitivity toward size- or location-defined stimuli, respectively (Fagioli, Hommel, & Schubotz, 2007). Hence, processing particular features of stimuli apparently involves neural systems that control those actions that typically make use of these features. This provides clear evidence of the existence of action-specific sensorimotor units and points to an important integrative role of the human premotor cortex in the anticipation of action effects and the control of the corresponding actions. Indeed, damage to the premotor cortex has been found to hamper stimulus prediction (Schubotz, Sakreida, Tittgemeyer, & von Cramon, 2004). As suggested by Schubotz and von Cramon (2001, 2003), the premotor cortex may integrate actions and their expected consequences into a kind of habitual pragmatic body map, a representational system for the "common coding" of perceptual events and action plans (Hommel et al., 2001; Prinz, 1990).

To summarize, there is evidence that action representations are both integrated (with respect to perceptual and motor

components) and distributed (with respect to the different features of an action). However, until now we have considered only the most obvious ingredients of action representations, namely, simple movements and their rather immediate sensory consequences. Let us now turn to perhaps somewhat less obvious ingredients and associates.

Affordances

Acquiring associations between actions and their effects tells the actor/perceiver something about his or her own action and, in some sense, something about his or her effector and the way it is functioning. In fact, acquiring action effects can be considered as the first step of individuation, that is, of distinguishing one's own body (which creates predictable effects) from one's environment (which creates unpredictable effects) (see Piaget, 1952; Prinz, 1992; Rochat, 1998). But actions are often directed at and dependent on the existence of objects. As Goodale et al. (1994) have demonstrated, people are able to make grasping movements to both present and remembered objects, but the kinematics of these movements look different: Whereas grasps to a present object show the typical profile of a narrow grip aperture in the beginning, a wide opening when approaching the object, and the final closing of the hand around the object, grasps to a remembered object are stereotyped with a wide and relatively invariant opening from the beginning to the end (see chapter 11).

This example not only shows that movements are not fully prespecified before they start (as the motor program view would have suggested) but also reveals that some parameters of actions are left to be specified by the environment, the object in this case. Indeed, given the lawful relationships between some object characteristics and movement parameters (*affordances* in the

sense of Gibson, 1979), it makes much more sense to exploit such relationships and outsource the control of the respective parameters of the action rather than to rely on fallible internal predictions. As discussed by Glover (2004), quite a number of such action-parameter–specific object affordances have been identified so far, such as object orientation (controlling hand orientation: Jeannerod, 1981), object position and velocity (controlling hand trajectory: Brenner, Smeets, & de Lussanet, 1998; Jeannerod, 1981), object shape (controlling hand shape: Klatzky, Fikes, & Pellegrino, 1995), and object size (controlling grasping aperture: Jeannerod, 1984).

Making use of action-related information delivered by objects makes it unnecessary to specify the respective parameters in advance, but it does require planning about which information should specify which parameter. For instance, the size of an object has rather different implications for a movement, depending on whether the actor intends to point at the object, to grasp it, or to use it to hit another object. This means that action representations need to include pointers to particular types of environmental information so that preparing oneself, say, for a grasp makes one more sensitive to size information (Fagioli et al., 2007). This action-induced facilitation of action-related stimulus information (i.e., information that can be used to specify movement parameters) can be seen as a sort of proactive attentional selection that effectively turns the cognitive system into a prepared-reflex machinery (Hommel, 2000). How beneficial this processing strategy works can be seen from observations of Prablanc and Pélisson (1990). These authors had subjects move their hands to a goal position indicated by a light that was sometimes shifted by a few centimeters after the movement had begun. Even though subjects were prevented from noticing the shift (by carrying it out during

an eye movement), they moved their hand straight to the new goal location without any signs of corrections. That is, once the location of an object has been linked to an action plan, any change in the location leads to an automatic update of the movement's parameters even if the change occurs outside the actor's awareness.

But there are also downsides to this form of self-automatization. Once a system has turned itself into a prepared-reflex machinery, it becomes vulnerable against misleading information from the "correct channels." A well-known example for this vulnerability is the Stroop effect (for an overview, see MacLeod, 1991), which is observed if people respond to the ink of color words: If the task-irrelevant meaning of the word happens to match the relevant ink color (e.g., the word RED in red ink), performance is much better than if meaning and ink do not match (e.g., the word GREEN in red ink). This obvious inability to fully ignore the meaning of the words has been taken to indicate that reading is a fully automatized skill, at least in Western cultures. However, the Stroop effect is much more pronounced if people respond verbally than by key pressing (see MacLeod, 1991). Even though one may argue that this reflects the greater experience we have in calling out words than in responding to them manually, it is a first indication that preparing for a task (pronouncing words in this case) makes the cognitive system more sensitive to stimuli that afford performing this task (i.e., words). Indeed, if subjects are not prepared to utter words but make a judgment whether a particular color is present or absent in a word, the Stroop effect disappears (Bauer & Besner, 1997).

More evidence in support of this possibility comes from the Simon effect, a variant of the Stroop effect (for an overview, see Lu & Proctor, 1995). This effect occurs if people respond to a nonspatial stimulus

feature by carrying out a spatially defined response, such as a left-versus-right key press in response to the letters X and O. Stimulus location is irrelevant in this task but varies nevertheless. And it does have an effect: Performance is better if the stimulus happens to appear in a location that spatially corresponds with the proper response, hence, if in our example the X appears on the left and the O appears on the right.

Again, an automaticity account may argue that people are used to carrying out responses to spatially corresponding objects, but there is increasing evidence that this kind of automaticity is induced or at least enabled by the task. For instance, it has been shown that stimuli in the Simon task activate spatially corresponding responses up to the level of lateralized readiness potentials (LRPs; Sommer, Leuthold, & Hermanutz, 1993), an apparently strong indication of automaticity. Valle-Inclán and Redondo (1998) have looked into the conditions under which LRPs occur in a Simon task. In their study, the relevant S-R mapping was not fixed but varied randomly from trial to trial so that participants were presented not only with a stimulus but also with a display showing how the stimuli were mapped onto responses. The temporal order in which the mapping display and the stimulus were presented varied as well so that sometimes the mapping preceded the stimulus (i.e., participants knew and could have implemented the mapping before encountering the stimulus) and sometimes the stimulus preceded the mapping. When the mapping preceded the stimulus, stimulus-induced LRPs were observed; that is, the stimulus activated the spatially corresponding response regardless of which response was correct. However, when the stimulus preceded the S-R mapping, stimulus-induced LRPs were no longer observed. It thus appears that the spatial affordance of a stimulus depends on the currently implemented task set, which seems to enable

the automatic processing of stimuli varying on task-relevant dimensions.

The same conclusion can be drawn from priming studies. For instance, presenting a task-irrelevant arrow prime while people are waiting for a spatial target stimulus has been shown to yield an arrow-related LRP (Eimer, 1995) even if the arrow appears subliminally (Eimer & Schlaghecken, 1998). However, arrow primes ceased to have an effect if the relevant stimuli were nonspatial (e.g., letters; Eimer & Schlaghecken, 1998). This suggests that the prime-induced activation of responses was automatic only if (and, presumably, because) the perceiver/actor intended to respond to prime-related information, which implies that "automatic" translation depends on intentions.

Taken altogether, these observations suggest that representations of actions contain pointers to environmental information that is suited to specify the concrete parameters of an upcoming or ongoing action (see Fagioli et al., 2007; Neumann & Klotz, 1994). By restricting the storage of action plans to fully predictable aspects of the action and using pointers to environmental information to fill in the aspects that cannot be predicted in advance, action plans can be tailored to context conditions of almost any degree of (in)stability. Note that this enormous benefit relies on the fact that action plans are both distributed composites and sensorimotor in nature. The reason is that environmental information specifies actions only on the level of action effects but does not provide muscle-specific information: The location of an object specifies the end point of a reaching action but not which muscles to activate for how long, and a word specifies the phonological codes to utter (which again presupposes some grapheme–phoneme translation) but not the movements of the vocal tract. If the units of action plans were not sensorimotor (and thus provide the translation rules

necessary to derive muscle parameters from effect representations) and distributed (so that different stimuli or stimulus aspects can be taken to specify different parameters of the action), human action planning would be much less flexible.

A by-product of integrating actions with pointers to stimulus information that can fill in action parameters online is that object-directed actions can be carried out even in the absence of objects. As already discussed, such actions look unnatural and pantomimed (Goodale et al., 1994), but they are easy to carry out by imagining the respective object. Apparently, the pointers contained in action plans can also pick up internally generated information about an object, information that is necessarily less specific and up to date than that provided by a real object but is nevertheless sufficient to specify the open parameters. This possibility allows people to play through alternative actions (e.g., to make a difficult decision) and to carry out mental practice.

Given the rich evidence that actions are coded in a sensorimotor fashion, it makes sense to suspect that stimulus events are also coded in such a way. Indeed, several authors have suggested that representations of stimulus events may include information about the actions afforded by these stimuli (e.g., Barsalou, 1999; Gibson, 1979; Hommel et al., 2001). Action-related information seems to be integrated continuously and rather automatically, as a number of recent observations suggest. For instance, Richardson and Spivey (2000) presented subjects with short video clips that appeared in various locations, each clip showing a speaker talking about a particular topic (e.g., plays of Shakespeare). When the subjects were later asked about facts related to these topics, they tended to look spontaneously at the location where the respective clip had been presented. Apparently, the representation

of the audiovisual events also contained information about where they had been seen so that retrieving information about the clip reactivated location information, which had a direct effect on eye-movement control. Along the same lines, Hommel and Knuf (2000) had subjects perform choice responses to cued houses on a visual map-like array. After having acquired the correct house-response mappings, participants evaluated statements about the spatial relationships between pairs of houses. Pairs were judged faster if the two houses had shared the same response in the acquisition phase, even when the map was no longer visible. This suggests that response-related information became associated with the houses' representations so that accessing one member of a pair for comparison spread activation to the other via the shared response code. Hence, the principle of sensorimotor representation may apply not only to action plans but to object and event codes as well (Hommel et al., 2001).

Verbal Labels

If action representations are associated with all sorts of stimulus codes and contextual information, it is easy to see how action plans can become activated in the presence of an action-related stimulus. But humans can plan actions even in the absence of related stimuli and even outside the situational context the action is planned for—just think of the preparation for a job talk. This raises the question of how action representations are retrieved and activated under such circumstances. We have briefly touched one possibility: One may imagine the stimuli that trigger the sought-for action. In fact, this is the original solution proposed by Lotze (1852), who suggested that voluntary action control is acquired by learning to mentally simulate the trigger conditions for actions.

Another important means to control one's actions has been promoted by Vygotsky (1962). He claimed that, in the course of ontogenetic development, the increasing ability to control one's action goes hand in hand with and is strongly supported by the increasing ability to employ internal speech (see Zelazo, 1999). Infants and young children often describe the outcomes of their actions verbally only after having produced them, but very soon they begin to talk while acting, and at some point, children verbally describe the intended outcome before beginning to act. Vygotsky assumes that at this stage speech has become a self-regulatory function in specifying the goal of an action and organizing the means to achieve it. Translated into our present terminology, verbalizing action outcomes associates action effect codes with verbal labels. This provides an additional retrieval cue allowing to activate the effect codes—and thereby the whole action representation they are part of—by overt or inner speech.

There is indeed evidence of a strong relationship between (overt and covert) speech and the ability to control one's action. Luria (1959, 1961) showed that children are much better in controlling stimulus-dependent responses and in avoiding unnecessary perseverance if they verbalize their action goal and the stimulus–response mapping. For instance, asking young children to respond to a stimulus often triggered immediate responding long before the stimulus actually appeared (Luria, 1961). But once the children learned to insert a verbal self-instruction ("Go!") into the sequence of stimuli and responses (stimulus–"go"–response), they could master the task perfectly.

In adults, verbalization has been demonstrated to reduce the mental costs associated with switching from one task to another (Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003; Goschke, 2000;

Kray, Eber, & Lindenberger, 2004). Even the acquisition of new action effects can be facilitated by verbalizing the action–effect relationship (Kray, Eenshuistra, Kerstner, Weidema, & Hommel, 2006). These behavioral observations are consistent with recent neurophysiological findings on the representation of words. As pointed out by Pulvermüller (2003; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005), words are likely to be represented by widely distributed cell assemblies with strong links to the perceptual and motor codes of their referents. In particular, assemblies representing words that signify visual events include neurons in visual cortices, and assemblies representing words that signify actions include neurons in motor cortices.

Thus, there is evidence that action representations entertain associative links to verbal labels describing the effects produced by the action and, hence, signifying the action's pragmatic meaning. These links provide the actor with retrieval cues that can be used to activate and maintain the elements of action plans by inner and outer speech. Using them allows for setting up action plans long ahead of action execution, and it provides the opportunity to acquire, communicate, and exchange action plans quite easily.

Affective Values

In addressing the role of action effects and their representations for action control, we until now have focused on physical effects and their perceptual representations. However, actions also have affective consequences. Learning theory has emphasized the function of affective consequences for the selection of actions: Actions followed by positive affective consequences will be more likely to be carried out in the future, whereas actions followed by negative consequences will be less likely (Thorndike, 1927). Affect in that case provides the glue

that binds actions to situations (Walker, 1969), but it does not become a part of the eventual binding. In other words, affect provides online criteria for associative learning, but it is no longer represented in the emerging associative structure.

Recent theories have considered a more representational role of affect, however. Rolls (1999) has suggested that, in the process of learning, animals acquire stimulus–reinforcement associations that can be used to evaluate the to be expected reinforcement properties of stimulus–response pairs. By using them, animals can "play through" if–then rules when making a decision and thus pick the behavior that maximizes the expected reinforcement. A very similar suggestion has been made by Damasio (1994). He assumes that actions become associated with so-called somatic markers, that is, representations of the bodily sensations resulting from an action. When making a decision, people can thus quickly simulate how it would feel to carry out a particular action and then go for the action that makes them feel best. Indeed, there is evidence that people show autonomic affective reactions (increased sweat production) before making risky decisions (Bechara, Damasio, Tranel, & Damasio, 1997), suggesting that they anticipate the possibly negative outcome.

Another argument supporting the assumption that representations of affect may become integrated into action representations has to do with the already discussed principle of sensorimotor representation. Affective bodily reactions can only impact decision making and action planning to the degree that they are (consciously or unconsciously) perceptually registered, which was the main point of James's (1884) theory of emotion. But once such reactions are perceptually coded, they should not be treated any differently than other, external consequences of the action (Hommel et al.,

2001). That is, integration processes should treat the perception that carrying out a given action makes one tremble, sweat, and feel terrible not any different from the perception that carrying out this action, say, produces a particular auditory signal or reduces one's income by 50%. If so, the codes underlying these perceptions should be bound to their respective actions in just the same way.

Indeed, recent evidence suggests that perceptions of affective consequences are integrated with the producing action just like perceptions of nonaffective consequences. Beckers et al. (2002) used the same paradigm as Elsner and Hommel (2001). In the acquisition phase, subjects performed binary-choice responses to the grammatical category of neutral words, with one response producing a mild electroshock. In the following test phase, subjects performed the same task but now to stimulus words with positive or negative affective valence. As expected, subjects performed better when the word valence matched the valence of the response: Negative words were responded to more quickly with the response followed by a shock, whereas the opposite was true for positive words. This suggests that the actions acquired the affective valence of their effects. Findings of Caessens et al. (2008) point in the same direction. These authors had subjects perform two overlapping key-pressing tasks where the two response alternatives in the secondary task triggered the presentation of a smiley and a grumpy, respectively. The results indicated that preparing the smiley-producing response facilitated the processing of words with positive valence in the primary task, while preparing the grumpy-producing responses primed words with a negative valence. Apparently, the actions were integrated with and thus affectively marked by the affective valence of their effects.

Summary

Representations of actions are not unitary codes but rather composites of several elements. Minimally, a representation includes sensorimotor associations between the perceptual codes of particular action features and the motor program realizing them. At least in humans, action representations are also likely to comprise of pointers to action-relevant stimuli and stimulus dimensions, that is, to environmental events that specify free action parameters. Links to verbal labels make action representations easily accessible and controllable by means of inner speech and external instruction. By integrating representations of the to-be-expected affective consequences, action representations can be quickly evaluated and compared.

Picking, Weighting, and Binding: Controlling Action

When cognitive psychologists talk about action control, they often refer to processes that take place between the occurrence of an action-triggering stimulus event and the execution of the triggered action. This perspective derives from the theoretical approach of Donders (1868), who developed the first stage model of information processing. Donders assumed that human will impacts information processing by selectively translating some but not other stimuli into overt movement. To measure how long what he called the "organ of the will" needs for decision making, he manipulated stimulus and response uncertainty in choice reaction-time tasks. First, he found that informing subjects about the upcoming stimulus sped up reaction time, and he considered the amount of facilitation as a measure of the combined effect of stimulus discrimination and the "determination of the will"—assuming that with preinformation, both could be achieved before the stimulus. Then, to isolate the stimulus-related component, he employed a go/no-go task, which pairs stimulus uncertainty with response certainty. The difference between the reaction time in this task and in a choice task without preinformation, so he reasoned, should reflect the time demands of will determination. Applying this logic left Donders with an estimate of 36 milliseconds for making up one's mind. Even though some details of Donders's theoretical claims have been criticized, modified (Sternberg, 1969), and extended (Pashler & Johnston, 1989), his basic approach is still popular and heavily used to theorize about action control, such as in the study of dual-task performance (Pashler, 1994).

Donders's emphasis on online control (i.e., processes after stimulus presentation and before response execution) was not shared by everyone. Exner (1879), for instance, gained a fundamentally different impression of how action control works. Based on his introspections, he considered it difficult to believe that control intervenes between stimulus and response. Instead, he claimed that the actual control takes place long before the stimulus comes up. As a consequence, he considered the preparation for responding a truly voluntary act but the eventual action in a certain sense involuntary. The main job of voluntary processes, so he reasoned, would be to automatize the cognitive system and turn it into a "prepared reflex" (Woodworth, 1938; see Bargh & Gollwitzer, 1994; Hommel, 2000).

In view of Exner's considerations, it seems important to distinguish between the point in time at which action control is exerted (i.e., when "control processes" determine what and how will be done) and the point in time at which these control decisions become effective (i.e., when the action is carried out). With this distinction in mind, it may well turn out that what Donders had

measured is not the time needed to make a decision but merely the online reflection of a (perhaps much more time demanding) decision that had been made much earlier (i.e., off-line). It is fair to say that the distinction between exertion and impact of control is widely neglected, often with severe theoretical consequences.

A prominent example is the theorizing about response inhibition. Following the spirit of Freud (1914), numerous authors have taken it for granted that unwanted response tendencies can be prevented from taking over action control only if they are actively suppressed (Logan & Cowan, 1984; Ridderinkhof, 2002). Accordingly, response inhibition has been granted the status of an executive process (e.g., Barkley, 1997; Logan, 1985) worthy and in need of further investigation. However, considering Exner's account of action control this reasoning is less straightforward than it might seem. The first flaw in this reasoning stems from the assumption that, if a particular response tendency is activated (e.g., as indicated in reaction-time patterns or LRPs) but the corresponding behavior is not shown, the tendency must have been suppressed. This is possible but by no means necessary. If response tendencies are evaluated with regard to their activation level, choosing the correct response will become more difficult (thus increasing choice reaction time) the more activated other tendencies are, but there is no need to assume that making the decision requires the suppression of these other tendencies. For example, it takes more time to determine the outcome of a (democratic) presidential election if there is more than one popular candidate, but reaching the eventual decision does not require the suppression or elimination of any votes or candidate.

The second flaw in the reasoning underlying many inhibition accounts is the strong belief that inhibition is necessarily "active"—which is commonly meant to imply intentional online control. Again, this is a possibility, but it is neither necessary nor self-evident, nor is it parsimonious. Consider how action alternatives are typically modeled in neural networks (e.g., Cohen, Dunbar, & McClelland, 1990; Gilbert & Shallice, 2002). If R1 and R2 were alternative responses, their representations would be assumed to be linked by inhibitory connections so that activating R1 would inhibit R2 and vice versa. Now assume that R1 would be the correct response and R2 would be an incorrect alternative that is primed by some misleading stimulus. Obviously, the activation of R2 would inhibit R1, which would explain why R1 would take longer to reach the threshold for response execution. However, if R1 does reach the threshold, it must have been activated more strongly than R2 (otherwise the incorrect response R2 would be performed), which again means that R2 is inhibited. Hence, any competitive system with a built-in winner-takes-all mechanism (which is a common in contemporary network models) produces inhibition of non-selected alternatives, without any particular "active" inhibition system. From this perspective, it makes sense to assume that the inhibition process is an automatic consequence of the way the cognitive system is configured and prepared rather than an achievement of online executive processes.

Considering examples of this sort, we doubt whether the seemingly clear-cut distinctions between executive and task processes or between intentional and automatic processes make sense. In fact, there is hardly any evidence that processes more complex than a knee-jerk reflex can be completely independent of the goals of an actor/perceiver and the way these goals have configured the cognitive system (see von Hofsten, 2004). That is, most or all processes are reflecting the actor/perceiver's intentions but are

automatic at the same time—conditionally automatic in the sense of Bargh (1989). In the following, we therefore do not attempt to track the time points at which control is implemented (because, as pointed out, we think that the implementation precedes its impact on processing) but, rather, consider when and how control is reflected in processing and behavior. In other words, we focus more on the effects than on the causes of control. To do so, we follow the schema of Heckhausen and Gollwitzer (1987) and distinguish between the phase of action planning proper (what Heckhausen and Gollwitzer call the preactional phase), the actional phase, and the postactional phase. We thus restrict our discussion to the short-term effects of creating and executing action plans and neglect long-term effects, such as stimulus–response learning or prospective memory.

Planning Phase

As James has pointed out in our introductory reference, intentional action must be based on some anticipation of the action's outcome almost by definition. What these anticipations look like, whether they necessarily include sensory expectations (as ideomotor approaches suggest) or whether they can also be abstract, is largely unknown. However, we do have evidence that anticipations play a role in action planning. First, choice reaction times have been observed to increase if the spatial relationship between the location of a response and its visual effect is incompatible as compared to when this relation is compatible (Hommel, 1993; Kunde, 2001). Likewise, the reaction time for vocal color-word responses increase if responses are followed by the presentation of a response-incompatible color (Koch & Kunde, 2002). This means that selecting an action is accompanied by activating the codes of the expected action effects, suggesting that such codes

are mediating selection. Second, Kunde, Hoffmann, and Zellmann (2002) had subjects perform a four-alternative choice-reaction-time task in which each response produced one of two auditory effects. In some trials, the subjects were cued to prepare one response but were then required to carry out another. If this other response was expected to produce the same auditory effect as the prepared response, reaction times were faster than if the other response was expected to produce a different effect. Again, this provides evidence that codes of the expected sensory consequences of actions are involved in action planning.

Considering that actions are represented in terms of their effects and that effect codes are indeed involved in action planning, the first step in the planning process can be conceived of similarly as the biased-competition scenario that Duncan and colleagues (Desimone & Duncan, 1995; Duncan & Humphreys, 1989) have suggested for the selection of perceptual events. The scenario assumes that, to find a target stimulus among distractors, a search template is created that contains a description of the sought-for target. Representations of registered events that are assumed to compete for selection are compared with this template and receive top-down support to the degree that they match. The best-matching event thus receives the strongest support so that it outperforms its competitors and is eventually selected for further processing. Along the same lines, the action goal may be thought of as a description of the intended action in terms of the to-be-achieved perceptual effects. This action template will then prime stored sensorimotor (i.e., action–effect) links to the degree that their effects are matching the goal, which eventually will activate the best-fitting links the most. Given that action representations are not unitary but composites, several sensorimotor links are likely to be selected, each

representing a relevant feature of the intended action.

In view of the evidence we have discussed so far, it seems likely that goals can refer to visual and auditory action effects, but other formats are possible as well. We have pointed out that inner speech seems to play an important role in action control and considered that action representations entertain links to verbal labels describing them. If so, it makes sense to assume that goal descriptions can also be of a verbal format so that sensorimotor structures are primed to the degree that their verbal labels match the verbal goal description. We speculate that verbal mediation of action planning is particularly important with respect to self-imposed or contextually primed strategies, such as the intention to perform particularly fast or accurately (Förster, Higgins, & Taylor Bianco, 2003). Goals may also refer to affective consequences of actions, bringing representations of affective action effects into play. Affect-related criteria may be particularly useful in cases where many action alternatives are active and competing for selection. Hence, if there are many ways to reach a particular goal, people may go for the alternative that is giving them the best "gut feeling" (i.e., the alternative that is associated with the most positive affective expectations). Finally, environmental information about the context and about action-related objects is likely to provide further biases toward particular action alternatives. Taken altogether, the selection of an action may thus represent the best compromise between functional, affective, and practical requirements and biases.

Specifying the relevant features of an action and activating the best-fitting sensorimotor links is an important first step in the action planning process, but it is presumably not yet sufficient to make a plan complete. The reason is that we commonly carry out more than one action at the same time and that we certainly entertain multiple action plans concurrently—just think of the multiple items on your daily agenda. Given that action plans are composites, this means that chances are high that multiple features belonging to more than one action plan are active at the same time—which again is likely to create confusion about which feature belongs to which plan. In other words, distributed planning creates binding problems as they exist in the processing of stimulus events (Treisman, 1996). To solve this problem and to avoid confusion and cross talk with other plans, the elements of an action plan need presumably to be integrated or bound before the plan can be executed (Stoet & Hommel, 1999). Support for this assumption comes from studies on the side effects of action planning. Müsseler and Hommel (1997) observed that creating and maintaining an action plan, such as preparing to press the left of two keys, strongly impairs the perception of visual events that share the same spatial feature, such as a left-pointing arrow. As Müsseler and Hommel argue, preparing a left action may have required or at least involved the binding of a <LEFT> feature to the action plan so that this feature was unavailable for the concurrent coding of feature-overlapping events. Consistent with this code-occupation hypothesis, Stoet and Hommel (1999) found that preparing an action with the left or right hand or foot interfered with planning another action with the same effector or on the same side. Along the same lines, Stoet and Hommel (2002) showed that holding a left or right stimulus event in short-term memory impaired the planning of a spatially corresponding manual action. Recent findings have demonstrated similar code-occupation effects in drawing movements (Schubö, Prinz, & Aschersleben, 2004) and weight judgments (Hamilton, Wolpert, & Frith, 2004).

Many researchers assume that human behavior is as flexible as it is because people can develop and apply clever strategies. Logan (1985), for instance, distinguishes between four functions of executive action control: the choice among strategies, the construction of a chosen strategy, the execution and maintenance of a strategy, and the inhibition of strategies if the goal changes. Unfortunately, however, the term "strategy" is commonly used without any definition. If we look it up in our *Collins Concise Dictionary,* we find two suggestions, "a particular long-term plan for success" and "a plan," which imply that executive control (and, thus, the handling of strategies) can be equated with the management of action plans (e.g., Norman & Shallice, 1986). Given that this management seems to be a more or less (conditionally) automatic function of activating a goal representation, which again may often be imposed by the social and physical environment (see the following discussion), we easily end up with a semantic paradox: What researchers call "strategy" may be the necessary consequence of contextual constraints and influences rather than reflecting conscious and willful decision making (as the everyday use of the term would imply). Indeed, recent findings strongly point in this direction. For instance, Bargh, Gollwitzer, Lee-Chai, Barndollar, and Trötschel (2001) found that people were doing substantially better in a word puzzle task if they had been nonconsciously primed with achievement-related words. Further experiments showed that behavior guided by these induced achievement strategies exhibits the same characteristics as behavior guided by self-set strategic goals: persistence at a task and task resumption after interruption (Bargh et al., 2001). Additionally, success and failure at nonconsciously induced strategic goals affect people's moods just like they do at conscious goals (Chartrand & Kay, 2008).

And yet, even if "strategies" may not be the most fortunate term to describe choices in the way an action is carried out, it is true that such choices can be induced and are being made: People instructed to act fast are commonly faster than people instructed to act accurately, people are more cautious (i.e., slower and more accurate) after having made a mistake, and asking someone to prioritize one of two concurrent tasks will improve his or her performance on this task. Hence, choices are being made, and they impact behavior, raising the question of how they do so. With regard to general "strategic" goals, however they may be induced, the answer is relatively easy. We have pointed out that adding a wanted feature to the goal description leads to changes in the top-down support for alternative actions competing for selection. Accordingly, adding the feature <FAST> to the goal description (e.g., as a consequence of instructing a subject accordingly) will favor action representations that also include this feature, again increasing the probability that a fast action (or a fast version of the action) will win the competition and be selected for execution. To be more precise: Given that action representations are composites, it is likely that there is only one <FAST> feature, which, if activated and bound to whatever other action components are selected, will speed up the execution.

An interesting implication of this assumption is that "strategies" may be misapplied, that is, extended to actions they were not "devised for." For instance, if instructing someone to carry out action X quickly leads to the activation of the <FAST> feature, carrying out another action Y should also be sped up. Even though we do not know of an experiment that has looked at this particular issue, there are two recent observations suggesting that our prediction may be correct. One stems from a study of Meiran, Hommel, Bibi, and Lev (2002), who had participants

switch between randomly ordered tasks. People were cued in advance which task to perform next and instructed to prepare as much as possible before indicating their readiness for the upcoming task. Assuming that preparing for a task should take time (e.g., Rogers & Monsell, 1995), we expected a *negative* correlation between readiness time (the time people took to prepare) and reaction time (the time to carry out the actual task). Hence, responses should be faster the better prepared the task was. Paradoxically, however, the correlation was *positive,* indicating that long preparation went along with slow responding. Apparently, random trial-to-trial fluctuations in concentration or set for speed versus accuracy affected both readiness time and reaction time (and the underlying processes) to the same degree. This suggests that carryover effects of "strategic" parameters are possible: If one goes for speed or accuracy in preparing a task, one automatically takes over this "strategic preference" in subsequent responding.

Another carryover effect was demonstrated by Memelink and Hommel (2006), whose subjects performed a two-dimensional S-R compatibility task (i.e., a task in which the horizontal and vertical stimulus–response compatibility varied independently). This task was alternated with or was embedded in a logically unrelated "priming task" in which subjects were to discover particular stimulus–response rules. Making the horizontal dimension relevant in the priming task increased the horizontal compatibility effect, and making the vertical dimension relevant increased the vertical compatibility effect, suggesting that the attentional set induced by the priming task carried over to the compatibility task.

Preparing for an action often involves not only the specification and binding of the relevant action features but also the specification of the conditions under which the action should be carried out. Several authors have emphasized the importance of creating linkages between action plans and environmental trigger conditions for self-automatization (Bargh & Gollwitzer, 1994; Ellis, 1996; Mayr & Bryck, 2007). Hence, action planning will often involve the implementation of stimulus–response links, especially if the temporal delay between planning and execution is long. More important for our purposes (given our focus on short-term effects) is that planning an action involves the activation of the stimulus pointers that we have argued to be associated with plan elements. More needs to be known about which actions are associated with pointers to which stimulus dimensions, but a couple of connections have been revealed already, such as between grasping and shape (including size and orientation), pointing and location, tapping or speaking and rhythm, and velocity and position (Brenner et al., 1998; Fagioli et al., 2007; Jeannerod, 1981; Klatzky et al., 1995; Schubotz & von Cramon, 2003). The purpose of activating these pointers is to allow low-level action parameters to be filled in online during the actional phase (see previous section).

Actional Phase

The actional phase is entered as soon as the planned action begins. This will often be the case when the planning phase is completed or, with prospective planning, when the defined trigger event occurs. Interestingly, however, there is evidence that the execution of a plan does not need to await the plan's completion. First, action planning and action initiation can be dissociated empirically, as evident from the observation that the two processes can create different and independent dual-task bottlenecks in information processing (De Jong, 1993; Ivry, Franz, Kingstone, & Johnston, 1998; Logan & Burkell, 1986). For instance, Ivry et al. tested a split-brain patient in a

dual-task experiment requiring speeded responses to lateralized stimuli. In contrast to healthy subjects who were strongly impaired if the stimulus–response mappings for two tasks were mutually incompatible (e.g., if stimuli appearing at the top and bottom of a display required top and bottom responses in one task but bottom and top responses in the other), the lack of callosal communication between the two cortical hemispheres allowed the patient to hold and apply the incompatible mappings concurrently without substantial drop in performance. And yet, the patient did show dual-task costs, suggesting that some late, postselection bottleneck was still operative.

Second, if the time available for planning is varied by means of a strict deadline technique, the kinematics of the action reflect a continuous transition from a default parameter (the average of all possible goal parameters) to the actual goal parameter (Ghez, Hening, & Favilla, 1990; van Sonderen & Denier van der Gon, 1991). This suggests that plans can be executed at any stage of (under)specification. These observations support Bullock and Grossberg's (1988) model of action-plan implementation (see also Rosenbaum, 1987). According to that model, a plan is executed whenever a respective go signal is given (which is considered to work much like James's "fiat"; James, 1890). This go signal is claimed to be nonspecific (i.e., blind to the action it launches) and temporally independent of action planning proper so that it can trigger the execution of a plan at any planning stage.

Even though we assume that actions are running more or less under "automatic pilot," this pilot is only conditionally automatic (Bargh, 1989) and thus reflects the current action goal. In particular, environmental information will get fast and automatic access to action control but only to the degree that it is rendered "legitimate" and salient by an action-related pointer. That is, novel shape information about the target of a grasp will have direct impact on hand control, and changes in the location of a pointing target will immediately affect arm control. An excellent example for this mechanism are so-called double-step experiments in which the location of a visual goal is moved after the subject has started a reaching movement toward it. Under such circumstances, people move their hand to the new goal location without showing any signs of hesitation or correction in the speed or acceleration profiles. This is true even for conditions under which the change in location is carried out during an eye movement, thus preventing subjects from consciously perceiving the change (e.g., Prablanc & Pélisson, 1990; see also Bridgeman, Lewis, Heit, & Nagle, 1979; Goodale, Pélisson, & Prablanc, 1986). This suggests that the molar, goal-relevant parameters of the action (i.e., moving the hand to the visual target) were specified in the action plan, while the more incidental parameters (i.e., the exact movement path) were not. However, pointers were established to determine from which informational source the missing (incidental) parameters should be derived, thereby allowing information from this source to be picked up automatically (even unconsciously) and exploited to fine-tune the ongoing action.

To account for observations of this sort, a number of dual- or multiple-route models have been suggested. Milner and Goodale (1995) have attributed the off-line business of action planning to the ventral cortical pathway of visual information processing (which they somewhat unfortunately call the "perceptual" pathway) and the online specification of actions to the dorsal pathway (which they call the "action" pathway). The model has been widely discussed, and a number of theoretical flaws (Glover, 2004; Hommel et al., 2001)

and empirical inconsistencies (e.g., Bruno, 2001; Franz, 2001; Jackson, 2000; Rossetti & Pisella, 2002) have been pointed out, but the basic distinction between the off-line planning process and the online specification of open parameters has found wide acceptance (e.g., Bridgeman, 2002; Glover, 2004; Hommel et al., 2001; Neumann & Klotz, 1994). Interestingly, not only can the online phase of action planning (or, perhaps better, parameter specification: Neumann & Klotz, 1994) operate independently of conscious awareness, as the findings of Bridgeman et al. (1979), Prablanc and Pélisson (1990), and others indicate, but the operations and computational products of this phase may even be inaccessible for conscious awareness in principle (Bridgeman, 2002; Glover, 2004; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Milner & Goodale, 1995). Even though more research on this issue is necessary, this assumption matches the observations of Münsterberg (1889) and Marbe (1901), who were perplexed to find nothing of theoretical interest in the introspective reports of their subjects about the time between a stimulus and the completion of the corresponding action. Among other things, it was this observation that was leading the members of the then-evolving Würzburg school to claim that task instructions are transformed into a cognitive task set before but not as a result of stimulus presentation.

Postactional Phase

Even though the way that actions are represented in the human cognitive system allows for the simulation of various alternatives and for the prediction of the most likely outcome of a given action, actually performing an action is the only way to find out whether one has made an appropriate choice. Accordingly, the postactional phase is important for evaluating actions,

strengthening successful actions, and preventing or improving unsuccessful actions. A number of postactional activities are relevant for long-term learning, an important issue that, however, we do not focus on in this chapter. Also important are short-term adaptations that feed back into behavioral control immediately. Here we will discuss the two of such adaptations: strategy adjustment and episodic binding. We introduce and discuss them separately because they are commonly investigated in different areas and with different theoretical goals in mind, but we conclude by considering how these two functions may work together.

Strategy adjustment refers to the fact that people learn from experience: We commonly do not repeat an action if it was unsuccessful, and we make active attempts to improve our actions all the time. This means that we must have had expectations about action outcomes, and/or representations of the ideal action that we compare with what we have actually achieved (Adams, 1968). Depending on the outcome of this comparison, we must be able to modify available action plans in such a way that the next execution of a given plan is likely to be more successful, thus minimizing the discrepancy between ideal and actual action. Such modifications may refer to any feature of an action, be it the smoothness of a golf swing, the affective tone of a musical piece, or the speed of a 100-meter sprint. *That* people can adjust all sorts of features of their action plans is obvious from many findings, such as the typical slowing down of responses after an error trial (Rabbitt, 1966), but there is not much we know about *how* the adjustment is done.

A number of recent observations suggest a possibly central role of conflict and conflict monitoring in error correction. Botvinick, Braver, Barch, Carter, and Cohen (2001) have suggested that the cognitive system may be comprised of a mechanism that

is sensitive to conflict anywhere in the system, be it created by the activation of multiple stimulus representations or of multiple responses. If so, the presence or absence of conflict could be used to stimulate the adaptation of parameters and processes in perception and action control. A number of recent studies have been taken to provide support for the conflict-monitoring account. For instance, it has been observed that the impact of irrelevant, response-compatible or response-incompatible flankers on behavior increases after trials with compatible flankers and decreases after trials with incompatible flankers (Gratton, Coles, & Donchin, 1992). This may be explained by assuming that the detection of conflict leads to the (increased) inhibition of flanker processing, whereas the absence of conflict leads to either no change or a decrease of flanker inhibition (Botvinick et al., 2001; see chapter 3). Likewise, it has been observed that stimulus–response compatibility effects become larger after compatible trials and smaller after incompatible trials (Stürmer, Leuthold, Schröter, Soetens, & Sommer, 2002), which may also be explained by conflict-induced adaptation of stimulus–response pathways.

However, the control-monitoring approach suffers from two problems, one theoretical and one empirical problem, and both of them point to a role of episodic binding. The empirical problem results from the fact that transitions between stimulus-compatible and/or response-compatible trials are often fully confounded with the sequential relationships between stimuli and responses. Assume, for instance, that a right response to a left stimulus is followed by a left response to a left stimulus. In the context of a study on control monitoring, this would count as the transition from a stimulus–response-incompatible to a stimulus–response-compatible trial. Finding that reaction time in the latter is higher than after a compatible trial (say, a right response to a right stimulus)

would be taken to mean that the conflict in the incompatible trial must have inhibited the impact of stimulus–response compatibility (e.g., Stürmer et al., 2002). Unfortunately, however, alternative interpretations are possible and, given independent evidence supporting it, in some cases even more plausible. It is known that performance is negatively affected by mismatches of stimulus–stimulus or stimulus–response conjunctions (Hommel, 1998), most likely because repeating one element leads to an automatic retrieval of the previously related elements (i.e., episodic bindings; Hommel, 2004). Accordingly, at least with two alternative tasks, it is impossible to tell whether worse performance in a compatible trial has resulted from the fact that the previous trial was incompatible or from the fact that the stimulus (or the response) is repeated while the response (or the stimulus) is not—and a clear-cut interpretation of better performance in an incompatible after a compatible trial is equally impossible (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003). More recent studies have attempted to test the predictions from the conflict-monitoring approach under conditions in which episodic retrieval is unlikely to account for the findings (Ullsperger, Bylsma, & Botvinick, 2005; Wühr & Ansorge, 2005), and it seems that measurable effects remain. However, given that we still know very little about the structure of episodic traces and the conditions under which they are created, more research is clearly necessary on this issue.

The theoretical problem with the conflict-monitoring approach is that it can predict *when* adjustments are being made (i.e., whenever conflict is detected), but, as Botvinick et al. (2001) admit, it fails to explain *which* adjustments are made and *how* they are accomplished. Once this problem is solved, it may turn out that conflict monitoring and episodic retrieval do not represent mutually exclusive explanations of

trial-to-trial variability but, rather, components of an adaptive network. Registering conflict in a given trial may increase the degree to which the current goal is activated. According to our present considerations, this should increase the impact of top-down processes on the competition between and eventual selection among stimulus events and, more important for present purposes, action alternatives. In particular, refreshing the goal representation should strengthen the impact of action-related pointers to the relevant stimulus and response dimensions, thereby increasing the relative impact of action-related information. As a consequence, the system would behave exactly as Botvinick et al. (2001) suggested: The detection of conflict would lead to a decreased impact of (task-irrelevant) flankers in a flanker task and of (task-irrelevant) stimulus–response compatibility in a compatibility task. Moreover, emphasizing the task-relevant feature dimensions will affect episodic retrieval in such a way that task-relevant stimulus and response features will contribute more strongly to the retrieval process; that is, repeating a task-relevant feature will be more likely to trigger the retrieval of a previous episode including that feature than repeating a task-irrelevant feature. And that task relevance affects the retrieval of episodic bindings has been demonstrated only recently (Hommel, Memelink, Zmigrod, & Colzato, 2008).

Summary

The control of human action comprises at least three different phases with distinct functions. The first, planning phase consists of specifying the relevant features of an action, activating the codes representing and controlling them, and integrating these codes into a coherent action plan. The second, actional phase consists of an interaction between the controlling action plan and sensorimotor streams that provide online information to concretize the action and to specify the parameters left open in the plan. The third, postactional phase consists of the evaluation of the action's success, the thereby informed and controlled storage of information that links the action to the current context (i.e., the creation of episodic bindings), and the adaptive modification of the action plan and the general strategy if necessary.

Conclusions

In this chapter, we have painted a picture of voluntary action as gradually emerging from sensorimotor experience, just as envisioned by James (1890). Infants, children, and adult novices in some sense observe themselves moving and extract from that experience systematic relationships between movement patterns and their sensory consequences. Representations of these consequences are then increasingly used to anticipate wanted action effects, and this at the same time primes the action producing these effects. That is, self-prediction and self-control go hand in hand. The distributed representation of action plans provides the backbone for human flexibility and adaptivity: Inappropriate plans can be quickly adapted by modifying only a few parameters, new plans can be derived from overlearned plans through extrapolation and generalization, and forgetting or cell loss can be compensated rather easily. Actions are thus at the core of larger representational networks that can include codes of the sensory and affective by-products of the action, codes of the most appropriate context, verbal descriptions of the action and its function in a particular context, and more. The representations of actions and the broader cognitive structures of which action plans are a part are not fixed or invariant, as the metaphor of a motor or action "program" may imply. Rather, action plans should be thought of as networks of feature codes that are continuously updated

and tailored to the current situation and the task at hand. Once implemented, such networks in some sense automatize the actor in taking care of the intended action outcome and channeling up-to-date, online environmental information to the appropriate motor systems. Hence, somewhat paradoxically, we control our actions long before we actually carry them out.

Acknowledgments

Note

1. We consider it reasonable to distinguish between functional units and anatomical units. Two or more elements are thus considered a functional unit if they tend to "go together," that is, if activating/involving one element will almost always lead to the activation/involvement of the other. This does not necessarily exclude the possibility that the elements of a functional unit are anatomically separable, for instance, by lesioning one component of a neural network but not the other.

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