Systems Theories and A Priori Aspects of Perception
J.S. Jordan (Editor)

CHAPTER 7

Perceiving One's Own Action—and What it Leads to

Bernhard Hommel

Introduction

The present contribution deals with the relationship between perception and action or, more precisely, with how the perception of action affects action control. Action effects, that is, the specific impact a particular action has on the actor-environment relationship, are what actions are good for—they represent the ultimate reason for why we carry out actions at all. This means that some anticipation of action effects must be available to, and used by, an actor in the course of selecting, initiating, and performing an action. In other words, representations or codes of action effects should play a crucial role in the control of action. To get internally coded, however, an action effect needs to be perceived, and its causal dependency on the corresponding action needs to be noticed. Only if we know that a particular action consistently produces a particular effect, can we anticipate the to-be-expected effect and use this anticipation, or the code it is produced by, to select the corresponding action. That is, the control of goal-directed movements critically depends on previous perceptions of movement-effect relationships, hence, on the integration of action effects.

Although no one would deny the importance of action-effect perception for action control, this importance is rarely reflected in our current theorizing on perception and action. Certainly, it is not too difficult to find action-related models that allow for some interactions between perceptual information and movement control, or at least for the utilization of information about movement success or failure (see overviews by Keele, Cohen, & Ivry, 1990; Rosenbaum, 1991; Schmidt, 1988). But what these approaches typically focus on is some kind of direct sensorimotor interaction rather than the integration and learning of action-contingent effects. This has not always been so. In fact, psychological theorizing about the conceptual role of action effects has undergone considerable change in the last 150 years. As I will point out in the following, the close relationship between action control and perception of action effects was strongly emphasized in the earliest theories on the emergence of voluntary action, neglected in later theories, once more discovered, and once again forgotten.

Based on a rough sketch of this historical-theoretical context, my diagnosis will be that the role action effects are seen to play in current theorizing is insufficient—a fact that is likely to stand in the way of a deeper understanding of the emergence of voluntary action and of the cognitive mechanisms subserving it. As a contribution to change this state of affairs, I will then present a theoretical framework that may help to initiate and guide both empirical investigations of, and theoretical reasoning about, perception-action relationships: the Action-Concept model (Hommel, 1997). After highlighting some of the model's implications, I will discuss empirical evidence which not only supports the basic assumptions of the model, but also demonstrates that the model can be used to predict novel effects and provide a fertile basis for the continued development of a comprehensive theory of voluntary action.

Changing Conceptions of Action Effects

Action Effects as the Basis of Voluntary Action: Lotze, Harleß, and the Effektbild

Perhaps the earliest attempts to develop a full-fledged theoretical account of the emergence of voluntary action in man can be found in the works of Lotze (1852) and Harleß (1861), whose ideas are perhaps better known to most psychologists in the guise of James' (1890) ideomotor theory or Greenwald's (1970) treatment of sensorimotor interactions. Lotze and Harleß were concerned with the fact that while we as actors know much about what we intend, or are going to do in a particular situation, we do not have the slightest idea about precisely how we are doing it. In fact, while we are able to give a number of reasons for why we are performing an action, what our action aims at, and so forth, we (as conscious perceivers/actors) are pretty ignorant as to the motoric realization of the action (i.e., which muscles are involved, how their activity is coordinated, or how movement elements are timed and sequenced). Nevertheless, we do activate and coordinate our muscles, as well as time and sequence our motor output in a way that allows us to accomplish an incredible number of action goals—how is that possible?

According to Lotze and Harleß, the solution to this puzzle has a lot to do with cognitive representations of action effects, or *Effektbilder* (effect images) as Harleß has called them, that are assumed to emerge as a result of self-perception. At birth the newborn perceiver/actor does not really act but makes random erratic movements that necessarily produce certain observable effects on the environment or the person-environment relationship. However, he or she will quickly discover that the movement-effect relationship is not arbitrary: Given a particular context, a certain movement will mostly result in predictable effects. Perceiving these effects and forming internal representations of them (i.e., cognitive effect codes) leads to an automatic association between the effect code

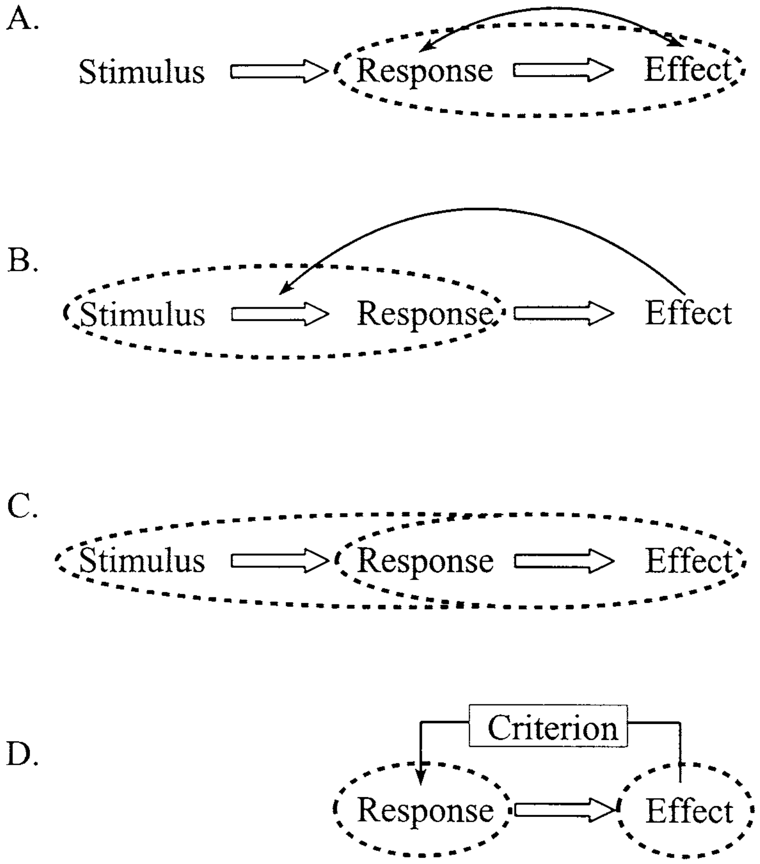

Figure 1. Differing conceptions of the integration of stimulus, response, and effect information, and the role of action effects. White, unfilled arrows indicate the temporal sequence of events; black arrows indicate effects of, or interactions between, these events. Broken circles indicate which events become integrated in the learning process.

and corresponding motor pattern, as illustrated in Figure 1A. The fact that this association is bilateral, hence can be used in a backward fashion, provides the basis for voluntary action: If the perceiver/actor now wishes a particular effect to occur, the only thing to do is to activate the internal code of the effect. Because of (and through) the learned association, this activation will spread to the corresponding motor pattern and, by activating it, bring about the intended effect. From the "insider's" perspective of the cognitive system, action-effect codes are the only way to voluntarily access the motor system and, thus, they *are* an action's cognitive representation.

Lotze and Harleß emphasized both the informational and the dynamical role of action effects: These effects not only inform the perceiver/actor about the features and consequences of a movement; their cognitive representations are also critically involved in planning and preparing an action. Thus, action effects do not serve as mere cues indicating success or failure—a role often exclusively focused upon in later approaches—but rather, are integrated with motor patterns into larger knowledge structures that make up a considerable portion of the cognitive system. It is interesting, but not surprising, to see that this early insight into the dual (or multiple) function of action-effect representations was not incorporated into the theoretical approaches that followed. This was especially true during the era of "pure" behaviorism in the United States, which tended to overlook one, if not both, of these roles that are played by action effects.

Action Effects as Learning Criteria: Thorndike and the Law of Effect

One of the most influential books in the development of behaviorism and the tendency to theorize in terms of stimulus and response was Thorndike's *Animal Intelligence* (1911). In this book, which is mainly devoted to the problem-solving capabilities of the cat, Thorndike laid the groundwork for the "Law of Effect" which he actually formulated a few years later (Thorndike, 1927). This principle, which has been widely discussed in the domain of learning and beyond (e.g., Postman, 1947; Tapp, 1969; Waters, 1934), rather simply states "that what comes after a connection acts upon it to alter its strength" (Thorndike, 1927, p. 212). Figure 1B illustrates this idea: If a stimulus has triggered a particular response, the strength of the association between the two is increased if the response is followed by a satisfying effect, but decreased if what follows is negative or annoying.

The general historical-theoretical context of Thorndike's approach differed considerably from that of Lotze and Harleß. The work of the latter was based on a phenomenal analysis of voluntary action, a perspective that quite naturally leads to (1) the question of how much we know about the means, not only the ends, of our action, and (2) the general conclusion that we actually know very little, indeed. In stark contrast, Thorndike attempted to account for human and infrahuman behavior from an "outsider's" perspective, hence a behavioristic standpoint, which, with equal naturalness, focuses on variables accessible from that perspective—stimulus, response, and experimenter-controlled reward—rather than on the perception of changes in the actor-environment (i.e., action effects as a whole). All this considered, it comes as little surprise that there are at least two important differences between the role Thorndike ascribed to action effects and the role these effects played in Lotze and Harleß's system.

First, in Thornidke's theory, the information provided by action effects no longer has anything to do with the features of the stimulus or the response; it is only the hedonic value that counts. Thus, the question of how a response is perceived and coded—most central to Lotze and Harleß—is neither addressed nor considered to be of theoretical importance. Second, although action effects have a strong impact on learning, they (or their representation) are not assumed to become part of the emerging knowledge structure. Thus, while Lotze and Harleß believed that what is learned is the response-effect relationship, Thorndike's law refers exclusively to stimulus-response relationships. In the words of Walker (1969), action effects are now assumed only to provide the "glue" needed to form or strengthen an S-R linkage rather than becoming an integral part of it.

Action Effects as Information: Tolman and the Mental Map

Although Thorndike's Law of Effect was extremely influential during the heyday of behaviorism, serious doubts, especially in the mere motivational function attributed to action effects, were raised by Tolman (1932). At that time, there were several observations that were inconsistent with the law as formulated by Thorndike.

First, it was found that behavior can be affected not only by the mere availability of reward but by its quality as well. In the study of Tinklepaugh (1928), for instance, monkeys had the opportunity first to observe that food was hidden under one of two containers and were then given the opportunity to choose between them. Sometimes, the original food (banana) was substituted with a different food (lettuce), so that correct choices were associated with a surprise. In these cases, the monkeys exhibited what Tolman (1932, p. 75) called "surprised hunting behavior," that is, they ran around and searched for the banana they were expecting to find under the container, while the lettuce was usually left untouched. Obviously, the monkey's behavior was not dependent on, or directed by, reward per se, but was attracted by a particular goal object.

Second, it was demonstrated that what rats acquire in maze learning is not so much a sequence of specific motor acts. Rather, what they learn is some kind of goal-directed behavioral strategy. For example, Macfarlane (1930) trained groups of rats to either swim or wade through a maze and then, after training, required them to do the opposite (i.e., wade or swim). Although the switch from swimming to wading or from wading to swimming led to some behavioral disruption, the animals adapted quickly and showed full transfer on the very first trial. Obviously, the animals learned the sequence of locations or places, what Tolman referred to as a "mental map," that could be used to steer wading as well as swimming behavior.

Third, it was demonstrated that the hedonic value of an action effect was much more important to performance than to learning. For instance, in the study of Tolman and Honzik (1930) there were three groups of rats that learned a maze for several days. The first group, which received a food reward on successful trials, performed much better in terms of errors than a second group, which received no reward. The third group also received no reward until the 11th day, at which time it began to receive rewards like those of the first group. As soon as this happened, the third group performed as well as the first, although until then it had performed as poorly as the second. This suggests that the groups differed, not in terms of learning, but rather, in terms of performance.

Finally, Tolman, Hall, and Bretnall (1932) were able to demonstrate with humans that the improvement of performance with practice may not depend on the hedonic value of action effects at all, that is, on whether correct responses are signaled by a "satisfying" or an "annoying" effect. Their subjects were presented with 30 pairs of holes, with only one hole of each pair being correct, and learned to punch the correct hole with a metal stylus. In one group, correct stylus placements were followed by the ringing of a bell, while in another group, correct placements were followed by the application of an electric shock. In two other groups, incorrect placements were followed by either a ring, or a shock, with each group experiencing only one of these possible outcomes. While the latter two groups demonstrated poorer performance than the former two, it did not matter whether the correct response was indicated via the ringing of a bell or the application of a shock. This strongly suggests that learning a skill depends much more on the information an action effect provides about the behavior to be acquired than it does on how the action effect makes the actor feel (i.e., good or bad).

Taken together, these observations stand in opposition to the notion that effects of action effects are merely motivational in nature. Obviously, action effects provide more than the glue that connect stimuli and responses. They also inform the actor about whether the response came out as intended and, if not, how it failed. Thus, according to Tolman (1932, 1959), learning should not only be thought of as the strengthening of S-R bonds. It should also, and perhaps more importantly, be regarded as the formation of expectancies (i.e., in the presence of a particular stimulus a particular response will produce a particular effect, see Figure 1C). Tolman's approach, therefore, seems to combine Lotze and Harleß's suggestion that action effects might be integrated with response-producing structures, with Thorndike's proposal that learning affects the relationship between stimulus and response. Although it took some time for this integrative view to receive broader attention, recent developments in the field of animal learning suggest that its basic assumptions may turn out to be heading in the right direction (e.g., Colwill & Rescorla, 1986; Fedorchak & Bolles, 1986; Urcuioli & DeMarse, 1996).

Action Effects as Controlled Input: Closed Loops and Systems Theory

In some sense, Tolman's understanding of action effects as information about the type and course of goal-directed behavior anticipated the main theme of systems-theoretical approaches that have grown in popularity since the foundation of theoretical cybernetics by Wiener (1948) and others. Among the many attempts to account for purposive behavior by using ideas and concepts provided by systems theory, the approaches of Miller, Galanter, and Pribram (1960), Hein and Held (1962), and Adams (1968, 1971) were especially influential.

According to Miller et al. (1960), goal-directed behavior is controlled by what they call TOTE (test-operate-test-exit) units. These units comprise two phases, a test phase and an action phase, which form a recursive loop. In the test phase, input information about some state of affairs (e.g., the distance between a reaching hand and the to-be-reached target) is compared against some internally stored criterion (e.g., zero distance in case of a reaching movement). If input and criterion differ, the action phase is initiated, that is, an action is performed that somehow serves to change the state of affairs monitored in the test phase (e.g., the hand is driven toward the target). Such comparison-action cycles continue to be executed until the difference between input and criterion is zero. Although Miller et al. are not very specific as to which kind of input is integrated, how this is done, or whether and how input representations become a part of learned knowledge structures, it is clear that, as far as the role of action effects is concerned, their approach is similar to Tolman's. Obviously, what they mean by input actually is perceived action effects, and what these effects do is inform the actor about the (current) success of his or her action, just as depicted in Figure 1D.

A closed-loop approach that explicitly aimed at accounting for learning phenomena, especially for motor skills, was proposed by Adams (1968, 1971). In his view, the learner acquires two different traces, a perceptual trace and a memory trace. The perceptual trace is a representation of the sensory consequences of the preceding response or, in the case of several responses, a kind of average across the decaying traces of previous responses. This trace is used as a reference against which succeeding responses are compared. However, it cannot be used as a learning criterion unless the learner also has knowledge of results (i.e., knows whether the preceding response was correct or not, or how correct it was). The memory trace is the motor part of the story. It is a motor control structure that brings about the movements producing the sensory consequences. What the learner then learns is the motoric means to produce a particular set of action effects and a perceptual criterion to judge whether this set actually occurs, as indicated by the two broken circles in Figure 1D.

A comparison of Miller et al. and Adams reveals that while Adams' perceptual trace (informed by knowledge of results) forms the heart of Miller et al.'s test phase, Adam's memory trace is the driving force of Miller et al.'s action phase. Thus, although Adams was more concerned with learning than Miller et al., the two approaches are rather compatible.

A third, highly influential closed-loop approach was proposed by Hein and Held (1962), whose reafference model applies von Holst and Mittelstaedt's (1950) reafference principle to sensorimotor adaptation. The problem Hein and Held addressed is how we can discriminate changes in the environment (e.g., the movement of a visual object) from our own movements (e.g., an eye movement) despite the fact that both involve changes in the relationship between ourselves and the environment (e.g., in the form of retinal displacement). The solution they offered is that actors can learn the correlation between motor commands and the sensory consequences of those commands (called reafference). If this is the case, then as soon as a motor command is issued the expected sensory input can be computed and used as a criterion against which the actual input can be compared. If expected and actual reafference match, a self-generated movement is perceived and an environmental change if not. This explains why the world does not seem to sway when we move our eyes during a saccade, although it does when we displace our eyeballs with our fingers.

All this sounds very much like the closed-loop model of Adams (1971), even though Hein and Held are more interested in perception, while Adams focuses on motor learning. Adams, however, claims the existence of two different traces to be learned independently (though often at the same time), while Hein and Held assume that motor commands and representations of action effects become interconnected. Thus, as regards to the results of learning, Hein and Held's view is more compatible with Lotze and Harleß's action-effect integration approach represented in Figure 1A than with Adams' separate-coding approach depicted in Figure 1D.

An interesting theoretical twist common to all these closed-loop models is that they, in a sense, reverse both the temporal and the causal arrow of information processing as commonly understood. As pointed out by Dewey (1896)—even before the advent of behaviorism—and emphasized only recently by Hershberger (1988, 1992), from a closed-loop perspective it is not the stimulus that causes and controls the response, but the "response" that is carried out to evoke and control the "stimulus" (see Powers, 1973, for a systems-theoretical elaboration of this theme). Note that this reversal of perspectives is already implicit in the early approaches of Lotze and Harleß who assumed that the motoric part of an action (corresponding to Adams' memory trace) is cognitively represented by codes of the action's sensory feedback (i.e., a perceptual trace). Recall that this motoric part is thought to be accessible only via activation of action-effect codes, so that selecting an action is not done directly (e.g., by calling a particular muscle program) but by activating the codes of the expected sensory consequences of the action, hence by anticipating a particular action effect. What intention and action-control thus refer to is input, not output, just as the closed-loop view implies.

Action Effects as Prescriptions: Open Loops and Motor Programs

On the one hand, the basic idea underlying closed-loop models—the proposed interplay between motor control structures and perceived movement outcomes—cannot be incorrect: It is hard to see how a certain behavior can ever become adapted to internal and external constraints if no information about the quality and environmental fit of this behavior is available to the learner. On the other hand, however, feedback-based approaches since the response-chaining hypothesis of James (1890), who stated that response elements are triggered by sensory feedback from the preceding element, have been challenged by observations that many motor actions can be performed by partially or totally deafferented human patients or animals. For instance, humans can be demonstrated to reproduce active movements even if kinesthetic feedback is absent (Lashley, 1917), monkeys are able to grasp, walk, and jump even when blindfolded and deprived of kinesthetic feedback (Taub & Berman, 1968; Taub, Perella, & Barro, 1973), and birds can sing songs acquired earlier even when deafened afterward (Konishi, 1965). Findings such as these have been taken to show that actions are not controlled by sensory-motor loops but by central motor programs, structures of more (e.g., Schmidt, 1975) or less (e.g., Keele, 1968) abstract prescriptions for muscle activity. Motor programs are loaded or activated before a movement or movement sequence is started and then take over control until the intended action is carried out without any consideration of sensory feedback. That is, the closed sensory-motor loop is broken, and the first half missing.

Although programming approaches can now be said to dominate the psychomotor field, the theoretical distance between open- and closed-loop models is much smaller, and the arguments in favor of the former are much weaker, than proponents of programming approaches tend to hold. First of all, subjects in most deafferentation studies experienced losses in a single modality only, so that information from other sensory channels may have contributed to guiding movement performance (cf., Adams, 1971). Second, deafferentation studies usually show that *already acquired* movements or actions can be performed in the (partial) absence of feedback information. This in no way proves that feedback was unnecessary in the course of *learning* the respective movement. While closed-loop models do predict that learning should be impossible without sensory feedback, they do not assume that feedback will always be required. Third, although the independence of performance and feedback is emphasized in programming approaches, when it comes to learning, even these accounts need some kind of movement-contingent feedback to explain how the learner can adjust the structure of his or her motor program to the task requirements (e.g., Keele & Summers, 1976). So, it may well be that the major difference between closed-loop and open-loop theories is not so much of a conceptual nature, but lies, rather, in the fact that the former focuses more on the learning process, while the latter deals more with the result of this process.

In addition to this, however, there is a related, yet more subtle problem with programming approaches, which is of special interest for the present discussion. Consider what happens if a particular movement is programmed, say, a simple keypress with the index finger of the right hand. According to the programming view (e.g., Rosenbaum, 1987; Schmidt, 1988), there are several parameters to be set, such as the hand parameter (i.e., choosing the right, not the left hand), the finger parameter, a force parameter, perhaps, and so forth. But now the question arises as to how we can do all of this. How do we know in which way, say, the finger parameter can be (and is) specified by setting the "index finger" value? Somehow in our early development we must have acquired knowledge about how to deal with tasks like these, but this fundamental learning process—much more fundamental than learning to press a particular key in response to some stimulus or to press it with a certain force—is in no way addressed by the programming approaches. That is, while programming approaches might be quite plausible when explaining how already-learned movements are prepared and controlled, and how already-acquired movement elements can be combined or recombined to form novel actions or action sequences, they are pretty silent as to the questions raised by Lotze and Harleß: Where do all these elements or parameters come from, and how do they come under voluntary control?

Taken all together, open-loop or programming approaches do not seem to provide a completely different view of the role of action effects in voluntary action. Although in these approaches action effects do play a minor role, this is not as much an indication of an alternative way of explaining how voluntary action emerges, as it is a consequence of fading out the very questions which motivated other approaches to bring action effects into the game.

The Action-Concept Model

We have seen that the manner in which action effects and their role in voluntary action have been conceptualized and considered in psychological theorizing has, over the years, been anything but straightforward: Basic insights got lost, were rediscovered, and then ignored. Moreover, there were far-reaching changes in theoretical terminology, as well as underlying metatheoretical perspectives (i.e., the switch from the introspections of Lotze to Thorndike's rigorous analysis of animal behavior). We have also seen, however, that not all of these changes led to completely new insights. In fact, it turns out that the basic assumptions made by Lotze and Harleß—especially their claim that actions are represented by codes of their effects and that these codes mediate and control voluntary action—were in no way challenged by later approaches: Very similar assumptions were made by Tolman, although he was somewhat vague as to the function action-effect codes have in actual performance. Closed-loop models not only allow for but strongly emphasize the integration of motor structures and effect codes, and although open-loop models take a different perspective, this seems to be possible only because they do not really address the actual emergence of voluntary action.

Given this remarkable agreement across so many theoretical schools of thought, one would expect action effects to be of central importance in current action theory—yet, apart from a few, isolated attempts (e.g., Greenwald, 1970), functional theories along the lines of Lotze, Harleß, or James are still lacking. In the following, I will sketch a theoretical framework, the action-concept model (Hommel, 1997), that may serve as the basis for such a comprehensive theory. In this framework, the theoretical ideas of Lotze and Harleß concerning action effects are employed to explain the emergence of not only action representations, but of what Prinz (1990, 1992; Prinz, Aschersleben, Hommel, & Vogt, 1995) has called a "common-coding system," a system where both stimuli and responses are represented as (self- or other-produced) events, and are thus, represented in a comparable and commensurable format.

The basic unit of this system, which again is assumed to form the basis of the cognitive system as a whole, is the *action concept*. Action concepts are integrated sensorimotor (better: perception-action) structures, minimally consisting of an action-related part—an activation pattern that functions to constrain sensorimotor coordination in a certain way—and a perceptual part—a representation of the effects the associated action-related part is producing (under certain conditions). Action concepts are assumed to be acquired just as Lotze (1852) and Harleß (1861) have claimed: Soon after birth (and often even earlier) the perceiver/actor starts moving in an uncoordinated and erratic fashion, driven by external, reflex-triggering stimuli or internal states. Whichever motor pattern is set up (see code m in Figure 2) and whichever movement is performed, he or she registers the perceivable effects of these movements and automatically associates the activation pattern produced by these effects (see codes e_1, e_2, and e_3 in Figure 2) with the activation pattern responsible for their occurrence (i.e., motor activity directly preceding and/or temporally overlapping with effect registration). Stable action concepts emerge if a given movement is often followed by the same effects, so that the association between movement-producing and effect-produced patterns (i.e., m and e codes) becomes stronger. With practice, action concepts may increase in their context sensitivity, that is, movement-effect associations may be modulated by codes representing relevant situational features.

Once acquired, action concepts can be used "in the backward direction." That is, associations between the movement-related and the effect-related part are bidirectional, so that the movement pattern can be set up by activating the associated effect code. This, then, forms the basis for voluntary action: selecting

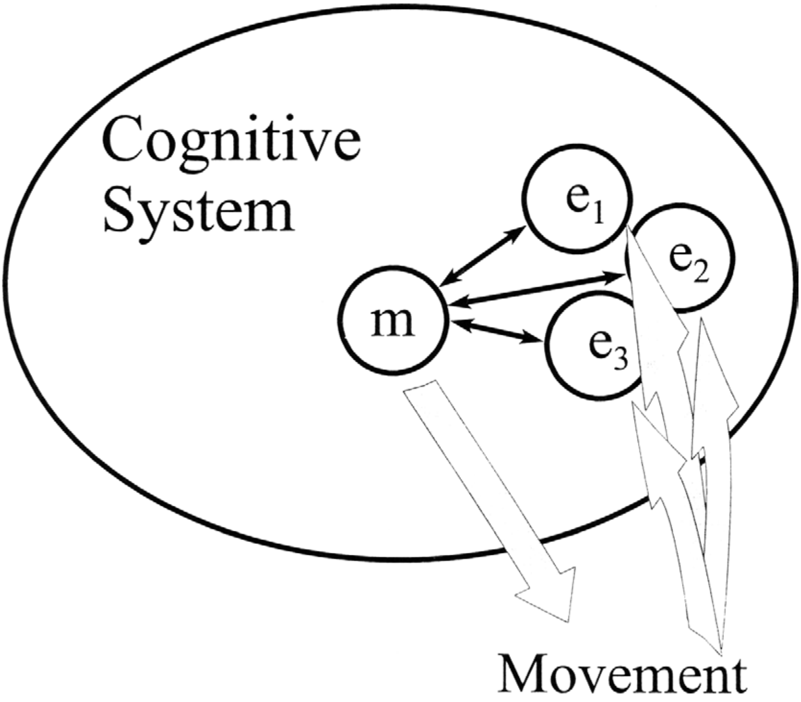

Figure 2. Basic elements of an action concept: Movement pattern m produces a movement event, the perceivable features of which are coded by effect codes e_1, e_2, e_3, ..., e_n. Temporal overlap between m and effect codes leads to the formation of bilateral m-e associations.

or "programming" a movement by "anticipating" its effects, hence priming the codes by which they are represented. Thus the emergence of action concepts through learning by self-perception—observing what one's own movements are leading to—provides the formerly moving observer with the cognitive means of becoming an acting perceiver.

The basic structural assumptions of the action-concept model developed so far (i.e., as described in Hommel, 1997) rest on the insights of Lotze and Harleß but extend their approach in three important respects. First, while both Lotze and Harleß exclusively referred to movement-produced or *intrinsic* feedback (according to the terminology suggested by Salmoni, Schmidt, & Walter, 1984), the action-concept model claims that any kind of perceivable action-contingent event can become integrated into an action concept, whether it is a movement-produced kinesthetic feeling or a car accident. That is, the model does not distinguish between proximal and distal effects or between movement-related and action effects. Whatever the event with which a movement finds itself correlated, the codes of both will become interconnected and form an action concept.

Second, action effects are assumed to be represented not by uniform, monolithic cognitive structures, but in the form of (bundles of) feature codes. Even if a movement evokes a single event only, this event will usually consist of several features, and each of these features will be coded by a different effect code (see e_1, e_2, and e_3 in Figure 2). Thus, action-effect learning results in an association, not between a mere motor control structure and the codes of one or more effects, but rather, between the motor-related pattern and several feature codes specifying the effect's attributes. If, for instance, a movement is accompanied by the perception of being forceful, it gets coded as a "forceful movement," and if it is accompanied by the perception of something green it becomes a "green movement." According to the action-concept model, the resulting feature-movement mappings are the cognitive basis for our ability to set and modify the parameters of an action without having to learn or "program" the whole action anew. A motor program or action plan thus corresponds to an integrated assemblage of effect codes that represent and describe the (to-be-perceived) features the action should have.

Third, in contrast to previous models of a similar kind, the action-concept model does not distinguish between stimulus and response codes. Both perception and action are seen as sensorimotor interactions extended over time. In fact, outside the psychological laboratory, perception is often more than passively awaiting and registering input impinging on the body's sensory surface at a given point in time. It is, rather, the active acquisition of information about the perceiver/actor-environment relationship involving the orienting of effectors and/or the body toward the source of information. Likewise, action is usually not restricted to emitting ballistic muscle output into an environmental void, but is informed by perceptual information at many points in time, and is often preceded, accompanied, and followed by active adaptations of receptor organs to allow for monitoring the action's context, progress, and outcome. This is by no means a new insight (see Dewey, 1896; Gibson, 1979), but it is rarely reflected in psychological process models, whose preference for S-R terminology leads one to see perception and action as temporally nonoverlapping cause and effect (see Hershberger, 1988, for an elaboration of this theme).

According to the action-concept model, both perception and action are mediated by action concepts, hence the same kind of representation. Of course, this does not preclude the notion that, say, in an experimental trial, one action concept codes the stimulus while another codes the response. Assume, for instance, that a subject responds to a green light by pressing a left-hand key. Clearly, the presentation of the green light will initiate some sort of sensorimotor coordination (e.g., movements and light adaptation of the eye), while response demands require the initiation of another coordination that eventually results in the keypress. Although both coordinations are mediated and controlled by action concepts, there is nothing wrong with calling the stimulus-mediating action concept a perceptual code or stimulus representation and the response-producing concept an action code or response representation. In fact, I will freely make use of this terminology throughout the present chapter and talk about "stimulus codes" and "response codes." Yet it should be clear by now that these labels are being used to refer only to different *roles* the respective codes or concepts are playing in a given task context, not to different *kinds* of codes.

The action-concept model has already been applied with some success to a number of phenomena, mostly in the field of S-R compatibility (for overviews see Hommel & Prinz, 1997; Proctor & Reeve, 1990), and several assumptions about the dynamics of stimulus and response coding have been added and empirically substantiated (see Hommel, 1997, for an overview). In the following, however, I will concentrate on the role of action effects in goal-directed behavior and on the way this role is conceptualized in the model. I will show that previous, seemingly puzzling findings can be fruitfully reinterpreted from an action-concept perspective, and I will also report several published and unpublished studies from my own lab that were undertaken to test central assumptions and important implications of the model. As we shall see, there is a good deal of evidence that action-effect codes are involved in action control and that multiple action effects are integrated in an automatic fashion, although the relative weights of their codes can be modulated by intentional processes.

Automatic Integration of Action Effects

If actions are cognitively represented by codes of their effects, actors should be able to perceive the contingency between a given action and the effects it produces. And in fact, there is evidence that they do: Although early research on how well subjects can estimate the degree of action-effect contingencies (e.g., between a keypress and a light flash) gave rise to rather disappointing results (Jenkins & Ward, 1965; Smedslund, 1963), more recent, methodologically improved studies have shown that people can perform quite accurately in such tasks (Allan & Jenkins, 1980; Shanks & Dickinson, 1987; Wasserman, 1990). However, the action-concept model predicts that perceivers/actors should not only pick up information about action-effect relationships if asked to do so, but should integrate action-effect information automatically. To demonstrate true automatic integration not only requires showing that action-effect contingencies are learned—whether intentionally or incidentally—but also that what is learned actually affects action control. How can this be shown?

A possible answer suggests itself if we consider how Lotze and Harleß would have described the emergence of voluntary action in a newborn child. In the very beginning, the baby has no idea what leads to what and, therefore, cannot perform goal-directed actions. What it needs to do, then, is to register the co-occurrence of movements and effects, hence experience a number of movement-effect sequences, coded as $m_1 \rightarrow e_1$. As a result, movement- and effect-related codes become interconnected by means of a bilateral association, $m_1 \leftrightarrow e_1$. By using the evolving structure "backward," the baby can now initiate m_1 by activating e_1, the action-effect code becoming an action-goal code. If activating e_1 really leads to the initiation of m_1, one can try to attain experimental control over the effect coded by e_1, then present the effect and see whether m_1 is activated, at least to some degree. There are at least two ways this can be accomplished.

One method is, as a first step, to establish a certain movement-effect association by having subjects perform, either spontaneously or in response to a stimulus, a particular response (R), which is then paired with an effect stimulus (E), say, a tone (R→E). The next step is to present, after some practice, the effect stimulus before the response (E→R) and to test whether the response is triggered. If presenting E triggers R, it must be assumed that (1) a bidirectional association between the internal codes of R and E was formed, and (2) this association was involved in, or had an impact upon, action control.

Another, similar method works with two or more stimulus-response-effect alternatives. In the practice phase, reaction stimuli are presented to signal choice responses that are followed by discriminable effect stimuli ($S_1 \rightarrow R_1 \rightarrow E_1$, $S_2 \rightarrow R_2 \rightarrow E_2$, etc.). In the test phase, there are two different conditions. In the *compatible* condition, reaction stimuli and response-compatible effect stimuli are presented together ($S_1+E_1 \rightarrow R_1$, $S_2+E_2 \rightarrow R_2$, etc.), the question being whether or not this manipulation increases speed and accuracy of performance. In *incompatible* conditions, reaction stimuli and response-incompatible effect stimuli are combined ($S_1+E_2 \rightarrow R_1$, $S_2+E_1 \rightarrow R_2$, etc.), with the expectation that such a manipulation hampers performance. Analogous to the single-effect method, an effect of E-R (or E-R-E) compatibility would count as evidence for the integration of action effects and for an influence of action-effect codes on action control.

Again, things started somewhat disappointingly. Working with the single-effect technique, Cason (1922) presented his (human) subjects with a light stimulus, which served as an unconditioned stimulus (UCS) for an unconditioned eyeblink response (UCR). In some conditions, the UCR was accompanied by a tone (S→R+E), while in others it was followed by such a tone (S→R→E). After extended practice, the UCS appeared either alone (S→R) or together with the tone (S+E→R), the critical measure being the specific effect of the tone on UCR intensity (i.e., the relative increase in intensity due to the addition of the tone to the UCS). In comparison to control measurements taken at the beginning of the experiment, the tone was found to have a facilatory effect following training involving UCR-tone overlap, but had no such effect following training involving sequential UCR-tone pairing. Clearly, this is not consistent with the idea that experiencing response-event sequences leads to an automatic formation of bilateral associations between the codes representing response and event. However, it should be noted that Cason's results are based on very few subjects, with only a single subject in the critical UCR→tone condition.

A more encouraging result was obtained with kittens in a study by Brogden (1962), in which cage-turning responses were consistently followed by a tone (R→E). After practice, the tone was presented when the subjects had been quiet for a period of 30 sec or longer, the expectation being that this might induce a response (E→R). In fact, the number of tone-induced cage-turning responses produced by this group of kittens was significantly higher than that produced by a control group that had not received response-contingent tones during training. Obviously, subjects in the experimental group had developed response-tone associations that were capable of working in both directions.

Also working with animals, Meck (1985) had rats choose between two response keys, each being followed by a tone of a particular duration ($R_1 \rightarrow E_1$, $R_2 \rightarrow E_2$). After extensive training, the short and long tones were used as response cues, hence they now signaled the correct response key. When the tone-key mapping was compatible, that is, consistent with the key-tone mapping learned during the training phase ($E_1 \rightarrow R_1$, $E_2 \rightarrow R_2$), performance was substantially better than when such mappings were incompatible ($E_2 \rightarrow R_1$, $E_1 \rightarrow R_2$).

At this point, it may seem that positive evidence for action-effect integration is much easier to obtain with animals than with human subjects, but recently, progress has been made with humans as well. In a study by Hommel (1996), human subjects performed binary-choice keypress reactions to visual stimuli, such as letters or color patches. Each keypress was consistently followed by a tone that varied in terms of either its location or its pitch ($S_1 \rightarrow R_1 \rightarrow E_1$, $S_2 \rightarrow R_2 \rightarrow E_2$). After practice with the respective response-tone mappings, effect tones were presented together with the visual reaction stimulus. In three experiments employing different types of stimuli and responses, compatible tones ($S_1+E_1 \rightarrow R_1 \rightarrow E_1$, $S_2+E_2 \rightarrow R_2 \rightarrow E_2$) yielded significantly faster responses than incompatible tones ($S_1+E_2 \rightarrow R_1 \rightarrow E_1$, $S_2+E_1 \rightarrow R_2 \rightarrow E_2$). This suggests that the auditory action effects were integrated and associated with the corresponding response, so that responses were primed by the presentation of "their" effect. If the primed response was the correct one (i.e., signaled by the reaction stimulus), response selection was facilitated and response speed increased. If, however, the reaction stimulus signaled the other response, the primed response had to be inhibited and the correct one selected, thus, the reaction time was prolonged.

The Hommel (1996) study demonstrates that humans show evidence for action-effect integration just like other animals do. An important aspect of this study is that all action effects employed were completely irrelevant for the task at hand, a fact that was pointed out emphatically to the subjects during the instructions. Nevertheless, although the subjects had every reason to ignore the effect tones altogether, they did not. This suggests that the acquisition of response-effect relationships is automatic (i.e., independent of usefulness and learning intentions) to at least a considerable extent. Further, there exists evidence which indicates that this is not a transient phenomenon: To test the stability of the compatibility effect, Hommel and Elsner (1997) gave subjects extended practice with the task used by Hommel (1996) and observed reliable effects even after the fifth session of about 380 trials each. Among other things, this rules out the possibility of accounting for action-effect integration in terms of curiosity; after all, it is hard to believe that subjects were still excited by simple sinus tones after 1,900 or so trials.

Further evidence for the automatic integration of irrelevant action effects comes from a study by Aschersleben and Prinz (1997) on sensorimotor synchronization. In synchronization tasks, subjects are typically presented with a regular and predictable sequence of auditory signals (clicks) that is to be accompanied by a sequence of keypresses (i.e., finger taps). Interestingly, subjects consistently produce *negative* timing errors in these tasks. That is, their tap usually precedes the click by an interval ranging between 20 to 50 msec (e.g., Aschersleben & Prinz, 1995; Fraisse, 1966). The hypothesis pursued by Aschersleben and Prinz (1997) attributes this negative asynchrony to the way subjects centrally control their tapping performance. Specifically, what subjects effectively control may be the temporal synchrony of perceived click and perceived tap, hence the controlled relationship is between sensory information about the click and sensory feedback from the tap. This brings in as factors the temporal relationship between (1) the actual click and perceived click (i.e., the click-delay or click-transmission time), and (2) the actual tap and perceived tap, (i.e., the tap delay). If both delays are of the same size, performance should be perfect, no matter how long they are. However, for simple anatomical reasons (i.e., nerve conduction times) click information will be available earlier than tap feedback, thus the actual tap must precede the click in order to achieve synchrony between perceived click and perceived tap.

A combination of this hypothesis with the assumption of automatic action-effect integration suggests an interesting prediction: By presenting after each tap an artificial action effect, such as a tone, one might be able to further increase the negative asynchrony, the more so the longer the delay between tap and effect. This is because if the action effect actually is integrated and becomes part of the tap's action concept, the tap has (at least) two effects, a kinesthetic one delivered rather early and an auditory one coming rather late. If the perceived timepoint of the tap takes into account the temporal characteristics of all of its (perceived) effects, and if, thus, kinesthetic and auditory effects are "temporally averaged," delaying the auditory effect should result in the tap being perceived as occurring later. This means that in order to achieve perceived-click, perceived-tap synchrony, the actual tap has to precede the actual click even more than in the absence of the auditory action effect. This is exactly what Aschersleben and

Prinz (1997) were able to demonstrate: The more they delayed the action-effect tone which followed the actual tap, the earlier the tap was performed, hence the larger the negative asynchrony.

Although much needs to be done to find out more about the learning conditions and contextual constraints for the integration of natural and artificial action effects, the available evidence clearly suggests that this integration takes place—in rats, kittens, and humans—just as predicted by the action-concept model. Obviously, human and subhuman subjects not only acquire information about the relationships between actions and consequences—as the mental-map approach of Tolman (1932, 1959) would have suggested—they also acquire this information automatically, and form direct associations between effect representations and response-related control structures, such that, activating an effect code leads to the priming, and sometimes even to the emission, of the associated response.

Multiple Coding of Action Effects

Having shown that even artificial, experimentally introduced action effects are coded and integrated, the next step is to demonstrate the validity of another assumption of the action-concept model; namely, that actions are, or can be, represented by several feature-based effect codes. This assumption actually includes two logically independent hypotheses, the first one being that several action-representing effect codes can coexist, and the second being that these codes are made up of bundles of effect-feature codes.

From an action-concept perspective, some of the above-mentioned results can be seen as supporting the multiple action coding hypothesis. Consider, for instance, the study by Hommel (1996), in which visual reaction stimuli were responded to by keypresses, which were followed by auditory effects. On the one hand, the resultant E-R (or E-E) compatibility effects suggest that the actions were associated with, and thus represented by, codes of the effect tones. On the other hand, however, the actual task consisted of pressing a left or right key or, in other experiments, of pressing a key once or twice. If, according to the action-concept model, effect codes mediate action control, then spatial or number codes must have been formed and used in addition to any auditory codes. Thus, auditory and spatial or number codes must have been able to coexist. A similar logic applies to the findings of Aschersleben and Prinz (1997): The fact that presenting an auditory action effect modified the asynchrony suggests that both kinesthetic and auditory effects were integrated and temporally averaged.

An obvious problem with such arguments is, however, that they in a sense presuppose the very model we wanted to test. Clearly, the case for multiple coding would be made more convincingly if we could find direct evidence of either interactions between experimentally induced and already-acquired (e.g., intrinsic) action effects or some sort of impact that one action effect might have on the impact of another action effect.

Preliminary evidence of this sort comes again from animal studies. Trapold (1970) was the first to show that the acquisition of binary-choice responses is facilitated if each response is followed by a different reinforcer, that is, action effect, ($S_1 \rightarrow R_1 \rightarrow E_1$, $S_2 \rightarrow R_2 \rightarrow E_2$), versus the same reinforcer ($S_1 \rightarrow R_1 \rightarrow E_3$, $S_2 \rightarrow R_2 \rightarrow E_3$). Further, this so-called differential outcome effect (DOE) has been shown in different species, with different foods, and with different kinds of distinctions between the outcomes, such as between food and water (Brodigan & Peterson, 1976), different amounts of the same food (Carlson & Wielkiewicz, 1976), or food and no food (Urcuioli, 1991). Even more interesting is the fact that the DOE also occurs even if the action effects do not have any reinforcing value, as is the case with flashes of light (Fedorchak & Bolles, 1986). From an action-concept point of view, these observations suggest that action effects become associated with the responses they follow, this way increasing the discriminability of the responses and, thus, discrimination performance. In other words, integrating the effect might have led to a modification of the original response representation.

The findings of Rescorla (1991) also suggest the coexistence of several different action-effect codes. In this study, rats were trained to perform a common nose-poke response to obtain sucrose or food pellets in the presence of light or noise, with light predicting a different action effect than noise ($S_1 \rightarrow R_1 \rightarrow E_1$, $S_2 \rightarrow R_1 \rightarrow E_2$). In a second phase, the animals learned to obtain the same outcomes by performing lever presses and chain pulls. One response was followed by a single outcome ($R_2 \rightarrow E_1$), while the other was followed, in different sessions, by one or the other outcome ($R_3 \rightarrow E_1$, $R_3 \rightarrow E_2$). In a third phase, light or noise stimuli appeared in the presence of the lever or the chain, the critical measure being the response rate. There were two important results. First, the response that in the second phase was paired with a single outcome ($R_2 \rightarrow E_1$) was performed more often in the presence of the stimulus that predicted the same outcome in the first phase ($S_1 \rightarrow R_1 \rightarrow E_1$) than in the presence of the stimulus that predicted the other outcome ($S_2 \rightarrow R_1 \rightarrow E_2$). This suggests some kind of interaction between R-E and S-E representations. Second, and more important, the rate of the response trained with two outcomes ($R_3 \rightarrow E_1$, $R_3 \rightarrow E_2$) was increased in the presence of either stimulus (S_1 or S_2), which shows that both R-E associations were fully intact. In follow-up studies, Rescorla (1993, 1995) further showed that if a response is first paired with one outcome and then with another, both outcomes can be selectively devaluated with correspondingly selective effects on performance. Again, this is evidence that a response can become associated with more than one action effect.

With human subjects, most evidence for multiple action coding comes from experiments on spatial S-R compatibility. In spatial compatibility tasks, people respond with spatially defined responses, such as pressing a left versus right key, to stimuli varying in spatial location. In one version, it is the location of the stimulus that matters for the response decision. The critical variable here is S-R mapping: So-called compatible mappings ask for responses to spatially corresponding stimuli (e.g., left R to left S, right R to right S), while incompatible mappings ask for responses stimuli that do not spatially correspond (e.g., left R to right S, right R to left S). As one may expect, compatible mappings are associated with much quicker responding and fewer errors than incompatible mappings (e.g., Fitts & Seeger, 1953). In another version, the so-called Simon task, subjects respond to a nonspatial attribute of the stimulus that randomly varies in location. Again, performance is better if the stimulus appears on the same side as the response, hence the two are spatially correspondent (e.g., Simon & Rudell, 1967).

When it comes to explaining effects of spatial compatibility, most models refer to some kind of match or mismatch of stimulus and response codes. If stimulus location is task relevant, translating the stimulus into the response is assumed to be easier the more similar the two codes are, because with similar codes there is simply less to be done (Fitts & Seeger, 1953). In the case of the Simon task (i.e., with stimulus location being task irrelevant), it is assumed that, apart from controlled S-R translation, stimuli tend to automatically activate responses with which they share features, such as the spatial feature "left" or "right" (Kornblum, Hasbroucq, & Osman, 1990). Therefore, if stimulus and correct response are on the same side, the correct response is activated twice; once through a controlled process involving the S-R mapping rules, and again through an automatic process brought about by feature overlap.

Obviously, this notion is consistent with the action-concept model. If, say, in a binary choice task (e.g., letter X→left key, letter O→right key) a left-hand response is performed, it produces several action effects on the left side; kinesthetic feedback from the response finger, mechanical noise from the key, visible motion where the action takes place, and so forth. All these effects have the feature of being left, so that the action is associated with several kinds of "left" codes, represented in Figure 3 by the bidirectional arrow between the codes "m" and "left." If then a left-side stimulus appears, it will also be coded as "left," among other thing, and hence, will activate the "left" code(s) associated with the response producing the left-hand keypress. This, of course, is an advantage if the left-hand keypress is correct (i.e., $S_1+E_L \rightarrow R_L \rightarrow E_L$), but a response conflict arises if the alternative, right-hand response is to be performed ($S_2+E_L \rightarrow R_R \rightarrow E_R$; see Hommel, 1997, for a more detailed discussion).

In a typical Simon task, several action effects are located on the same side, thus one cannot know whether it is a single effect, the single effect's spatial correspondence with the stimulus, or a combination of several action effects which brings about the compatibility effect. Consider, for example, a task where

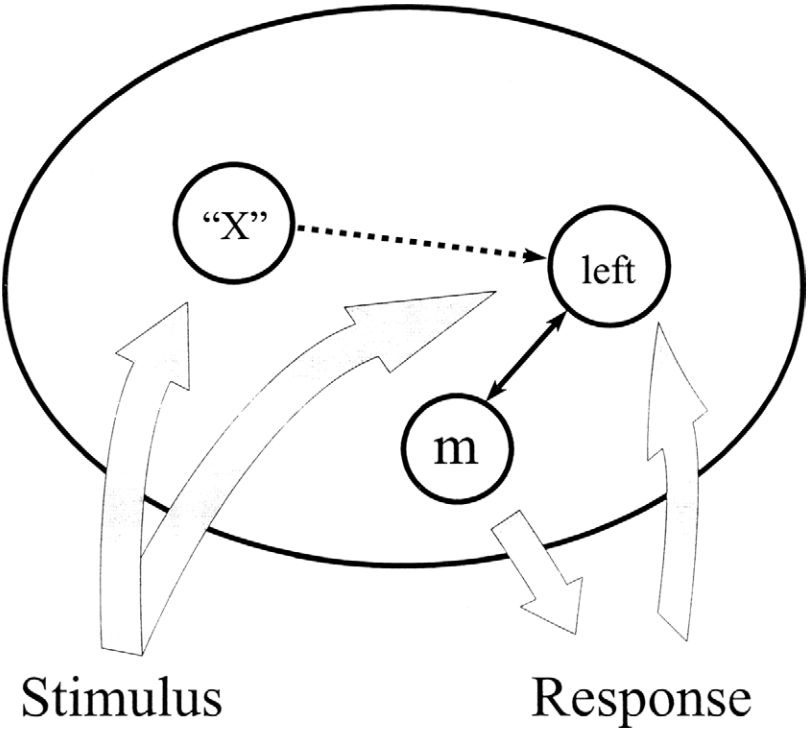

Figure 3. The Simon effect from an action-concept view: Letter X signals a left-hand keypress performed by motor pattern m. Letter code and spatial action-effect code are linked by an instruction-based short-term association (see dotted line). The effect code is also bilaterally associated with m (see straight line), due to (pre)experimental experience with the contingent relationship between activation of m and the occurrence of left-hand events. Left-side stimuli are also coded as "left," hence they activate or prime the correct action-effect code. Right-side stimuli would be coded as "right" and, thus, would activate the incorrect action-effect code (not shown), thus resulting in a response conflict.

people respond to the pitch of a left or right tone by producing a particular action effect, say, a flashing light on the left or right side, by pressing a left or right key with their left or right hand. Now assume that left-side flashes are produced by pressing the left key with the left hand and right-side flashes are produced by pressing the right key with the right hand, as depicted on the left side of Figure 4. As Hommel (1993, Exp. 1) has shown, choice performance is much better in this case if tone signal and response key correspond (e.g., if the tone signaling the left-hand keypress is presented through a left-side loudspeaker) than if not (e.g., if the left-hand keypress is signaled through a right-side loudspeaker). However, as all perceivable effects belonging to an action were located on the same side, such an

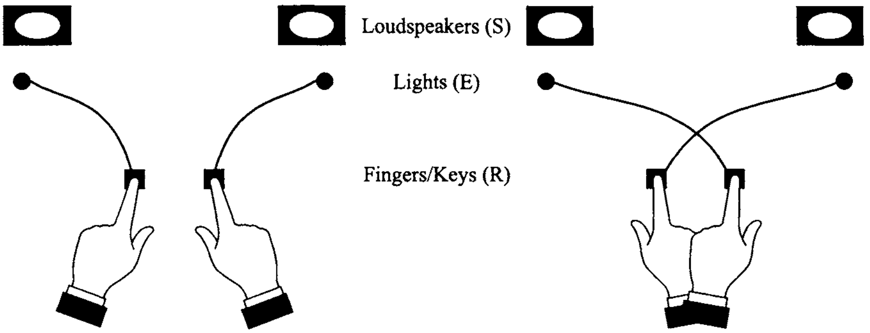

Figure 4. Schematic illustration of two example conditions in Hommel's (1993) Experiment 2. The left panel shows the combination of uncrossed hands and parallel key-light mappings, whereas the right panel shows crossed hands and inverted key-light mappings.

outcome could be due to the spatial relationship between stimulus and action-contingent light, to that between stimulus and hand location, or to that between stimulus and anatomical status of the hand, or to some combination of these relationships.

According to the action-concept model, we expect all these relationships to contribute: Clearly, the subject should be aware of, and thus perceive that, say, a visual event on the left side is directly preceded by some left-side (finger and key) movement that has something to do with the (anatomically defined) left hand. Consequently, at least three spatial codes should be associated with the corresponding action; one referring to the light, one to the effector location (be it the finger or the key), and one to the hand. If all these codes are (or include the feature) "left," a left-side stimulus should activate all of them, such that the associated response is primed via three different routes. Increased priming should produce better performance in compatible conditions, and poorer performance in incompatible conditions, thus producing an increase in the size of the compatibility effect (i.e., the difference between compatible and incompatible conditions). If, however, action effects are not all located on the same side, the spatial compatibility effect should decrease, the more so the more the action effects are spatially distributed. That is, a response should be coded as left or right—and produce effects depending on that—to an extent that depends on the number of action effects located on that side.

This expectation was tested by Hommel (1993, Exp. 2). Specifically, the above-mentioned action effects (i.e., action-contingent light, key or hand location, and anatomical hand) were systematically varied in an orthogonal fashion. Subjects performed left and right keypresses to low or high tones (relevant stimulus feature) presented randomly on the left or right side. Pressing a response key produced a light flash on the same side or, in other conditions, on the opposite side. Instructions referred to the lights, in that subjects were asked to "flash the left (right) light in response to the low (high) tone." In different conditions, the hands were either crossed or uncrossed (i.e., left hand on right side and vice versa), and the key-light mapping was either parallel (i.e., key and light on same side) or inverted (i.e., key and light on opposite side). This rather complicated design allowed for an orthogonal variation of spatial tone-light, tone-key, and tone-hand compatibility: Assume, for instance, the tone appears on the left side and signals flashing the right light. If hands are uncrossed and key-light mapping is parallel (see Figure 4, left side), this would mean incompatible tone-light, tone-key, and tone-hand relations. If, however, hands are crossed and key-light mapping is inverted (see Figure 4, right side), a left-side tone would be incompatible with the (right) light, compatible with the key (right light is flashed by pressing left key!), and incompatible with the (right) hand. It turned out that all three spatial relationships produced their own S-R compatibility effect. That is, independent of the other relations, performance was better if tone and light corresponded, if tone and key (or active effector) were on the same side, and if tone location matched the active hand's anatomical status. Clearly, this suggests that spatial information about the three variables (i.e., light location, key or hand location, and anatomical hand status) was integrated and used to form action-effect codes that became connected to the respective response ($R \leftrightarrow \{E_1+E_2+E_3\}$). This again supports the multiple-coding hypothesis of the action-concept model, for it demonstrates that action concepts can include information about more than one action effect, and a given action can be associated with, and represented by, several action-effect codes.

Further evidence for multiple coding has been found by Hommel (1996). In one experiment (Experiment 1), subjects performed a standard Simon task by pressing a left or right key in response to the color of a visual stimulus presented randomly on the left or right side. Each keypress produced a tone that was on the same side in one part of the experiment, and on the opposite side in another part of the experiment. Although the auditory action effects were irrelevant to the task (the instruction referred to the keys), their location was expected to produce an effect. With same-side tones, all action effects occurred on the same side, so that each keypress should have been coded as left or as right, depending on the location of the key ($S_1 \rightarrow R_1 \rightarrow E_1$, $S_2 \rightarrow R_2 \rightarrow E_2$). With opposite-side tones, however, both the left-hand and the right-hand keypress produced left and right action effects (e.g., kinesthetic on the left side, auditory on the right), such that each response was associated with both "left" and "right" codes. Consequently, each response should have been coded as both left and right, so that left- and right-side stimuli would always activate both responses. As expected, the Simon effect was significantly smaller with opposite-side tones than with same-side tones. That is, the benefit associated with spatial stimulus-key correspondence was less pronounced if keypress and tone were on opposite sides. Again, this suggests that information about the location of both the response and the response-contingent tone was coded and integrated into the action concept controlling the response.

Altogether, these findings not only support the assumption that multiple action-effect codes can coexist, they are also consistent with the idea that action concepts, as well as single action-effect codes, are not unitary, homogeneous structures, but are, rather, composed of feature bundles representing the attributes of the respective action effects. For example, in the animal studies by Brogden (1962) and Meck (1985) the same signal was used as action effect and as inducing stimulus (i.e., transfer of $R \rightarrow E_1$ to $E_1 \rightarrow R$). One might claim that the ability of the stimulus formerly presented as action effect to evoke the associated response may have been due to the fact that it was *identical* to the learned action effect. The assumption that actions are represented by feature codes suggests, however, that an identical match between the inducing stimulus and the action effect is not necessary. All one needs, rather, is some degree of overall stimulus *similarity*, in which there is an identical relationship among certain stimulus features, and not the stimulus as a whole. In fact, the observation that compatibility effects can be obtained with spatial correspondence between an auditory stimulus and a visual action effect, as in Hommel (1993), or between a visual stimulus and an auditory action effect, as in Hommel (1996), support the notion that action concepts incorporate multiple feature representations, rather well.

Intentional Coding of Action Effects

The empirical findings available so far support the assumption that action effects are perceived, integrated, and associated with the corresponding responses or motor-control structures even if they are completely irrelevant to the task at hand. In other words, when we perform a particular action to achieve a particular outcome we also acquire information and knowledge about *what other* effects this action is able to produce. Acting, therefore, always means learning about new possible action goals. In fact, from a non-nativistic perspective it is difficult to see how the random and uncoordinated behavior of a newborn child could ever give way to purposive action, if some kind of automatic effect-learning mechanism is not involved. The point to be made here is that, as James (1890) has noted, "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" (p. 487). Only after having some idea about what effects a movement may cause can we anticipate the effect before the cause, hence select an action *be-cause of its effects.*

However, while the automatic integration of action effects represents a central presupposition for voluntary action, it does not tell us about how a given action is actually selected, whether and how effect codes are usually involved in that selection, or whether and how goal-related and goal-unrelated effect codes differ in their impact on selection and intentional control of action. So let us now turn to intentional coding processes and their interplay with automatic effect-integration mechanisms.

Some first indication of intentional coding processes comes again from a study on spatial S-R compatibility. In an experiment by Morin and Grant (1955), subjects faced a horizontal row of eight red stimulus lights and a row of eight response buttons. On each trial, two of the stimulus lights would flash and different groups of subjects were to respond by pressing the spatially corresponding keys, the keys on the opposite side, or some other, arbitrarily assigned keys. However, the instructions did not refer to the keys. Rather, they referred to a row of green lights located directly below the red stimulus lights. The green lights were connected to keys according to the required S-R mapping rules, such that each key flashed the green light directly below the red stimulus it was assigned to. The task, therefore, was to respond to the illumination of a red light by flashing the green light below it, hence the spatially corresponding "action-effect light." After having given the subjects some practice (and after having observed stable effects of the S-R mapping), Morin and Grant disconnected the green lights from the keys. Although the authors did not explain why they did so, their manipulation had a remarkable effect: Performance dropped to the level of the very first trials, corresponding to about a doubling of reaction times.

Obviously, the presence of the green feedback lights was (or became) important for how Morin and Grant's subjects dealt with the task, suggesting that some internal representation of these lights (i.e., action-effect codes) was involved in action control. Of course, as we know from many other choice-reaction time tasks, feedback lights are not necessary for a subject to perform at all, or to perform well, but once they are available and emphasized in the instruction, they seem to play a dominant role. From an action-concept perspective, this role could be attributed to effect-code weighting (Hommel, 1993, 1997). Consider a keypressing action that is associated with two effects, say, the perception of a kinesthetic sensation in the left-hand index finger (E_1) and of a light flashing on the right side (E_2). Once an actor has acquired this relationship ($R \leftrightarrow E_1 + E_2$), he or she will be able to perform R by activating E_1 or E_2, whichever is more suitable or convenient. That is, although R is associated with both effect codes, one of them may be "emphasized" by increasing its basic activation level relative to the other. Thus, the very same response or movement may be represented more as a left-index-finger action ($R \leftrightarrow \mathbf{E}_1 + E_2$), or as a right-light-flashing action ($R \leftrightarrow E_1 + \mathbf{E}_2$), depending on the effect to which the actor's intention refers. It appears then, that Morin and Grant's (1955) subjects first learned to put substantial weight on the codes of the green visual action effects and were then forced by the light-withdrawal manipulation to rearrange their relative effect-code weights in favor of the codes of other, remaining action effects.

Further evidence for at least some flexibility in action coding comes from the studies of Guiard (1983) and of Stins and Michaels (1997), in which subjects manually operated a steering wheel in response to nonspatial or spatial features of a stimulus. In Guiard's study, subjects responded to the pitch of a tone, randomly presented on either the left or right side, by rotating the wheel to the left or right. In one experiment (Experiment 3), they gripped the wheel with both hands at its bottom, hence the 6:25 position (see Figure 5). In this position, steering to the left requires a rightward movement of the hands, while steering to the right requires a leftward movement. There were pronounced individual differences: Some subjects performed better with correspondence between stimulus location and steering direction—a finding Guiard consistently obtained with hands in the 9:15 position, whereas other subjects performed better with correspondence between stimulus location and the direction of hand movement.

A similar finding was obtained by Stins and Michaels (1997), who had subjects respond to the location of a left or right stimulus light. The wheel was always operated with one hand only, the hand being placed at either the 12:00 or the 6:00 position (see Figure 5). In the 12:00 position, subjects consistently performed better with correspondence between stimulus location and steering direction, which in this case was always identical with hand-movement direction. The 6:00 position, however, produced large differences in the subjects' behavior: While some showed no effect of stimulus-response correspondence, some showed better performance with correspondence between stimulus and steering direction, and some were better with correspondence between stimulus and hand-movement direction.

From an action-concept view, this rather complicated result pattern is not too difficult to explain. When the hands are in the bimanual 9:15 position, and only small movements are required, there is no sense in which the hands are changing their horizontal location, at least not from the perspective of the actor. Consequently, the only action effect that is or can be coded in terms of left or right is steering direction, so that the only possible match between stimulus and response features (or the codes representing them) involves the direction of steering, not of hand movement. Things are different, however, if steering direction and hand movement are both defined in the horizontal dimension. If they always go together, as in Stins and Michaels' unimanual 12:00 condition, the spatial codes representing steering direction and hand-movement direction are always of the same content. Consequently, left-side stimuli will always activate the leftward response and right-side stimuli the rightward response, no matter if the subject codes his or her action in terms of wheel or hand movement. If wheel and hand always go in opposite directions, however, as in Guiard's 6:25 condition or in the 6:00 condition of Stins and Michaels, the actor's coding choice

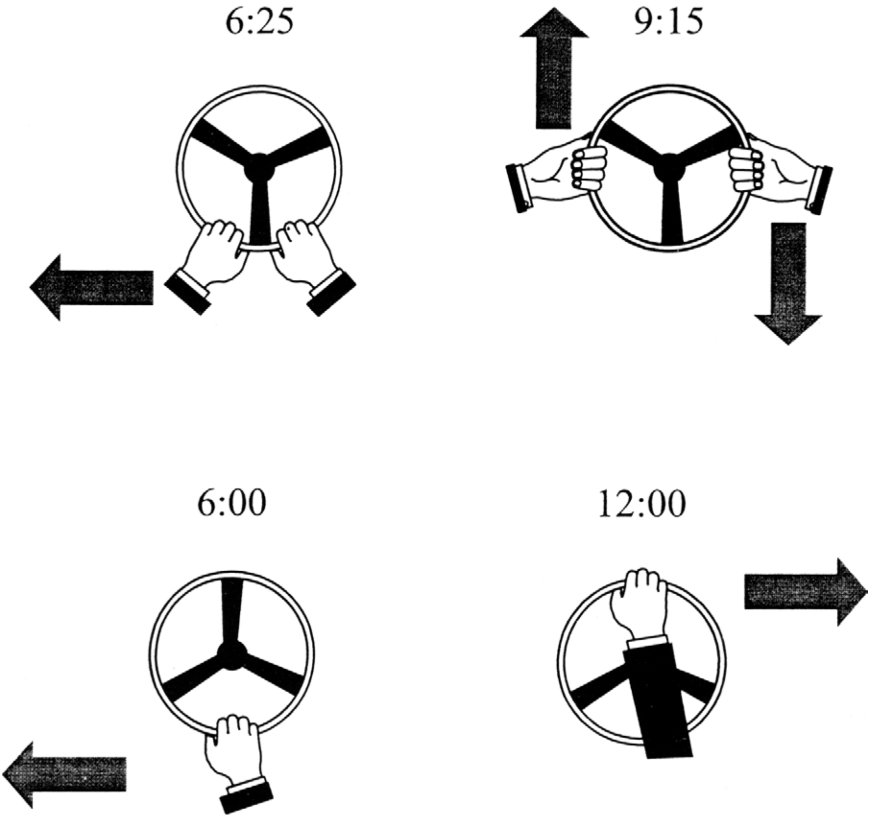

Figure 5. Schematic illustration of some conditions in the steering-wheel studies of Guiard (1983; upper row) and of Stins and Michaels (1997; lower row).

is crucial. If the actions are coded in terms of wheel rotation, leftward and rightward rotations should be quicker with left and right stimuli, respectively, while coding the action in terms of hand movement should yield the opposite result. Thus, the individual differences obtained by Guiard (1983) and by Stins and Michaels (1997) might be the result of different subjects having coded their actions differently by intending and anticipating different action effects.

Although the effect-code-weighting hypothesis is of some use in accounting for the individual effects observed in the wheel studies, the account it provides is necessarily post hoc and, thus, less convincing than a successful prediction would have been. The findings of Hommel (1993, Experiment 1) show, however, that such predictions can in fact be made with some success. Subjects pressed a left or right key in response to the pitch of a tone, which was randomly presented through a left or right loudspeaker. In two groups of subjects, pressing a response key produced a light flash on the opposite side ($S_1 \rightarrow R_L \rightarrow E_R$, $S_2 \rightarrow R_R \rightarrow E_L$), as indicated in Figure 6. The two groups had exactly the same task, including the tone-key mapping, but they received different instructions: One group was asked to "press the left/right key in response to the low/high tone," while the other was told to "flash the right/left light in response to the low/high tone." The idea was that, although each response had left and right effects, the instruction manipulation would lead the subjects to weigh their effect codes differently. If, for instance, a left-key response evoked kinesthetic sensations on the left and visual ones on the right, people in the key group should code this response as left rather than right (i.e., weigh or prime left code/s stronger than right ones), while light-group subjects should code it as right (i.e., weigh right code/s stronger than left ones). If this is the case, then different S-R correspondence effects would be expected in the two groups: While the key group should be better with stimulus-key correspondence (=stimulus-light noncorrespondence, see left panel of Figure 6) than with stimulus-light correspondence (=stimulus-key noncorrespondence, see right panel of Figure 6), the light group should show the opposite pattern, that is, be better with stimulus-light correspondence than with stimulus-key correspondence.

This is exactly what was found: While for the key group stimulus-key correspondence was much more beneficial than stimulus-light correspondence, the light group showed superior performance with stimulus-light correspondence as compared to stimulus-key correspondence. Thus, what mattered most was the spatial relationship between the stimulus and the intended action effect, hence the action goal. This suggests, as predicted by the weighting hypothesis, subjects actually weighted the effect codes belonging to a particular response according to the instruction, thus reflecting the emphasis put on some action effects, but not on others.

In a follow-up study, Hommel (1994) investigated the interaction between intentional code-weighting and automatic action-code integration. In the first experiment, which was very similar to the one just described, the task was again to press a left or right key in responses to the pitch of a tone appearing on the left or right side. This time, however, by pressing the left or right key, subjects flashed an upper or lower horizontally-centered light. The instruction described the actions exclusively in terms of light location and defined the action goal as flashing the top (bottom) light in response to the low (high) tone. The basic question was whether providing a spatial action-effect that could be coded on a different dimension than the stimulus would prevent the S-R compatibility effect from occurring. Thus, after having learned the relationship and contingency between the horizontal location of the response and the vertical location of the action-effect light, actors might be able to code the action exclusively in terms of top or bottom, and there would no longer be any effective feature overlap between stimulus and response, which again should eliminate spatial compatibility effects. Clearly, such a finding would be inconsistent with the

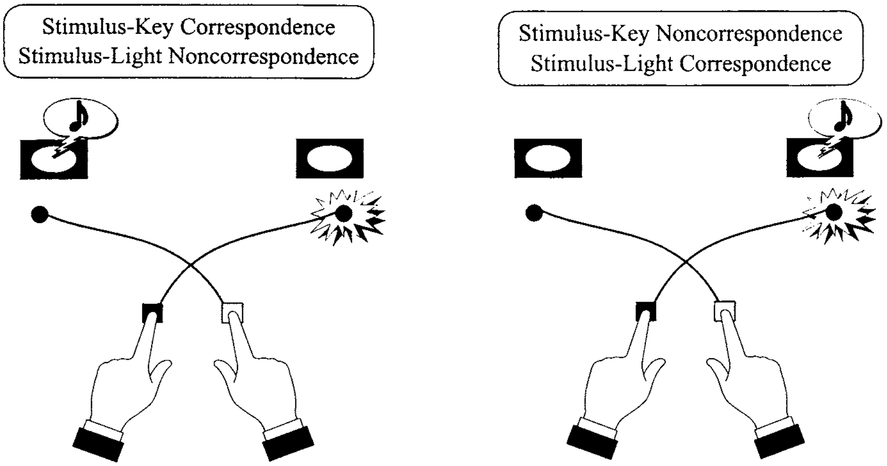

Figure 6. Schematic illustration of two example conditions in Hommel's (1993) Experiment 1. A low tone signaled a left-hand keypress that produced a light flash on the right side. Instructions were in terms of either keys or lights.

proposed automatic-integration hypothesis and, thus, would require substantial modifications of the action-concept model. The results, however, showed a pronounced stimulus-response correspondence effect of about the same size as in the Hommel (1993) study, which is very much in line with the assumption that action effects are integrated automatically. Obviously, horizontal action features, such as hand or key position, were considered in action coding, even though these were not related to the instructed (and, hence, intended) action effect.

In a second experiment, Hommel (1994) went one step further and introduced nonspatial (dimensions of) action effects. There were four groups of subjects. In one group, pressing a key flashed a red light on the same side as the key, and the subjects were instructed in terms of key location. A second group received the same instruction and the effect lights were also on the same side as the keys. However, the lights were red and green, so that actions could also be coded in terms of color. In two more groups, the keys were connected to lights of different colors and the instructions were given exclusively in terms of color. The lights differed as to their locations in the third group but not in the fourth, where both lights appeared at the center. That is, at least the fourth group had the opportunity to code their actions with respect to a completely spatially-neutral event. All of these attempts to prevent horizontal action coding failed, however. In all four groups, full-blown correspondence effects of virtually identical sizes were present, and there was not the slightest hint of any effect of instruction, light color, or an interaction between them. Thus, while the correspondence effect can be inverted by inducing different action goals, it cannot be eliminated.

Hommel (1994) made a final attempt to eliminate correspondence effects by investigating highly overlearned stimulus-response pairings. Skilled typists were presented with the letters *f* or *j*, which appeared randomly on the left or right side, and then responded by depressing the corresponding *F* or *J* key on a computer keyboard with their left or right index finger, respectively. Because in the standard initial typing position the index fingers are positioned in exactly the same way, these particular S-R pairings should be highly overlearned with professionals. In fact, they typically yield faster reaction times than any other letter-key combination (Salthouse, 1984). As the goal event that matters in computer-based typewriting is to type the letter on the screen rather than to move a particular finger, there should have been a tight connection between the letter code and the corresponding response. This opens the possibility that overlearned keypressing actions are mainly or exclusively coded in nonspatial terms, so that the spatial correspondence between stimulus and response key should not matter. The results showed, however, that it did: Performance was much better, in terms of reaction times and errors, with letter-key correspondence than with noncorrespondence. This suggests that whatever may change with typing practice, it does not prevent typists from coding their keypressing actions as left or right, just as unpracticed subjects do. Thus, practice neither eliminates spatial codes from action concepts nor seems to permit stimulus information to circumvent the stage where action concepts reside.

Altogether, the available evidence supports the idea that people select and control their actions by using and differentially weighting the effect codes associated with the to-be-performed motor pattern. Although action effects are integrated automatically, their relative contribution to action control—as measured by occurrence and size of S-R correspondence effects—is subject to modifications by intentional processes. On the one hand, not much practice is needed for intentional processes to come into play: A single session suffices to allow a simple manipulation of instructions to invert an otherwise extremely stable compatibility effect (Hommel, 1993). On the other hand, even extended practice does not allow the intended action effect to dominate other response-produced effects completely: Even highly experienced typists are unable to ignore the spatial features of their typewriting responses. This does not mean, however, that practice is completely ineffective. For instance, Castiello and Umiltà (1987) found that spatial left-right compatibility effects are much more pronounced in volleyball players than in soccer players, possibly due to the stronger functional specialization of left versus right effectors in volleyball as compared to soccer. Thus, learning to discriminate between alternative actions on a particular dimension may well involve emphasizing the codes that represent the values of this dimension, such as "left" and "right." Yet although this may increase the relative dominance of the respective effect codes even more than short-term instruction manipulations, the dominance is incomplete and, thus, leaves room for other effect codes to play some role.

Conclusions

The purpose of this chapter was to highlight the role of perceived action effects and their representations in the control of voluntary action. We have seen that the way this role was .conceptualized underwent drastic and gross change since the action theory resulting from Lotze and Harleß's analysis of the "inner view" of human will. We have also seen that while more and more aspects or functions of action effects came to be considered and investigated, others came to be more and more neglected and were eventually forgotten. Thus, the question is not so much which view is right and which is wrong, but rather, how all these functions can be combined to form a comprehensive theory of (the emergence of) voluntary action.

The action-concept model I have proposed here does not, of course, fulfill all the reasonable demands one should make on such a theory, but it may serve as a useful tool for developing one; and I have tried to show that it already has. There is now substantial evidence from animal and human studies which support the notion that performing an action leads to the acquisition of knowledge about action-contingent events, hence action effects, whether these events are currently of relevance or not. Once acquired, this knowledge has an impact on action control: Activating the code of a learned action effect by presenting the respective effect stimulus before the response serves to facilitate the response if the primed response is the required response, but leads to interference if a different response is required. This suggests that in addition to being learned, effect codes also become associated with the response such that effect-code activation leads to the priming of the associated response. As action effects are not integrated as a unitary whole but form bundles of feature codes, response priming may occur even in cases of only partial overlap between effect and inducing stimulus.

Action-effect integration is highly automatic, but the impact of a particular effect code is modulated by intention. On the one hand, all our efforts to eliminate action coding in left-right terms—by making horizontal response location irrelevant or by providing alternative coding opportunities and instructing subjects to make use of them—completely failed. This implies that action features are coded automatically and become integrated. As it seems, all features of an action that can be and are in fact perceived are processed automatically and cognitively coded, and these codes get associated with the motor pattern controlling the action. On the other hand, instructions to perform responses to attain a particular goal, hence to intend a particular effect, have a strong impact on the relative dominance of action effects. This suggests that, although actors cannot prevent codes of action-contingent events from being integrated into an action concept, they do have control over the relative weight a particular effect code has in a particular task. Thus, there appears to be a wellorganized division of labor between automatic and intentional coding processes. In considering intended as well as unintended action effects, automatic integration always keeps the perceiver/actor informed about possible, alternative action goals, that is, about what could also be done or achieved by performing the very same movement. Intentional processes, on the other hand, seem to be relevant in selecting the intended effect, that is, in specifying the to-be-expected outcome of an action. Among other things, this should be important for action evaluation, which requires determining whether the intended effect is actually produced as expected.

Taken all together, we have reason to doubt that the potential of action effects is best understood from one of the more or less single-function views developed over the years. Quite to the contrary, even a brief look at the few of the empirical examples discussed here strongly suggests that action effects serve nearly all the functions attributed to them: The observation of automatic effect integration and the indications of effect-action associations nicely correspond to the idea of Lotze, Harleß, James, and others, that actions are represented by codes of their perceived effects, although the data also show that an effect can be more (i.e., more distal, more remote, more abstract) than a movement-produced kinesthetic sensation. The finding that knowledge about action-contingent events is acquired even if they are completely irrelevant to the task and have no hedonic quality strongly supports the informational approach of Tolman and his basic critique of motivational theories of learning. The demonstration that actions can be primed by presenting stimuli that resemble the effects that action would produce provides considerable support for the assumption that action-effect anticipation (i.e., the specification of to-be-expected input) plays a crucial role in action control, a point of central concern in the systems theory approach to voluntary action. At the same time, however, although the anticipatory control of action is based on movement-produced feedback perceived earlier, it in no way relies on *currently* available feedback, which is in agreement with the basic idea of open-loop or programming approaches. Finally, if action control is based on representations of the intended action effect, hence on a description of to-be-expected input, one might imagine that this representation is used to evaluate the action's success, which again may serve as a learning criterion or "reward" in the sense of Thorndike.

Action effects and their cognitive representations, then, are good for many things: They provide information about an action, are involved in selecting and controlling it, help to decide whether the intended effect was produced, and so forth. Thus, there is every reason to grant them a central role in our theorizing about action control—a greater and more differentiated role, at least, than they currently play.

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