How we do what we want: A neuro-cognitive perspective on human action planning

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ABSTRACT

Humans perform actions to reach particular goals, that is, to intentionally create or modify personally relevant events—we move our eyes to learn more about a novel event, reach for a cup to quench our thirst, and move our lips to share our thoughts with someone else. Accordingly, even primitive actions must involve some kind of planning, some sort of anticipatory control. Indeed, there are at least three defining features that the simplest behavioral acts share with more complex ones. First, all of them are planned in terms of anticipated goal events. In particular, the first step of action planning consists in specifying the features the action is intended to possess; this is achieved by activating the appropriate action-effect codes, i.e., sensory-motor assemblies controlling the production of those features. Action-effect codes emerge through the perception of movement-effect contingencies, and they are acquired from the first months in life on. Besides action planning they are involved in the perception of both one's own actions and actions of others. Second, selected features of an intended action need to be integrated into a coherent, durable action plan, which is achieved by temporarily "binding" distributed feature codes. Third, planning an action turns the cognitive system into a kind of reflex machinery, which facilitates the proper execution of the plan under appropriate circumstances. This involves the implementation of automatic stimulus-response associations and the increase of the salience of action-related situational information, thereby delegating action control to the environment.

INTRODUCTION

The present chapter approaches the issue of action planning—i.e., the preparation and implementation of goal-directed movements—from a cognitive psychology and, to some degree, cognitive neuroscience point of view. It will focus on actions that are much simpler than most of those discussed in the other chapters of this book and consider empirical findings from both behavioral experiments and neurophysiological studies. Accordingly, the chapter deals with the *how*, rather than the *why*, of action planning and, thus, will be concerned more with the transformation of behavioral goals into overt behavior than with the issue where those goals are coming from and why they have been chosen.

On first sight it may not be self-evident that bodily expressions as simple as pressing a key, moving one's hand, or uttering a syllable—the typical responses used in cognitive labs—really deserve to be called actions. One may also tend to doubt that they are planned the same way as the often more complex, multi-step actions performed in everyday life, such as baking a cake. It is especially the required sequencing of action steps that makes the need for advanced planning obvious and, indeed, efficiently sequencing one's behavior in tasks like the Tower-of-London problem is considered to be an important aspect of people's action-planning abilities in clinical psychology (e.g., Shallice, 1982). In contrast to more complex action sequences the elements of these sequences are often understood as mere movements—in the service of an overarching action goal—or *re*-actions to a triggering stimulus.

However, I shall provide evidence that even the most primitive element of an action chain needs to be, and actually is, planned much like any other, more complex and extended action or action sequence. That is, even elementary "re-actions" as used in standard experimental tasks carry the signature of, and therefore count as, planned intentional actions. The three following sections will elaborate in more detail on how this signature looks like. In particular, I shall argue that (i) actions are planned in terms of their perceptual effects, (ii) action plans are no monolithic units but integrated assemblies of action-effect codes, and (iii) action planning can be characterized as preparing a cognitive reflex.

ACTIONS ARE PLANNED IN TERMS OF THEIR EFFECTS

It is fair to say that modern cognitive psychology has put much more emphasis on the receptive than on the productive side of human behavior (e.g., Rosenbaum, 1991)—presumably a swing-back reaction to behaviorism. Indeed, almost any cognitive psychology textbook covers the topics of perception, attention, memory, reasoning, and decision making (almost always in that very order), while the issue of how all these processes are transformed into coherent, goal-directed action is commonly neglected altogether or dealt with in passing. Implicitly, action is often seen as a consequence of, and as actually caused by stimulus processing (Prinz, 1997), as obvious from the standard information-processing model depicted in Figure 1: Action is conceived of as a stimulus-induced re-action, even though filtered and constrained by internal, cognitive processes. In a sense, acting is just another, rather late step of stimulus processing. Unfortunately, however, this view does not capture the goal-directed nature of intentional action, as the following example illustrates.

************ Figure 1 ************

A case example

Take a typical experimental reaction-time task as sketched in Figure 2. The example task requires a speeded press of a left versus right key in response to a low or high tone, respectively (the lights come into play only later). As the mapping of tone pitch to response location is arbitrary, performing the task presupposes some instruction and some kind of maintenance of the instructed stimulus-response mapping rules (low? left, high? right) in working memory. With respect to the model shown in Figure 1 this means that the transition from stimulus identification to response selection is mediated by working memory, which can be thought of as “containing” the mapping rules (e.g., Anderson, 1983).

If this were the whole story, any stimulus-response mapping should yield equally good performance, provided that the number of rules (and, thus, the required capacity) is held constant. However, this is not what experimental evidence shows. What it does show, instead, is that performance is sensitive to the similarity between stimuli and responses, so that mapping a left response onto a left stimulus and a right response onto a right stimulus produces considerably faster reactions and fewer errors than mapping a right response onto a left stimulus and a left response onto a right stimulus (e.g., Broadbent & Gregory, 1962). This benefit of stimulus-response feature overlap affects performance even if the overlap is task-irrelevant. With regard to our example this means that responses will be faster to stimuli that spatially correspond (as in the left panel of Figure 2) than to stimuli that do not (as in the right panel)—the so-called *Simon effect* (Simon & Rudell, 1967; for an overview, see Lu & Proctor, 1995).

Apparently, then, the translation of stimulus information into responses does not strictly obey to the task-defining mapping rules but is also affected by background knowledge and hard-wired or overlearned stimulus-response routines. This insight has led to the formulation of dual-route models of information processing, in which response tendencies can be triggered by both intentionally applied mapping rules and long-term associations between stimulus and response codes (De Jong, Liang, & Lauber, 1994; Hommel, 1993; Kornblum, Hasbroucq, & Osman, 1990). The general idea underlying these models is built into our processing model in Figure 1, where two pathways lead from stimulus to response processing, one supported by short-term requirements and another by long-term procedural knowledge.

************ Figure 2 ************

Processing models of this sort have been quite successful in accounting for a wide range of observations and phenomena, and in generating new predictions in many fields of cognitive psychology. Indeed, one or another variant of such models can be found in almost any introductory textbook—and predecessors were with us from the beginnings of experimental psychology (Ach, 1910). And yet, they do not tell us much of interest about how an intentional action is actually planned. Indeed, planning is confined to a single, not further specified process: the implementation of mapping rules into working memory. What is lacking, however, is any consideration of the role intentions and goals play in the planning process, possibly a reflection of the fact that in experimental tasks goals are commonly externally defined by the instruction given to the subjects.

But goals do have an effect, as can be demonstrated by means of a slight modification of the standard Simon task. Consider, again, the task depicted in Figure 2, but assume that each key is connected with a light source on the opposite side. Thus, pressing the left key switches on a light on the right side, while pressing the right key flashes a light on the left side. If one describes the task goal as “pressing the left (right) key in response to a low (high) tone” the result is a normal Simon effect, that is, people are faster to press the left key if the tone appears on the left than on the right side, and vice versa (Hommel, 1993, Exp. 1: key condition). Hence, subjects find the situation depicted in the left panel of Figure 2 easier than that shown in the right panel. However, consider the very same task is described differently, namely as “switching on the right (left) light in response to a low (high) tone”. In this case, people are much faster to press the left key if the tone appears on the right than on the left side, and vice versa (Hommel, 1993, Exp. 1: light condition). That is, they prefer the situation shown in the right panel of Figure 2.

This observation shows that the way a task and the stimulus-response rules it comprises are planned depends on the goal the actor has in mind. Apparently, this goal determines how responses are cognitively coded and represented, that is, what those responses mean and what effects they produce. If it is “pressing a key” that is intended the response is coded in terms of the location of the key and/or the finger performing the press, so that a stimulus sharing this feature facilitates selecting it. However, if it is “flashing a light” that is intended the very same response is coded in terms of the location of the light the finger movements affects. In other words, responses are coded and selected in terms of the intended effects they produce (Hommel, 1996, 1997).

Ideomotor approaches to action

The emphasis on action effects in action control echoes the ideomotor approaches of Lotze (1852), Harless (1862), and James (1890). Deeply rooted in the introspective tradition of theorizing, these authors found it rather natural to think of actions set up by personal intentions, not as evoked by instructed target stimuli. Accordingly, the theoretical problem they had to deal with consisted of the question of how motor patterns can be brought under intentional control, an issue commonly not addressed by information-processing models. The answer they proposed is sketched in Figure 3. Without any experience with one’s own body and, its possible artificial extensions, there is no connection between the content of the cognitive system and the motor system responsible for executing movements. However, performing (at first, mostly random) movements produces specific effects that can be, and are perceived and cognitively coded. Due to an (presumably rather primitive) associative mechanism the motor codes that just produced a given movement and the cognitive codes that represent the movement’s perceptual consequences get connected, so that a kind of cross-domain, sensory-motor structure emerges (Figure 3, left panel). Once such a structure is acquired it can be used either way, which means that the individual has acquired a “mental cue” (to use the words of James) to access motor patterns to achieve intended goals. From now on the previously involuntarily experienced movement effects can be produced intentionally by activating the codes of these effects, which then spread their activation to the associated motor codes. In other words, actions are planned by (literally) anticipating their effects.

************ Figure 3 ************

Probably because they fit so nicely with the phenomenal experience of an acting individual, ideomotor approaches to action control were almost common wisdom during the heyday of introspective psychology (see overviews by Greenwald, 1970; Prinz, 1987; Scheerer, 1984) but were almost forgotten thereafter, even "officially" discredited by both behaviorists (Thorndike, 1913) and early information-processing theorists (Miller, Galanter, & Pribram, 1960). This does not mean that action effects would not have played an important role in explaining the acquisition of action control. However, this role was commonly confined to providing information about an action's success or failure, as in closed-loop models of motor-skill learning (Adams, 1971; Schmidt, 1975), but did not capture the function of a mental cue used in action planning as considered in ideomotor approaches (Hommel, 1998a). And yet, ideomotor concepts have seen a renaissance in the last decade or so, and empirical evidence in their support is steadily increasing. Interestingly, this support comes from four different, but converging lines of investigation: the study of acquired, remote action effects, studies on the development of action planning, the discovery of so-called "mirror neurons", and the investigation of somatic markers.

Remote action effects

The ideomotor approach of James (1890) distinguishes between "natural" sensory effects of a movement and more remote effects. In some cases such a distinction is very clear and easy to draw, such as with switching a room light on. Performing that action produces all sorts of feedback from the hand and finger movements involved but it also changes the visual conditions in another, more remote part of the room, and in some sense one may even tend to see the former to cause the latter. In other cases, however, the distinction is less clear, such as when steering a bike or dancing with a partner. Indeed, it is quite often difficult to say exactly where one's own body ends and one's tool or one's physical or social environment begins; indeed, subjects have a hard time to tell whether an observed movement is performed by their own hand or the hand of an otherwise invisible confederate (Daprati et al., 1997). From a developmental standpoint the distinction between more and less natural action effects is even more obsolete. After all, if the ideomotor approach is correct in assuming that infants first need to learn what effects their movements have, the only thing that should count is the contingency between movement and effect but not the sensory channel registering the effect or whether the effect is more proximal or distal (Hommel, 1997, 1998a; Wolff, 1987).

Giving up the conceptual distinction between body-related and remote action effects opens the door for a wide range of empirical investigations, simply because external, remote effects can be much better experimentally manipulated than proximal, body-related effects. Indeed, manipulating the latter would require blocking of one or more sensory channels, a rather dramatic intrusion, or studying human patients or animals that suffer from the loss of one or more channels, problems which often come with other deficits of unpredictable impact (e.g., Aschersleben, Stenneken, Cole, & Prinz, 2002). Working with remote action effects is much easier and has shown to yield promising results. The probably first study to demonstrate the role of remote action-produced events in human action planning, the one of Hommel (1993), was introduced above already. As described above and shown in Figure 2, responses were consistently followed by light flashes in the opposite location. The fact that performance depended on the instructions given to the subjects—with the stimulus facilitating actions with spatially corresponding goals—has two implications: First, subjects apparently associated their responses with the remote effects and, second, they somehow made use of these associations when selecting the responses.

************ Figure 4 ************

The observation that action-effect associations are used for selecting intended actions is consistent with the ideomotor approach, but it covers only part of its predictions. What remains to be shown is that such associations are established automatically, a prediction that can only be tested if subjects are not instructed to attend to the novel action effects or rewarded for using them. To provide such a test, Hommel (1996) had subjects run through two different experimental phases, which were designed to mirror the natural sequence of acquisition and use of action-effect associations, respectively. In the first, acquisition phase subjects were to press a response button once or twice, as signaled by a visual stimulus. The two actions produced different auditory effects so that, for instance, a single keypress would result in a low- and a double press in a high-pitched tone (see Figure 4, left panel). Subjects were told that there would be tones sounding but it was pointed out that these would not be important or informative in any sense and that they should be ignored. Nevertheless, it was expected that subjects would acquire associations between the cognitive tone representations and the actions the tones accompanied. This was tested in the second, test phase by presenting randomly chosen low- or high-pitched tones together with the visual stimulus (see right panel). Again, it was pointed out that these tones were not informative and could safely be ignored. However, if tones and actions really became associated in the acquisition phase, presenting a tone should prime (i.e., pre-activate) the associated action, thereby facilitating performance if the primed action is to be carried out (upper part of right panel) and impairing it if the other, alternative response is actually required (lower part). Indeed, this was observed in a series of experiments with varying stimuli, responses, and action effects, suggesting that events that accompany particular responses are really picked up and integrated with those responses in an automatic fashion.

A recent study of Elsner and Hommel (2001) shows that action-effect associations cannot only affect the speed of response selection but also its outcome. In the acquisition phase their subjects were also presented with response-contingent tones much like sketched in the left part of Figure 4. In the test phase, however, subjects performed free-choice reactions to low- and high-pitched tones. The question of interest was not how quickly people react under these conditions but whether they tend to select and carry out the response that is "suggested" by the acquired action effect. If so, we had direct evidence for the notion that action-effect representations play a crucial role in action planning. Indeed, Elsner and Hommel observed a pronounced tendency to perform actions that previously produced the tone that now appeared as stimulus. Importantly, this tendency remained unchanged in size and direction when the free-choice task was carried out under heavy mental load induced by a secondary task, which rules out any strategic use of action-effect associations. A follow-up study combining Elsner and Hommel's task with positron electron tomography (PET) revealed that this effect-induced action tendency is directly reflected in the activation of neural assemblies in the supplementary motor area (Elsner et al., 2002), which is known to play a central role in action planning (Decety et al., 1994).

Converging evidence for the use of action-effect codes comes from a recent study of Kunde (2001). He used a four-alternative choice-reaction time task, in which each of two effect tones was mapped onto two responses (4:2 mapping). In each trial, one response was precued, i.e., it was indicated which response would be the most likely in this trial. As one would expect, valid cues facilitated performance, that is, subjects performed much better if the precued response was actually asked for than if another response was required. However, performance in these latter conditions depended on the action effects. Although responses were slowed, the slowing was reduced if the required response shared its effect tone with the precued, prepared response. Apparently, then, preparing a response was associated with activating the acquired effect-tone code, which then also primed the other response associated with it.

Development of action planning

An important implication of the idea that actions are planned in terms of their effects is that intentional planning presupposes and, thus, follows the acquisition of movement-related consequences. As discussed in the previous section, this hypothesized sequence can be successfully simulated in adults by confronting them with novel, arbitrary response-contingent events. But it is as interesting to see whether comparable, or at least consistent evidence can be found in the cognitive development of infants and children. Indeed, there are indications that bilateral response-effect associations are formed from the first months of age on, whereas the development of action-planning abilities is much slower and much more extended in time.

To investigate the acquisition of response-effect associations, Watson and Ramey (1972) hung rotating "contingency mobiles" over the cribs of 2-months-old infants. If the mobile's movement was contingent on the pressure the infant exerted on his/her pillow, pillow responses were more frequent than if the mobile moved noncontingently, or not at all. Comparable results were observed by Rovee and colleagues (Rovee & Rovee, 1969; Fagen & Rovee, 1976), who had only slightly older infants manipulate mobile movements by means of strings attached to their feet. Interestingly, infants showed mobile-related behavior even after retention delays of two days or longer (Butler & Rovee-Collier, 1989; Fagen, Rovee-Collier & Kaplan, 1976). Thus, perceived action effects do not just motivate infants to show the critical behavior more often but their representations become integrated with the behavior they accompany. Using a different method Rochat and Striano (1999) found increased sucking behavior in 2-months-olds if the pressure the infant applied to his or her pacifier systematically modified the pitch of a tone. Likewise, Kalnins and Bruner (1973) report that even 5- to 12-week-old infants adapt their sucking behavior if that increases the optical clarity of a film presented to them.

These findings show that infants can pick up movement-effect relationships very soon after birth and just a little experience is sufficient for the acquisition of relatively durable memory traces. However, it takes much longer to learn how to make efficient use of these traces, that is, to plan goal-directed actions. Sure enough, some degree of action control will develop during the first months, the most obvious being saccadic eye-movements. And yet, most action-related executive functions emerge at considerably higher age, as does the organization of brain structures presumably mediating those functions. There is evidence for at least two major steps in the development of action control.

The first step can be roughly located around 7-10 months of age. During that time, infants exhibit considerable improvement with regard inhibiting counter-productive grasp and withdrawal reflexes (Diamond, 1990), ignoring alternative goals (Diamond & Gilbert, 1989), and suppressing inefficient strategies (Diamond, 1990) during goal-directed reaching. There is also evidence for the improvement of action-related working-memory or task-set functions, such as needed in Piaget's A-not-B task. In this task, subjects are first rewarded for reacting towards an object hidden in location A. Then the object is placed in A again and then visibly moved to B, an adjacent location. A common finding is that infants (Gretch & Landers, 1971; Fox, Kagan & Weiskopf, 1979) and monkeys with lesions in the dorsolateral prefrontal cortex (Diamond & Goldman-Rakic, 1986) have considerable problems with this task, the more so the longer the delay between hiding the object in B and the response. However, infants show dramatic improvements between 7 and 12 months, with an increase of the tolerated delay from one to about 10 seconds (Diamond, 1985). The basis for these developmental trends is not clear; they may be related to the observation that metabolic activity in the frontal cortex lags behind other cortical areas and approaches adult values not before 8-12 months of age (Chugani & Phelps, 1986; Chugani, 1994).

A second major step in the development of action control seems to take place at about 5-6 years of age. There are several indications suggesting considerable gains in the ability to inhibit prepotent responses around that time. Children of 4 years or younger are unable to wait for a more preferred or bigger reward in the presence of a less preferred or smaller, but immediately available reward, whereas children of 5-6 years commonly manage to wait (Mischel & Mischel, 1983). Likewise, children of 3-4 years often fail to inhibit their responses in no-go trials of go/no-go tasks, whereas 5-6 year-olds have little problem (Bell & Livesey, 1985; Livesey & Morgan, 1991). A similar observation was made by Luria (1959, 1961). He reported that preschool children were able to squeeze a bulb in response to a light flash, but they failed to refrain from squeezing when the light was extinguished, even though they did recall and understand their instructions to do so. Even more interesting in the present context, children of 5 years or older show strong improvements with regard to the ability to switch between S-R rules and to perform stimulus-incompatible actions. If children of 2.5-3 years are asked to sort drawings according to one criterion and then to switch to another they often fail and show perseverance of the old sorting rule—even though they have no difficulty remembering and verbalizing the new, correct rule (Zelazo, Reznick & Piñon, 1995). Failures of young children in inhibiting inappropriate but stimulus-compatible responses have been reported by Diamond and colleagues. Gerstadt, Hong, and Diamond (1994) asked children between 3.5 and 7 years of age to perform a Stroop-like task that required saying "day" in response to a card showing a moon and stars, and saying "night" to a card showing a bright sun. While children younger than 5 performed close to chance, performance of the older children improved dramatically and approached that of the oldest age group. In a very similar task, Diamond and Taylor (1996) asked 3.5-7-year-olds to perform Luria's tapping task, which requires tapping once when the experimenter taps twice, and vice versa. Again, children younger than 5 performed badly, while 6-year-olds reached accuracy of 95% already.

Even though the detailed mechanisms underlying this developmental leap are not yet unravelled, there is consensus that the (slow) maturation of the frontal cortex plays a major role (e.g., Diamond, 1990; Fuster, 1989; Johnson, 1999; Shallice & Burgess, 1998). Indeed, patients with frontal-lobe damage tend to exhibit very similar executive deficits as children younger than 5-6 in having difficulties to suppress stimulus-induced or stimulus-compatible actions in Stroop-like tasks (Drewe, 1975; Luria, 1966; Perret, 1974), spatial-compatibility tasks (Décary & Richer, 1995), or everyday life (L'Hermitte, 1983). In view of the fact that the frontal cortex shows the longest period of development of any brain region (Chugani & Phelps, 1986; Huttenlocher, 1990), this suggests that executive functions mature relatively late in ontogenesis. Thus, the ability to acquire action-effect associations does indeed seem to precede the capacity to make intentional use of them.

Mirror neurons

According to the ideomotor approach to action planning we learn to master our actions by means of self-observation. That is, we move, observe ourselves while moving, and thereby connect the codes of what we do (i.e., motor patterns) with the codes of what we perceive (i.e., action effects). As argued above this mechanism should work independent of whether the observed action effects are proximal, body-related sensations or distal, remote events, and I have already discussed evidence supporting this assumption. Moreover, there is evidence that perceiving action effects tends to prime the corresponding action, which is in agreement with the idea of a close coupling of perceptual and motor codes. Such a view opens an interesting possibility with respect to the effect of social perception: Observing the behavior of others should tend to invoke comparable behavior in the observer, just as implied by the old idea of “behavioral contagion” and empathy (e.g., McDougall, 1908/1923).

Recent neurophysiological findings provide strong support for the assumption of integrated perception-action codes. Di Pellegrino, Fadiga, Fogassi, and Rizzolatti (1992) measured single-cell activity in the rostral part of the inferior premotor cortex of a macaque monkey while he was either performing particular goal-directed actions himself or watching an experimenter doing so. It turned out that the same cells were active in both cases. Control experiments showed that very specific conditions need to be met to trigger the firing of these so-called “mirror neurons”. They only (or at least most strongly) react to the experience of interactions of an agent and a goal object, but are insensitive to either objects alone or object-less pantomimes (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996).

More recently, progress has been made in extending these insights to humans. Interestingly, watching actions activates the human homologue of that part of the macaque brain where the mirror neurons were detected (Grafton, Arbib, Fadiga & Rizzolatti, 1996). And these structures also seem to share their functional characteristics, especially the sensitivity to goal-directed, meaningful action. That is, human subjects show premotor activity while watching a familiar, purposeful action but not when facing a novel, meaningless movement (Decety et al., 1997). Indeed, this is what the ideomotor account would lead one to expect, as only familiar actions should be represented by integrated clusters of perceptual and motor codes. Once an action is acquired, observing it primes the same muscle groups that one would use to carry it out oneself (Fadiga, Fogassi, Pavesi & Rizzolatti, 1995).

The discovery of mirror neurons had and still has a huge impact on many fields of cognitive psychology and the cognitive neurosciences. Indeed, it provides a source of inspiration for all sorts of speculations on the basis of empathy, human sociability, imitational skills, or the origin of language, the validity of which needs to be carefully investigated. What is clear, however, is that they (or their human homologues) are ideal neural examples of integrated structures connecting perceived action effects and the motor patterns producing them, and therefore prime candidates to mediate effect-based action planning.

Somatic markers

Human decision-making is influenced by many factors, such as background knowledge, logical reasoning, situational biases, and emotions. However, not all of those factors are equally appreciated by experts and advisors on skilled decision-making, or researchers investigating the decision process. Indeed, it seemed obvious for centuries that cognitive, rational contributions are much more helpful in reaching an appropriate decision than emotions and personal preferences. And yet, this widely shared view came under increasingly heavy attacks in the recent years. There are both logical and empirical arguments challenging the superiority of cognitively based decisions.

For one, cognitive processes, and especially the integration of all relevant knowledge, have been argued to take too long under many circumstances in everyday life, so that some kind of short-cutting full-fledged reasoning is often essential for efficient action (Gigerenzer & Goldstein, 1996). Moreover, there are many simple, “fast-and-frugal” heuristics available that do not only allow for much faster decisions but that also provide solutions the quality of which can be surprisingly high. For instance, if asked to judge which of two cities has more inhabitants (e.g., San Antonio or San Diego) people often prefer the city the name of which sounds or is more familiar to them—with rather good success (Goldstein & Gigerenzer, 1999). That is, reasonable decisions need not be, and often actually are not based on exhaustive reasoning.

The same line of thought has led Damasio (1994) and his colleagues to postulate a guiding role of emotions in decision-making. In a nutshell, he assumes that performing actions produces positive or negative somatic states, which then become associated with the actions' representations. If so, people can retrieve the somatic markers of possible actions when making their mind up which one to perform. That is, they can anticipate which somatic states each action would create and base their decision on this quickly available "gut feeling". Damasio assumes that a whole neural network is responsible for acquiring and using the hypothesized links between actions and somatic markers, with the interaction of the pre-frontal cortex and the amygdala playing a major role (e.g., Damasio, Tranel & Damasio, 1991). Accordingly, Damasio's approach predicts a breakdown of efficient decision-making in case of lesions or disorders in pre-frontal brain areas. Indeed, the approach was originally motivated by an attempt to make sense of the sad story of Phineas Gage, a previously likable railroad worker whose personal and social decline began when an explosion drilled an iron rod into his forebrain (Damasio, 1994). The hypothesis that efficient decision making is based, and perhaps even depending on pre-frontally mediated associations between actions and somatic markers finds support in a number of observations.

First, patients suffering from lesions in the ventromedial part of their frontal cortex perform particularly badly in experimental card-drawing games with complicated contingencies between the deck the cards were drawn from and financial gains and losses. Bechara, Damasio, Damasio, and Anderson (1994) had frontal patients, patients without frontal lesions, and healthy controls play such a game. There were two advantageous card decks, with small gains but few losses, and two disadvantageous decks, with high gains but frequent losses, to draw from. All three groups would start drawing randomly from all four decks. However, whereas non-frontal patients and controls then gradually started to prefer the more advantageous decks, frontal patients continued to frequently draw cards from the disadvantageous deck, suggesting that they did not realize the overall loss. In fact, they lost their entire game budget and needed to take loans.

Second, taking an unfavorable decision seems to be accompanied by particular emotional states, indeed, at least in individuals with intact frontal lobes. This is suggested by findings of Bechara, Tranel, Damasio, and Damasio (1996), who measured galvanic skin conductance responses (GSCRs) of frontal patients and healthy controls while playing the card-drawing game. Of particular interest were the GSCRs during the decision interval, hence, the few seconds before a card was drawn. Whenever, they were about to draw from the disadvantageous deck controls exhibited increases in GSCR (i.e., sweated more), and they did more the more experience they had. Not so frontal patients, who showed comparable, non-increasing GSCRs before drawing from "good" and "bad" decks. That is, an intact frontal lobe seems to enable people to emotionally anticipate loss, and it is not unreasonable to assume that it is this ability that underlies good performance in the card-drawing game.

Although developed on a more motivational than cognitive background, it is interesting to note that the somatic-marker account follows the same line of thought than the ideomotor approach: On both accounts people acquire information about the consequences of their actions and use anticipations of these consequences to select appropriate actions. Indeed, there is empirical evidence suggesting that the mechanisms underlying the integration of perceptual and emotional action effects are at least comparable. Beckers, De Houwer, and Eelen (2002) used basically the same paradigm as Hommel (1996) and Elsner and Hommel (2001). In an acquisition phase, subjects performed binary-choice responses to the grammatical category of neutral words. One response was consistently followed by a mild electroshock, that is, accompanied by an unpleasant action effect. In the following test phase, the stimulus words were chosen to possess positive or negative emotional valence. As expected, subjects performed better when the valence of the stimulus matched the pleasantness of the response, that is, negative words were responded to more quickly with the response followed by a shock, and the opposite was true for positive words. Apparently, then, the actions acquired the emotional valence of their consequences.

A similar conclusion is suggested by findings of Van der Goten, Lammertyn, Caessens, De Vooght, and Hommel (submitted), who had subjects perform two overlapping keypressing tasks. The two responses in the secondary task triggered the presentation of a smiley or a grumpy, respectively. Results show that preparing smiley-producing responses facilitated the processing of emotionally positive words in the primary task, while preparing grumpy-producing responses primed words with a negative valence. That is, the responses must have been integrated with the emotional valence of their effects, thereby emotionally “marking” them.

To summarize, there is strong, increasing evidence that actions are planned in terms of their effects. In particular, perceived and felt effects of movements are acquired in a presumably automatic fashion and from infancy on, and they become integrated with the motor patterns that evoke (or at least accompany) them. Complex neural networks have been suggested to underlie the integration of actions and consequences, with the prefrontal and premotor cortices playing a central role.

ACTION PLANS ARE INTEGRATED ASSEMBLIES

Human action planning has often been likened to writing and compiling a computer program, that is, to creating an ordered list of instructions that is later read out by the motor machinery (e.g., Miller et al., 1960). Indeed, most work on planning-related issues in the artificial intelligence domain has implicitly or explicitly employed this interpretation of the planning term. With regard to long-term projects like writing a book or raising one’s children this is certainly a reasonable approach that is likely to capture the essence of the presumably rather abstract cognitive representations involved. However, it is important to see that such high-level descriptions only solve part of the problem, which makes them an unlikely candidate if it comes to more concrete planning processes as discussed in this chapter. True, instruction lists do solve the sequencing part of the planning problem by specifying the necessary steps in the order in which they need to be carried out. But how the symbols specifying a given step are actually translated into “motor language”, that is, how the planning symbols are “grounded” (Harnad, 1990) remains a mystery.

In contrast to symbolic accounts ideomotor approaches provide an obvious solution to this translation or grounding problem. It is assumed that with increasing experience more and more motor patterns become connected with cognitive “cues” or “markers”, which makes them available to planning processes. On this view, concrete planning consists of anticipating the features of the intended action goal, which means priming the corresponding cognitive codes. As these codes are associated with the motor patterns producing them, activation will spread to the motor system where the required movements are then ready to go. If we would only be busy with one plan and one action at a time, this sketch would be perfectly plausible and it may therefore well capture the planning processes going on under such circumstances. Unfortunately, however, these circumstances are rare. Typically, the action plans we have prepared strongly overlap in time and we often carry out more than one plan concurrently, such as when talking while walking or driving. This overlap of plans creates what is commonly called a “binding problem”.

The binding problem in action planning

Concurrently held and carried out action plans introduce a serious problem that symbolic accounts commonly overlook. Consider the left panel of Figure 5, which sketches the way the cognitive codes of the intended goal translate into motor activity. Now consider the situation that two plans are maintained and/or translated into behavior at about the same time, as depicted in the right panel. Note that on both the cognitive and the motor level there is no way to tell members of one plan from members of the other—there is just a bunch of codes being active. Given the representational structure of the human brain this is a real problem.

************ Figure 5 ************

Indeed, there is converging evidence that the primate brain uses different neural populations in various cortical areas to represent and control different features of an action. For instance, distinct cell assemblies have been shown to code the direction (Alexander & Crutcher, 1990; Georgopoulos, 1990), force (Kalaska & Hyde, 1985), and distance (Riehle & Requin, 1989) of arm movements in monkeys. Likewise, human subjects exhibit different electrophysiological brain patterns (so-called Bereitschaftspotentials, Deecke, Grozinger & Kornhuber, 1976) depending on the duration (Vidal, Bonnet & Macar, 1991) and force (Bonnet & MacKay, 1989; Kutas & Donchin, 1980) of a planned action, and on the to-be-used hand (Osman, Bashore, Coles, Donchin & Meyer, 1992). These observations suggest that action planning involves the coordination of multiple codes distributed across a wide range of brain areas. In fact, even in the rhesus monkey preparing an action activates a whole neural network including the posterior parietal cortex, the premotor cortex, and the primary motor cortex (Requin, Lecas & Vitton, 1990). Correspondingly, a simple grasping movement activates the superior parietal cortex, the premotor cortex, the basal ganglia, and the cerebellum of the human brain, as studies with PET have revealed (Rizzolatti et al., 1996).

Given this preference of brains to represent action plans in a distributed fashion the question arises of how they are able to coordinate all the elements belonging to a given plan. And, even more pressing, we need to ask how brains can distinguish between the elements belonging to one plan and those that belong to another, concurrently maintained plan—the so-called "binding problem" sketched in Figure 5. Let us now consider how this problem might be solved and what the cognitive implications of the solution are.

Integration of action features

Logically, there are at least two possibilities to deal with binding problems, hierarchical command structures and coordinative structures (see Singer, 1994). The first solution presupposes a strictly hierarchical representation of action elements, much like in an army. Thus, there is a command neuron or neural assembly that governs a subordinate layer of elements, which again may rule another, even more subordinate layer, and so forth. A given action plan would therefore be defined and coordinated by its chief, so to speak, which is directly responsible for its immediate subordinates and indirectly responsible for lower layers. The problem with this view is that such types of structures were very vulnerable to cell loss and dysfunction, especially if their “chiefs” are concerned. Moreover, one would need to assume a distinct command neuron or assembly for each possible course of action, a not overly parsimonious solution in particular if one thinks of action sequences.

An alternative solution would be to somehow “tag” or “mark” all the elements belonging to a particular plan, so that all plan members would share the same tag. According to the current state of the discussion the prime candidate to represent such a tag is the temporal behavior of cells. That is, the firing of neurons or networks of neurons belonging to the same action plan may become synchronized, so that the integrated elements are rhythmically coupled (Abeles, 1991; Singer, 1994; Von der Malsburg, 1995).

Indeed, experimental animal data has been accumulated over the last decade supporting the view that temporal synchronization serves as a neural mechanism to functionally link neurons within and between cortical areas and subcortical structures (for reviews see MacKay, 1997; Singer, 1994). Most of these studies have investigated the role of synchronization in visual feature binding, but there is also evidence for some role in action control. For instance, action-contingent synchronization of cell groups has been observed in the motor cortex of monkeys (Sanes & Donoghue, 1993), between motor and somatosensory areas of the monkey (Murthy & Fetz, 1992, 1996), and across the visual and parietal cortex and the parietal and the motor cortex of the cat (Roelfsema et al., 1997).

In humans, the presence and functional significance of neuronal synchronization has been investigated mainly by using electroencephalography (EEG) and magnetoencephalography (MEG). Most importantly, recent studies provide evidence for a relation between the temporal coherence among cell assemblies and the planning and initiation of action. For instance, Pfurtscheller et al. (1994) and Salenius et al. (1996) observed that the onset of gamma oscillations in the primary motor cortex is time-locked to the initiation of finger, toe, and tongue movements. But synchronization may also mediate the coupling of primary motor cortex and spinal motor neuron pool, that is, the transfer of action plans to the periphery. Indeed, significant coherence can be observed between EEG/MEG signals from the primary motor cortex and the rectified EMG of various muscles (for review see Hari & Salenius, 1999). Thus, there is evidence that the cortically distributed neural elements that make up an action plan are integrated by coordinating their temporal behavior, thereby “tagging” all the ingredients belonging to the same plan.

Occupation of feature codes

The integration of action features into coherent action plans has a couple consequences. Most of them are, of course, positive in unequivocally marking each feature code and, thereby, allowing for the concurrent maintenance of multiple plans. Given that feature codes are also open to, and affected by perceptual information (see above) there are even more positive implications that will be discussed in the following section. However, there are also drawbacks. Ironically, it was these drawbacks that turned out to be particularly diagnostic in experimental analyses of the integration process.

************ Figure 6 ************

Assume, for instance, some action plan *A* is created and the relevant action-feature codes are integrated, as indicated on the left side of Figure 6. Now assume that the given individual is willing to create another plan *B* before carrying out A. If there is no overlap in features between the two plans there is no obvious hindrance for that, apart from possible (and likely) capacity limitations of the cognitive system with respect to the number of plans to be concurrently entertained (cf., Raffone & Wolters, 2001). However, consider the situation if there is some feature overlap. For instance, the two planned actions may be intended to be performed with the same effector, the right hand, say. If so, the features RIGHT and HAND should have been integrated into plan A already, so that they are less available for, i.e., more difficult to integrate into plan B. Thus, feature overlap between an already created and a to-be-created action plan should impair forming the latter, because the overlapping feature codes are, in some sense, occupied by the former (Stoet & Hommel, 1999).

Indeed, there are a number of findings that support this rather counter-intuitive prediction. A first hint comes from studies on verbal planning by Meyer, Gordon and colleagues (Meyer & Gordon, 1985; Yaniv, Meyer, Gordon, Huff & Sevald, 1990). They had subjects prepare one of two utterances, such as the syllable “up”, and to utter it as soon as a go signal appeared. In some trials, however, another signal would appear and call for the alternative utterance, the idea being that the corresponding delay of reaction time reflects the amount of the re-planning required. Interestingly, the delay increased with the similarity between the prepared and the eventually uttered syllable. For instance, switching from one voiced to another voiced syllable (up ? ut) took more time than switching from an unvoiced to a voiced syllable (ub ? ut), as if binding the feature VOICED to a syllable would somehow block access to this feature by another utterance.

A similar observation was made by Rosenbaum, Weber, Hazelett, and Hindorff (1986). They had subjects recite letter strings of different length with alternating stress (e.g., AbCdAbCd...). Curiously, strings of an uneven number of letters were more difficult to perform than strings with even numbers, irrespective of the overall length. For instance, subjects found it harder to perform the string AbCaBc... than AbCdAbCd…. Again, it seems that integrating a particular letter with the feature STRESSED or UNSTRESSED interferes with (re-) combining it with another feature.

Even stronger evidence for code-occupation effects comes from a recent study by Stoet and Hommel (1999). They used an ABBA design, in which subjects were asked to create an action plan A, then to create and carry out another plan B, before eventually performing the planned action A after B was completed. In some trials there was a feature overlap between the two plans, such as if subjects carried out a simple movement with the index finger of their left (or right) hand while holding in mind a plan of a more complex action with the same hand. In other trials the two plans did not overlap, such as when the finger movement and the more complex action were carried out with different hands. Results showed that feature overlap impaired performance, so that moving the left-hand index finger, say, was slowed-down by holding in mind an action plan referring to the same as compared to a different hand. Again, it seems that considering a particular feature in creating an action plan occupies the corresponding cognitive code of that feature. Interestingly, Stoet and Hommel (1999) found competition between plans even if the two actions were carried out with different effectors sharing egocentric location only, that is, planning to perform an action with the left hand impaired responses with the left foot. This suggests that occupied action features need not refer to an effector but apparently can be of any kind.

In the previous section I have argued that actions are planned in terms of their perceptual effects and that the medium of those planning activities are acquired perceptuo-motor structures (see Figure 3). Accordingly, what is integrated and what gets bound in the process of creating an action plan is actually not a single motor code but a perceptuo-motor assembly, so that an action plan is actually an integrated assembly of (previously) integrated assemblies. As the latter are perceptuo-motor structures they have a dual function in both controlling a particular action feature (i.e., making sure that the planned action possesses the corresponding feature) and registering perceptual information about that feature (see section on mirror neurons). Hence, these structures mediate both the production and the perception of the feature they represent (Hommel, Müsseler, Aschersleben, & Prinz, 2001a, 2001b).

A particularly provocative prediction from this view is that planning an action should actually affect the perception of a feature-overlapping event the same way as it affects the planning of a feature-overlapping action. For instance, creating the plan to perform a left-hand action should interfere with perceiving a “left” event. To test this prediction, Müsseler and Hommel (1997a) had subjects prepare a left or right keypressing action and perform it at leisure. However, before pressing the intended key subjects were asked to “signal” the upcoming response by means of a double keypress, which served as an indicator of when subjects had completed action planning. This double press triggered the brief presentation of a pattern-masked left- or right-pointing arrow, the direction of which was to be indicated at leisure at the end of the trial. Hence, subjects were presented with a “left” or “right” stimulus while maintaining a feature-overlapping or not overlapping action plan. As predicted, arrow perception was drastically affected by action planning: The accuracy of reporting a left- or right-pointing arrow was much lower if the arrow appeared while maintaining a feature-overlapping action plan than if arrow direction and keypress location did not correspond. In a follow-up study, Müsseler and Hommel (1997b) even found the detection of stimuli to be impaired by planning a feature-overlapping action. Thus, creating an action plan does not only occupy codes needed to plan other feature-overlapping actions, but also codes that mediate the perception of feature-overlapping events. This provides strong support for the idea that action plans are integrated assemblies of sensorimotor structures.

ACTION PLANNING CREATES A PREPARED REFLEX

Having discussed the *how* of action planning let us now turn to the *when*. In information-processing models of human performance planning an action is commonly equated with selecting a response. Accordingly, the time point of planning is often assumed to follow the perception of action-relevant situational circumstances, that is, after the left part of the model shown in Figure 1 has been run through. Indeed, we sometimes do encounter situations in which we first realize a particular action opportunity, then make up our mind how to proceed, and eventually perform the apparently most appropriate action—shopping would be an example.

And yet, most situations do not really fit this example, not even in laboratory experiments. Commonly, we have planned how to react long before the relevant stimulus conditions occur, as Sigmund Exner noted in 1879 already. In his chapter on attention he mentions the example of a speeded hand movement that he carried out in response to a visual stimulus. Exner noticed that long before the stimulus came up, he had already set himself into some kind of state that ensured that the response would be carried out as intended. Evoking that state, he considered, must be a voluntary, attentional act. However, once the state was created he felt that the eventual response became involuntary in the sense that no further effort of will was needed to perform it. In a way, Exner concluded, the cognitive system works like a prepared reflex (see Hommel, 2000).

Exner was not the only one to challenge the seemingly self-evident notion that the will intervenes between stimulus processing and response execution. In a series of reaction time experiments, Münsterberg (1889) found evidence that even with unpracticed stimulus-response pairs motor responses are often initiated long before their trigger stimulus is completely identified and consciously perceived. This made him doubt that stimulus-response translation depends on a mediating decision or act of will—a position nicely supported by recent investigations of Neumann and Klotz (1994), Eimer and Schlaghecken (1998), and others. Similar considerations were put forward by Marbe (1901) and his Würzburg colleagues from a more phenomenological perspective. To study acts of response-related decision, Marbe had his subjects respond to all sorts of questions, ranging from weight judgments to arithmetic problems. However, when he asked them to describe the processes that intervene between hearing the question and giving the response, the answers were not very informative: some description of the stimulus or the response, but nothing that would refer to a decision. Among other things, it was this outcome that led adherents of the then-evolving Würzburg school to believe that task instructions are transformed into a cognitive task set before, but not as a result of, stimulus presentation.

Only recently, the general issue of how people set themselves to perform a task has seen a renaissance in cognitive psychology and the cognitive neurosciences (for overviews, see Hommel, Ridderinkhof, & Theeuwes, 2002; Monsell & Driver, 2000), although most research efforts are devoted to handling, or switching between, multiple tasks and the side-effects that produces, rather than to the mechanisms underlying the prepared reflex Exner observed. However, there is evidence that at least three functions serve to prepare the cognitive system to act in a reflex-like, apparently effortless fashion: (i) the increased attention to appropriate context or trigger conditions for the planned action; (ii) the implementation of then automatically working stimulus-response associations defining the task; and (iii) the delegation of control to lower-level movement routines. All three functions basically serve to delegate parts of action control to the environement, thereby keeping the action plan flexible and the cognitive load of the planning individual at a minimum. Let me discuss these functions in turn.

Enabling automatic detection of appropriate context conditions

Although there are situations in which we carry out an action as soon as the planning process is completed most actions are planned for the future—be it near, as in an experimental task with trials occurring every few seconds, or far, as when preparing for a journey. However, planning for the future requires some sort of specification of the appropriate action context, that is, of the stimulus conditions that are supposed to trigger the prepared action plan. Accordingly, action plans must include information about the context and the stimulus conditions under which the planned action is to be carried out. Such information may refer to particular stimulus-response rules that specify how situational parameters are translated into action parameters—an issue I will get back to in the next two sections. But there also needs to be some information that, in a more general sense, defines the circumstances appropriate to execute the plan. An example might be the sign or visual characteristics of a particular underground station that signals to you to leave the train right now, that is, to launch your behavioral "exit routine". Obviously, the identification of appropriate trigger conditions is a crucial precondition for successful performance, which is why several authors have suggested that action planning may lead to the automatic (i.e., effortless) detection of such conditions (Bargh & Gollwitzer, 1994; Lewin, 1926; Patalano & Seifert, 1997). Indeed, there is converging evidence that associating a planned action with particular, anticipated stimulus conditions facilitates the detection of trigger conditions, or of stimuli related to them.

For instance, Gollwitzer and Mertin (reported in Bargh & Gollwitzer, 1994) asked subjects to name actions they intended to carry out in the near future and then had them perform a dichotic-listening task. In this task, subjects monitored one of two auditory channels for target words, to which they responded as soon as possible. As to be expected, presenting words in the unattended channel slowed down performance considerably.

However, performance was particularly impaired if these words were related to the action plans the subjects had mentioned before. Apparently, the plan-related words attracted attention automatically and thereby drew it away from the task-relevant channel.

Further evidence for the prioritized processing of plan-related stimuli comes from Goschke and Kuhl (1993). Their subjects were instructed to either perform a particular set of actions themselves or to watch an experimenter performing it. Before carrying out or observing the actions they were presented with to-be-recognized words that were either related to the respective actions or neutral. If subjects expected to observe an action reaction times to action-related and neutral words were equivalent. However, if they expected to perform an action themselves action-related words were recognized considerably faster than neutral words. Importantly, this advantage for action-related words was only obtained if the recognition test preceded performance of the action but not if the action was completed before the test. These findings were replicated and extended by Marsh, Hicks, and Bryan (1999), who demonstrated that canceling an action plan has the same effect as carrying it out. Hence, maintaining an action plan sensitizes the individual to stimuli related to it.

A final example for the attentional consequences of action planning has been reported by Craighero, Fadiga, Rizzolatti, and Umiltà (1999). In their study, participants planned to grasp a bar that was rotated 45 degree to the left or right. The initiation of the movement was signaled by a picture of a bar that appeared on a monitor. The orientation of the pictured bar was entirely irrelevant to the task and varied randomly, and subjects were urged to ignore it. Nevertheless, the planned movements were initiated faster if its orientation matched the bar's orientation. To test whether this was a true perceptual effect the authors included trials in which the visual bar also appeared while a manual grasp was planned, but where it signaled a foot response. Foot responses were still faster if the visual bar was congruent with the manual action plan, showing that the plan really facilitated perceptual processes.

Enabling automatic stimulus-response translation

Having detected that a particular action can be carried out does not necessarily tell the individual how this is to be done. For instance, even if I have successfully approached a supermarket and recognized that this provides me with an opportunity to carry out my plan to buy the ingredients for my favorite dish, I still need to recall those ingredients, recall or figure out where to find them, put them into my shopping kart, and so forth. Thus, to carry out an action plan does not only require the detection of trigger stimuli but also the use of if-then or stimulus-response rules that define how to deal with particular situational stimuli and constraints (e.g., Allport, 1980; Anderson, 1983; Meyer & Kieras, 1997).

Although this assumption is uncontroversial, it is controversial whether the implemented rules can be used as automatically as the prepared-reflex metaphor suggests. On first sight there are reasons to doubt that they can, especially in view of what has come to be known as the Psychological Refractory Period or PRP effect (Telford, 1931). This term is used to describe the common observation that performance on the second of two tasks decreases with increasing temporal overlap between the tasks; hence, people have difficulty to carry out more than one task at a time. Considerable research effort has been devoted to find out where this difficulty comes from and there is consensus that it has to do with stimulus-response translation (for recent overviews, see Meyer & Kieras, 1997; Pashler, 1994). In particular, it has been claimed that humans are unable to apply more than one stimulus-response rule at a time, so that applying the rules of a secondary task needs to await the completion of the primary task (e.g., McCann & Johnston, 1992; Pashler, 1994; Welford, 1952). If this were so, it implied that stimulus-response translation, i.e., the application of stimulus-response rules, draws on cognitive resources. If so, the prepared-reflex metaphor would be seriously misled, as it rests on the idea that once a rule is implemented in the cognitive system its application is entirely stimulus-driven and, hence, effortless.

************ Figure 7 ************

Interestingly, recent studies have challenged the believe that the PRP effect reflects a problem with stimulus-response translation. In fact, there is increasing evidence that stimulus-response translation is fully automatic (once the rules are implemented), thus lending credit to the prepared-reflex metaphor. The basic logic underlying these studies is shown in Figure 7. For instance, in Hommel's (1998b) experiments subjects performed two tasks in a row: a manual response to the color of a visual stimulus followed by a vocal color-word response to the shape of that stimulus. That is, if a red H appeared subjects would press a left key and then say “red”, if a green H appeared they would press a right key and then say “red”, and so forth. Note that the colors red and green are involved here as both stimulus colors of the primary stimulus (i.e., stimulus for Task 1) and meanings of the secondary response (i.e., the response in Task 2), but that secondary responses were associated with stimulus *shape*, not stimulus *color*! Hence, subjects were *not* to name the color of the stimulus.

Now, consider the secondary stimulus would be translated into the secondary response only after the primary response is selected, as the claim of a stimulus-response translation bottleneck implies. Then the primary task should not be affected by the identity of the secondary response, that is, by whether this response is compatible or incompatible with the color of the primary stimulus. However, if both sets of task rules were applied concurrently, as the prepared-reflex account predicts, one might expect the processing of the colors in the primary task to be affected by the meaning of the secondary response, as indicated by the dotted lines in Figure 7. Indeed, it turned out that responses to red stimuli in the primary task were faster if the secondary response was “red” rather than “green”, and the opposite was true for green stimuli (Hommel, 1998b). More recent studies (Logan & Delheimer, 2001; Logan & Schulkind, 2000) replicated and extended these findings in a variety of tasks, suggesting that more than one stimulus can be translated into an instructed response at a time.

Even more direct evidence for the effortlessness of stimulus-response translation has been gathered by Hommel and Eglau (2002). In one experiment they had subjects perform the above-described dual task of Hommel (1998b) in the context of a third task that was considered to draw on working-memory capacity. Before being presented with the red or green Hs or Ss subjects memorized the order of a randomly assembled string of two (low load) or eight (high load) digits, which they would try to recall at the end of the trial. Yet, the effect of the secondary response on the processing of the primary stimulus was virtually identical in the two load conditions, suggesting that stimulus-response translation does not depend on working memory. In another experiment of the Hommel and Eglau study subjects performed Hommel's (1998b) dual task for half a session before beeing asked to drop the secondary, vocal task and to proceed with the manual part of the task only. Interestingly, the compatibility between the (no longer performed) secondary response and the primary (and now only relevant) stimulus continued to matter, and it did so until the end of the session. Apparently, then, stopping to carry out the secondary task did not prevent subjects from translating the no longer relevant secondary-task stimulus into the no longer emitted secondary-task response—a particularly strong demonstration of the automaticity of implemented stimulus-response rules.

Delegating control to sensorimotor loops

Planning is a double-edged sword. On the positive side, it makes creative use of anticipations, expectations, and future possibilities, and thereby strongly enhances the temporal operation space of purposeful action. On the negative side, however, planning an action strongly relies on the accuracy of those predictions of future events and, thus, is likely to fail if some of them turn out to be invalid. The latter may be less of a problem in typical laboratory situations, where the tasks are often simple and well-defined, stimuli and responses are few, and distraction is absent. However, these characteristics do commonly not apply to everyday situations, which makes them much harder to predict. Accordingly, it would seem to be an optimal strategy to plan as much as necessary to reach an intended goal—but no more. Indeed, not all parameters of an action are relevant for its success: If one intends to take a sip of juice it does not matter exactly how the glass is grasped and moved towards the mouth—if one only gets that drink. Action plans could therefore afford to be incomplete in specifying only what is important for reaching the intended goal and what can reliably be predicted before the limbs begin to move. Accordingly, several authors have argued on both theoretical and empirical grounds that action planning underspecifies the intended action and leaves open "slots" to be filled by on-line sensory information (Jeannerod, 1984; Schmidt, 1975; Turvey, 1977).

Indeed, the available evidence suggests that the planning process is restricted to the molar aspects of the action. For instance, Prablanc and Pélisson (1990) asked subjects to move their hands to a goal position that was indicated by a light. In some trials the goal light was shifted by about 2-4 cm after the movement began. Cleverly, the shift was carried out while subjects moved their eyes, so that they were entirely unaware of it. Nevertheless, the hand almost always moved to the new goal location, and it did so without any hesitation or signs of correction in the speed or acceleration profiles. That is, the action plan was adapted to the changed situation in the absence of any conscious awareness that a change was taking place (cf., Bridgeman, Lewis, Heit & Nagle, 1979; Goodale, Pélisson & Prablanc, 1986). The molar, goal-relevant aspects of the action (i.e., moving the hand to the light) were apparently included in the plan while the more incidental features (i.e., the exact movement path) were not.

Based on these and other empirical observations Milner and Goodale (1995) have proposed a neuro-cognitive model of visuo-motor manual action, in which off- and on-line channels of information processing are considered. In their model, on-line sensory-motor processing proceeds along the dorsal visuo-motor pathway that begins to segregate in the primary visual cortex and then connects to the motor cortex via relay stations in the posterior parietal cortex. This channel is assumed to deliver information about grasp- and reaching-relevant visual information, such as location and size, that directly feeds into systems responsible for hand control. Milner and Goodale claim that information processed along this route is not available to consciousness, which apart from the double-step studies mentioned above fits with the observation that patients suffering from form agnosia are able to properly grasp objects they at the same time are unable to identify (Goodale, Milner, Jakobson, & Carey, 1991). The other, off-line channel is assumed to run from primary visual areas straight to the infero-temporal cortex, that is, to areas responsible for object recognition. It has access to memory, is accessible by consciousness, and its main function is proposed to be restricted to perception. If this channel is impaired, as in optic ataxia, people may be able to identify an object but at the same time be unable to grasp it properly (Perenin & Vighetto, 1988).

************ Figure 8 ************

Milner and Goodale's two-pathway model has been widely discussed and in some cases challenged. For instance, the authors assume that manual grasping is not affected by visual illusions (as the former is processed dorsally, the latter ventrally), but such effects do occur under some circumstances (Bruno, 2001; Franz, 2001). Moreover, the model has not much to say about how the two streams interact to produce coherent action and it seems to underestimate the degree to which they interact (Jackson, 2000). Action planning is ignored altogether (Hommel et al., 2001b), so that the model seems to attribute most of the action control to the stimulus. However, taken more generally, Milner and Goodale's distinction between a memory-less on-line channel that provides ongoing actions with the most up-to-date sensory information and a memory-based off-line channel that is more sensitive to the thoughts and intentions of the individual is in good agreement with, and provides a useful summary of the data available so far (Hommel et al., 2001b; Rossetti & Pisella, 2002). This leaves us with a picture along the lines of Figure 8, which sketches the complementary functions of an off-line perception-action pathway setting up general plans for goal-directed action and an on-line sensory-motor channel filling in the slots left open by the planning process.

Taken altogether there is increasing evidence suggesting that planning an action leads to the implementation of direct stimulus-response associations and of the delegation of some aspects of control to lower-level sensori-motor systems. Although the implementation of such routines is undoubtly an intentional and presumably attention-demanding process the implemented processes seem to live pretty much their own life. Thus, planning results in a kind of self-automatization in the sense that the trigger conditions defined in the plan automatically call up the action elements needed to deal with the situational constraints at hand—sometimes even outside the actor’s awareness.

UPSIDES AND DOWNSIDES OF HOW WE PLAN OUR ACTIONS

According to the findings and arguments discussed thus far human action planning takes place in terms of the perceivable effects of the planned action, the plans emerging from the planning process are integrated assemblies of action-feature codes and trigger information, and the function these plans have consists in some sort of self-automatization of the acting individual. Why does it work like this? Why, for instance, has human evolution provided us with distributed representations of action plans, rather than, say, ordered lists of symbol strings as used by the computer this chapter was prepared with? What sense does it make to first create a binding problem and then solving it by a relatively complicated neural mechanism? Although any attempt to address these questions is obviously speculative, it makes sense to briefly compare the benefits and the disadvantages of action planning and the way it seems to work in humans.

Effect-based planning

Planning an action in terms of its expected effects has a number of apparent drawbacks. The perhaps most obvious drawback is that it leaves the actual realization of the action underspecified: For instance, planning to grasp a visible cup of coffee in terms of effects is likely to include information about the location of the cup while at the same time failing to fully specify the hand to be used, the kinematics of its movement, and the time-force function of the final grasp. As some effector has to move eventually, to travel a particular path, and to exert a particular force on the cup, the question is where this information is coming from.

However, once we take into consideration the planning individual, her learning history, the structural constraints her body imposes, as well as the situational context she is acting in, it becomes clear that there is a multitude of information available. For instance, people are commonly right- or left-handed, which implies that hand selection is usually determined by hand preference. The visible object and its spatial relation to one's body and hand provide further constraints for kinematic-related choices, while the cup's shape specifies the kinematics of the grasp (e.g., Jeannerod, 1997). The exerted force may be determined by stored knowledge about the cup's stability and weight, visually derived estimations of these parameters, or controlled by tactile information that is generated by touching the cup. As the information available from on-line vision and tactile channels is lawfully related to muscle movements, there is every reason to leave the control of the action's motor parameters to these channels. The action plan proper thus can afford to focus on what is relevant: the goal of the action and the effects it is intended to produce.

An obvious virtue of this strategy is to open up the temporal horizon for planning. The less detailed a plan is the less its execution will suffer from inaccurate predictions, simply because less had to be predicted when creating it. In other words, the strategy to restrict action planning to the general level and to delegate the control of action details to the current situational constraints allows humans (and, presumably, some infra-human species as well) to develop action plans that are much more flexible and resistant to situational changes than a more detailed planning would.

Another advantage of effect-based action planning is that it facilitates transfer. For instance, consider the ability of people to write their signature not only with their preferred hand, but also with the other hand, their feet, and even with their mouth (Raibert, 1977). Although this ability, as well as the quality of the signature, no doubt improve with practice, the transfer from one effector to another takes surprisingly little time. This would not be possible if the underlying action plan would entirely consist of low-level, muscle-specific routines. Rather, the plan seems to be in terms of size-scalable spatial relations of the to-be-produced action effect, so that it can be used to control different effectors. Effect-based planning also allows the transfer of action between people, that is, learning by imitation. Indeed, recent research has revealed strong links between action perception and action planning (see Bekkering & Wohlschläger, 2002, for an overview), and some authors have speculated that the above-mentioned mirror neurons may represent the physiological substrate of this link (see Rizzolatti, Fogassi, & Gallese, 2001).

Distributed planning

Action plans are represented in an anatomically and functionally distributed fashion. This calls for binding mechanisms, that is, mechanisms that integrate the distributed elements of an action plan into a coherent structure—the action plan. Obviously, distributed representations create considerable processing problems and computational costs. Apart from inviting erroneous bindings, a major drawback of the requirement to integrate action features before carrying out the corresponding action is that this may be responsible for the type of dual-task costs discussed earlier: To make sure that only the relevant codes are bound to a given action plan it seems necessary to temporally block or suppress other codes, which implies that only one action can be planned at a time (Jolicœur, Tombu, Oriet, & Stevanovski, 2002; Stoet & Hommel, 1999). Moreover, maintaining an action plan may create crosstalk effects such as evident from the above-mentioned code-occupation phenomena. In view of all these problems, it is reasonable to ask what the advantages of distributed representations might be.

One advantage becomes obvious when considering the phylogenetic development of man or other animals making use of distributed representations. In the course of this development there must have been gross changes with respect to the anatomical and functional potential to perform actions: the body posture changed to upright, hands and feet changed in structure and flexibility, vocal abilities emerged and developed. These developments considerably enlarged the action repertoire and, thus, increased the number and types of brain codes representing and controlling all those actions and their characteristics. Instead of restructuring the action-related parts of the brain every time new action features became available, the strategy to code those features in a distributed fashion must have facilitated this task enormously.

On an ontogenetic scale, distributed representations reduce the impact of brain lesions produced by injuries, illness, or genetic defects, as at least smaller lesions are unlikely to eliminate an entire class of actions (cf., Bach-y-Rita, 1990; Evarts, 1980). A further, more functional advantage of distributed action plans is that they facilitate adapting and modifying them. For instance, people are able to specify and program some features of an action before all of its features are known (Rosenbaum, 1980) and modify particular parameters without replanning the whole action (Rosenbaum & Kornblum, 1982).

All taken together, the difficulties distributed representations create seem to be outweighted by the opportunities they provide. Moreover, there are reasons to think that some of the difficulties can be overcome by practice. Assume, particular feature codes are integrated into the same plan over and over again, would that not suggest to create some more enduring memory trace that can be retrieved as a whole? Systematic studies of the transition from integration to retrieval are still lacking but there is some evidence that supports a retrieval-based consideration. For instance, even though combining two tasks is known to produce considerable costs in performance, recent studies have indicated that having highly motivated subjects practice the tasks for an extended period of time can actually eliminate those costs (Schumacher et al., 2001). This might suggest that relying on stored "bindings", hence, retrieving already integrated action plans, is a way to circumvent time-consuming on-line integration processes.

Delegating control

We have seen that the human brain delegates control to lower-level sensori-motor routines and to the environment in a number of ways. This has obvious advantages by (i) restricting the computationally expensive planning phase proper to one brief period in time, thereby minimizing interference with other ongoing processes; (ii) confining the plan to relevant aspects, thereby minimizing its extent and complexity; (iii) automatizing the detection of trigger conditions, thereby minimizing cognitive load; and (iv) maximizing the plan's sensitivity to the environmental conditions on execution, thereby minimizing errors due to inaccurate predictions. However, these advantages come with a cost.

Indeed, even though plans can automatize a number of processes they can only do so if they are properly maintained. Maintenance, however, does seem to require capacity. For instance, De Jong (2000) argues that switching to a new task presupposes a sufficiently high activation of the corresponding intention or action goal, and he discusses evidence suggesting that performance on a new task is worse the less likely the action goal had been activated in advance. Altmann (2002) shows that even performance within a particular task gets worse from trial to trial, and he attributes this effect to goal forgetting. The ability to maintain action goals depends on the integrity of the frontal lobe of the human brain, as evident from the frequent observation of "goal neglect" in patients suffering from frontal lesions (Duncan, Emslie, Williams, Johnson, & Freer, 1996). This might explain why aging, which is known to affect the frontal lobes in particular, impairs the ability to switch between tasks (Kray & Lindenberger, 2000) and to recall that a planned action is to be carried out—at least if environmental support is limited (Maylor, 1996). Even age-independent individual differences modulate goal maintenance, as indicated by the strong (negative) correlations between IQ and goal forgetting obtained by Duncan and colleagues (1996). In other words, what appears to us as intelligent behavior may reflect to a large degree the ability to actively maintain one's action goals.

CONCLUSIONS

The purpose of this chapter was to characterize action planning from a cognitive and cognitive neuroscience point of view, hence, from a level of analysis laying at the most molecular end of the range represented in this book. Accordingly, the type of actions investigated in the studies reported and discussed are often rather simple and artificial, and many would tend to call them mere movement or re-action rather than true voluntary action. Nevertheless, it was my intention to show that even these, however undemanding acts share central, defining characteristics with the most complex expressions of human behavior. In particular, even the most primitive behavioral acts can be shown to be prospectively controlled by cognitively represented goals. Not only are their features assembled in a way to reach the intended behavioral outcome, the feature codes themselves are meaningful, behaviorally grounded representations of anticipated future action effects. To become a functioning and “maintainable” action plan these codes need to be integrated and linked to the stimulus conditions that ought to trigger the action later on. Code integration has negative effects, such as difficulties to code similar perceptual events or action plans, but the host of the effects is positive. In particular, creating a plan is associated with the implementation of stimulus-response rules and sensori-motor routines, and with sensitizing the cognitive system for the detection of appropriate action conditions. In a sense, action planning is like arming the cognitive system to behave like a reflex machinery. All these characteristics are shared by more complex behavioral acts, which supports the idea of a continuum between “true” action and apparent “re”-action (Hommel et al., 2001a; Prinz, 1997). After all, what counts for acting humans is the satisfaction provided by reaching relevant goals, not the number and size of muscles employed to reach them.

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AUTHOR NOTES

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FIGURE CAPTIONS

Figure 1. A standard stage model of human information processing.

Human action planning V2 Figures.doc#_Figure1

Figure 2. Sketch of a reaction-time task. It requires a left-hand keypressing response to a low tone (shown in this example), and a right-hand response to a high tone (not shown). The location of the tone varies randomly (i.e., is presented via the left or right loudspeaker, as shown in the left and right panel, respectively), and subjects are asked to ignore it. As a less typical design feature each key is connected with a light source on the opposite side, so that pressing the left key switches on a right light while pressing the right key switches on a left light (see Hommel, 1993). Note that the tone precedes and signals the response, whereas the light flash follows it.

Human action planning V2 Figures.doc#Figure2

Figure 3. A two-stage model of the emergence of action control (after Elsner & Hommel, 2001). At the first stage, shown on the left side, the motor pattern producing a particular, perceived effect becomes integrated with the cognitive codes representing that effect. At the second stage, shown on the right, the motor pattern is intentionally executed by activating the cognitive codes that represent its anticipated effect.

Human action planning V2 Figures.doc#Figure3

Figure 4. Sketch of the experimental design used by Hommel (1996). In the first, acquisition phase (left panel) subjects pressed a reaction key once or twice, this triggering a low- and high-pitched tone, respectively (for one example). In the second, test phase (right panels) randomly selected tones were also presented as task-irrelevant, to-be-ignored primes. The

prime tones matched the tone the correct response would produce in some trials (upper panel) but not in others (lower panel).

Human action planning V2 Figures.doc#Figure4

Figure 5. Illustration of the feature-binding problem in action planning. No problem arises if only a single action is planned, or a single plan is maintained, at one time (left panel). However, if more than one action is planned the relationship between plan elements and plans become undetermined (right panel).

Human action planning V2 Figures.doc#Figure5

Figure 6. Sketch of the implications of sequential action planning. Planning action A leads to the integration of the corresponding feature codes. Later planning of action B is unaffected if there is no feature overlap between A and B. However, if features already integrated into plan A are needed for plan B as well, a *code-occupation* problem arises.

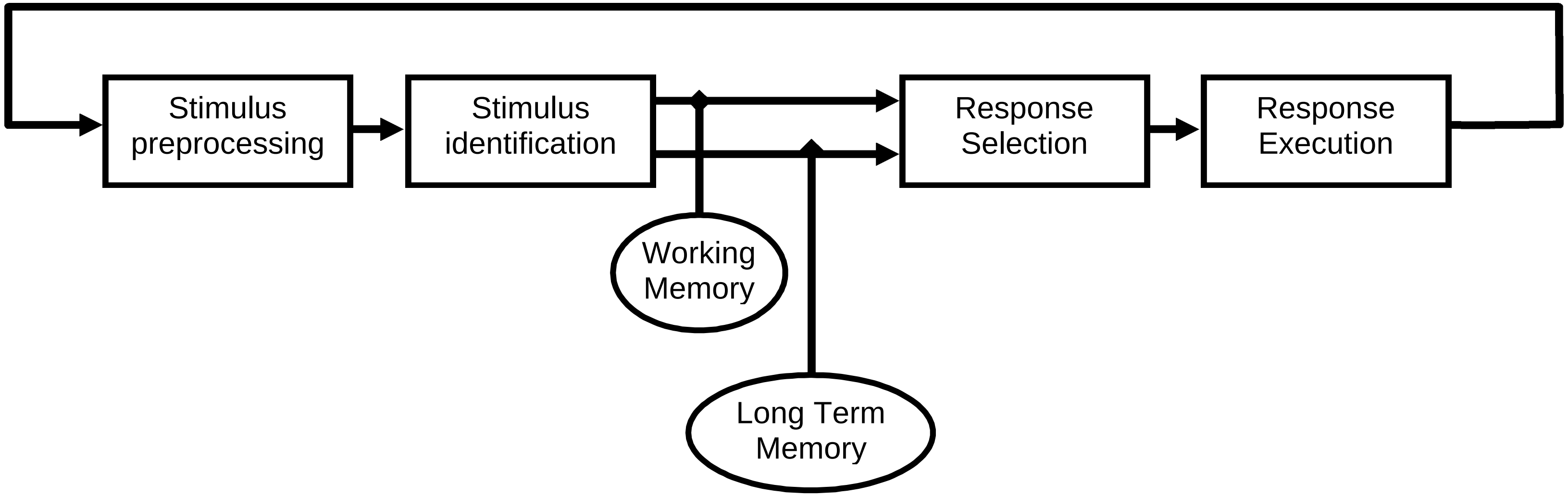
Human action planning V2 Figures.doc#Figure6

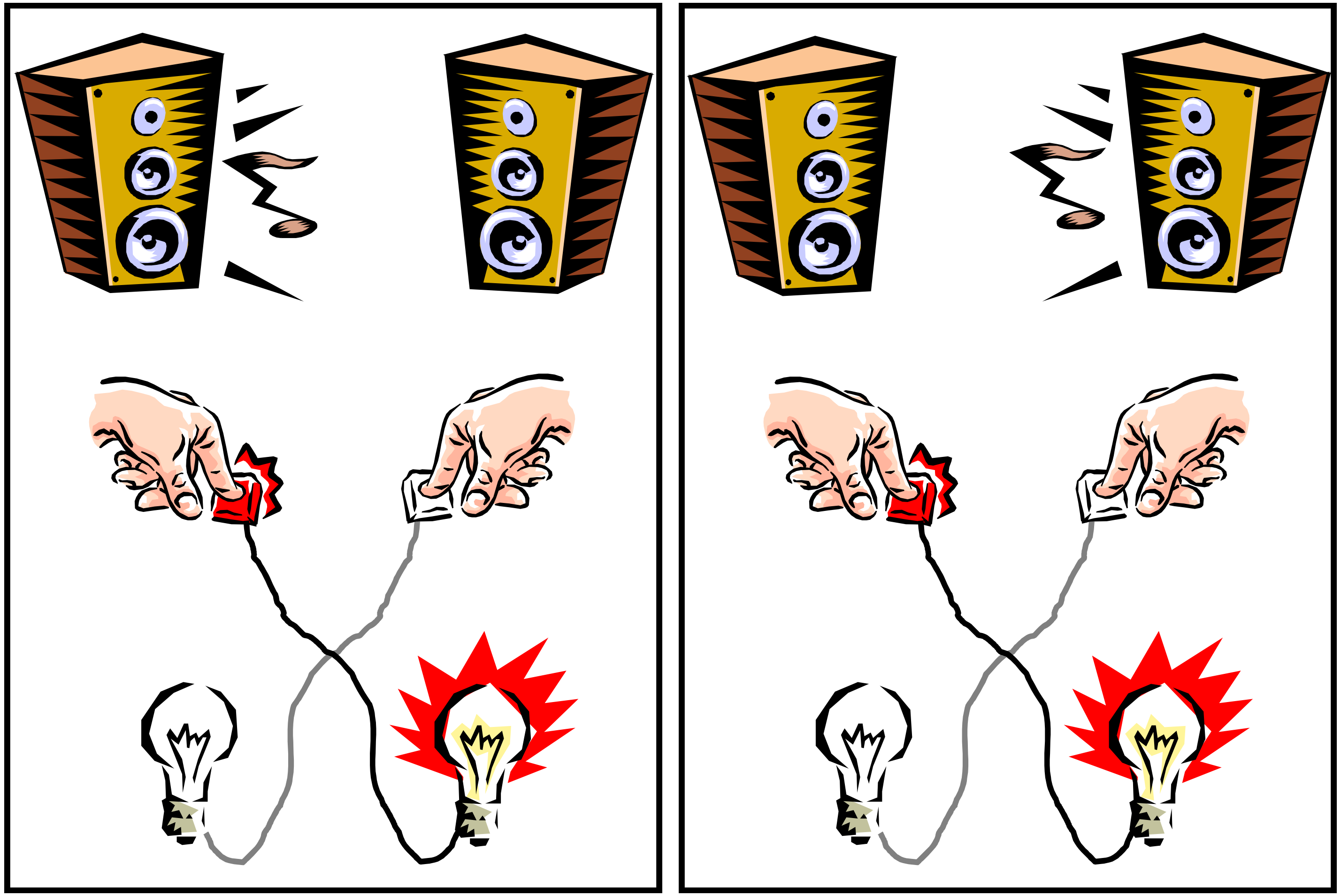
Figure 7. Sketch of the dual-task design employed by Hommel (1998) and Hommel & Eglau (in press). Subjects first perform a manual left-right keypress response to the color of the stimulus, followed by a vocal color-word response to the shape of the stimulus (i.e., the letter). Note that with some combinations the secondary response feature-overlaps with the primary stimulus.

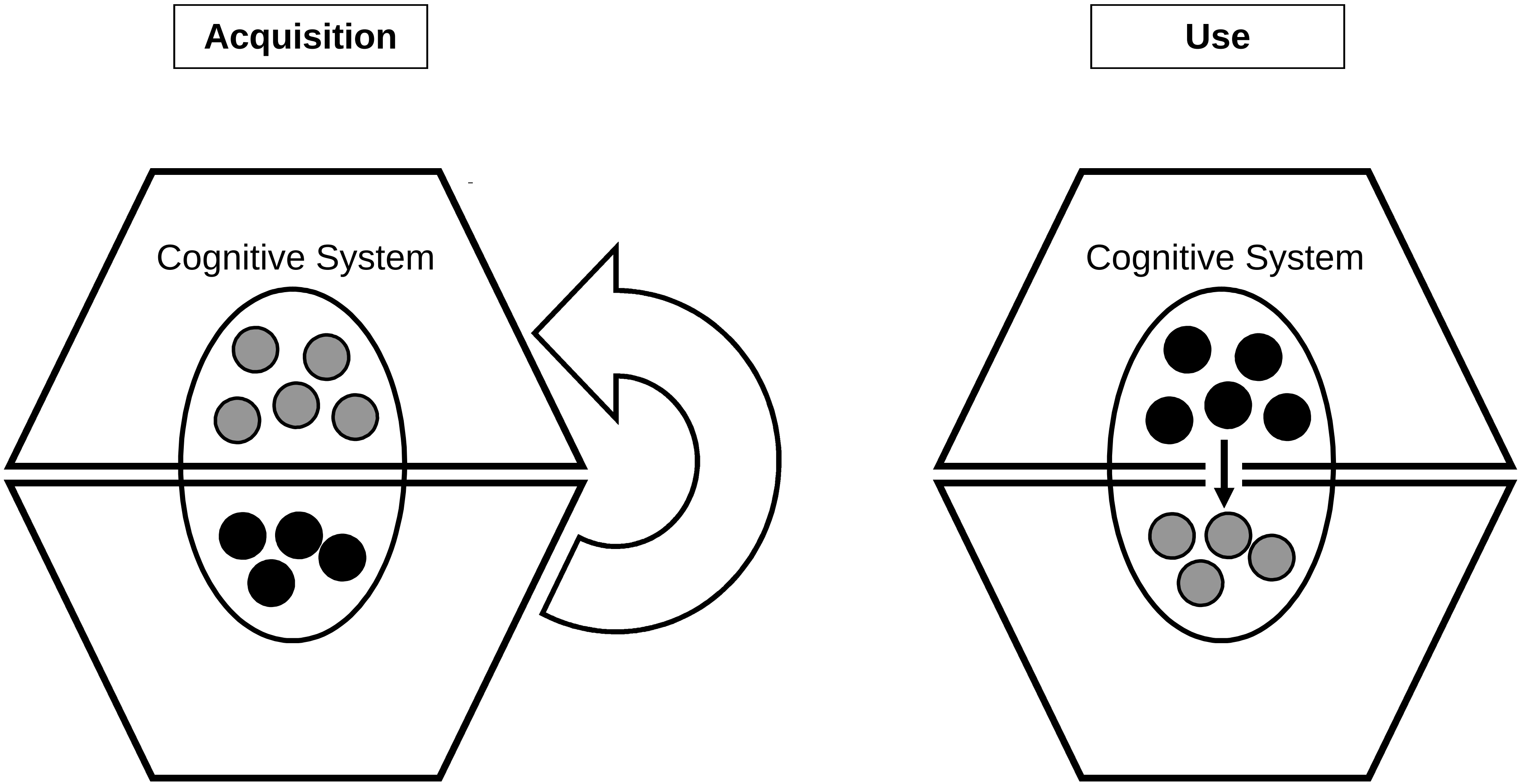
Human action planning V2 Figures.doc#Figure7

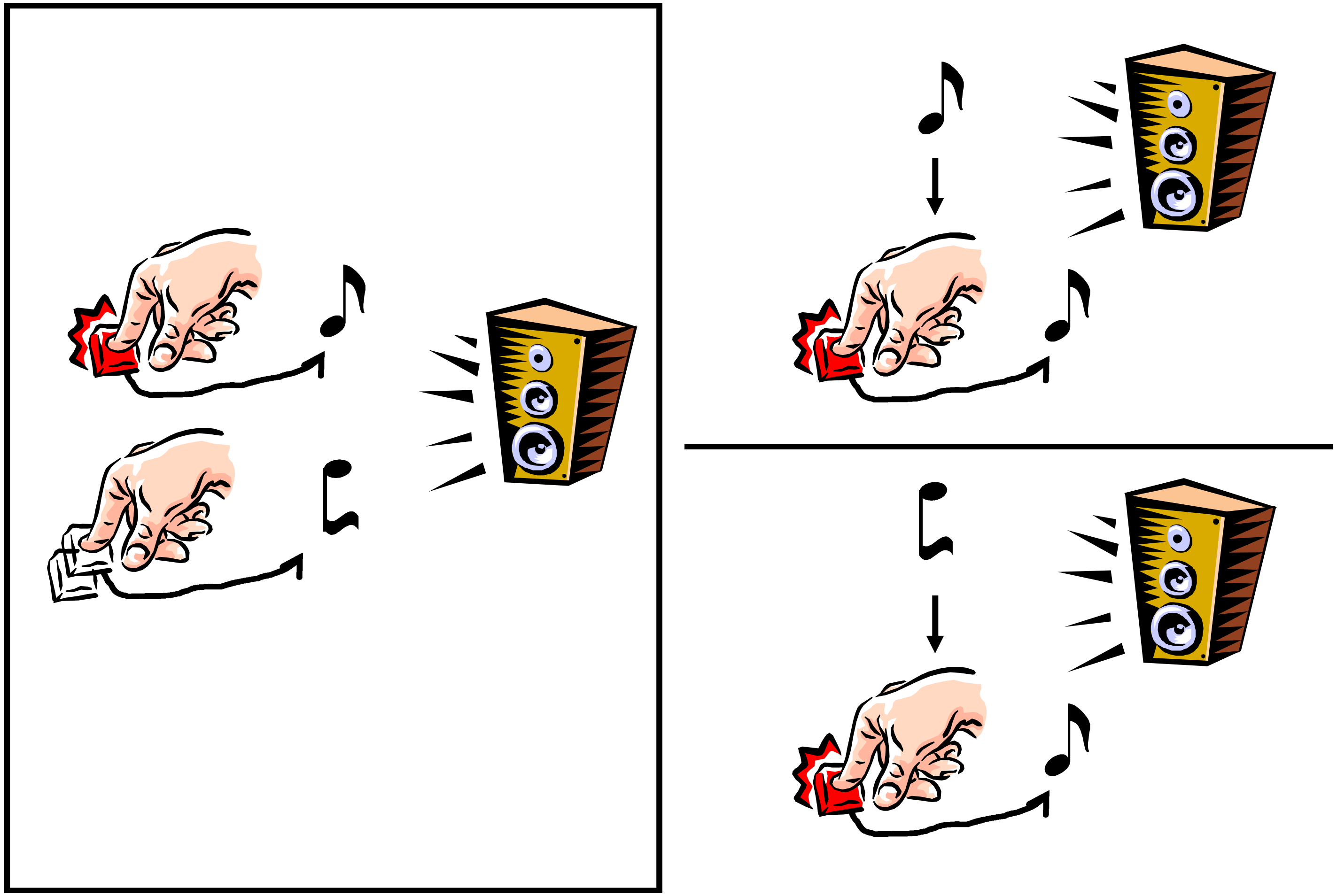
Figure 8: The interaction of sensorimotor processing and action planning. Action plans are worked out off-line and then, after completion, specified by on-line sensorimotor processing.

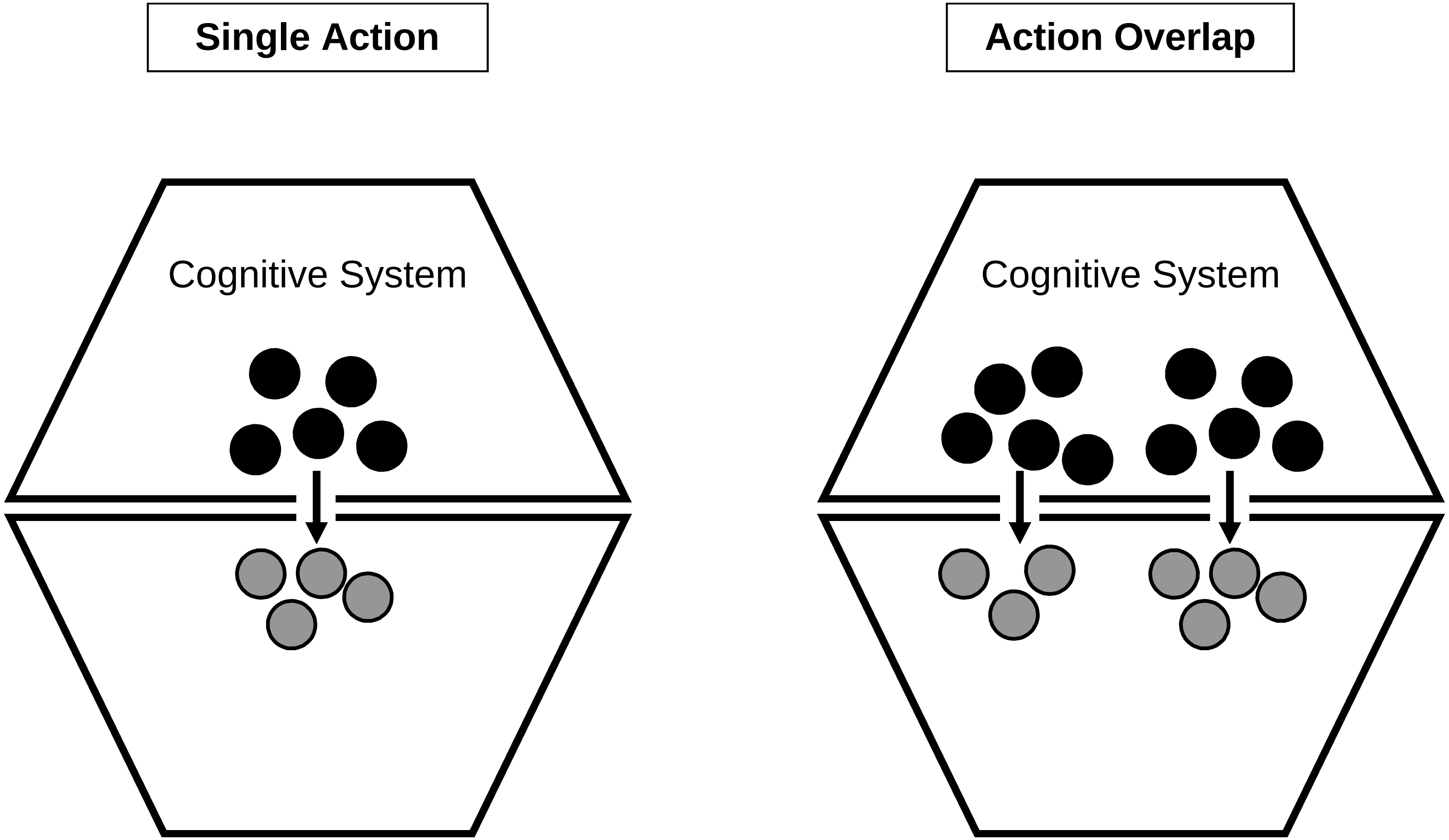
Human action planning Figures.doc – Figure8

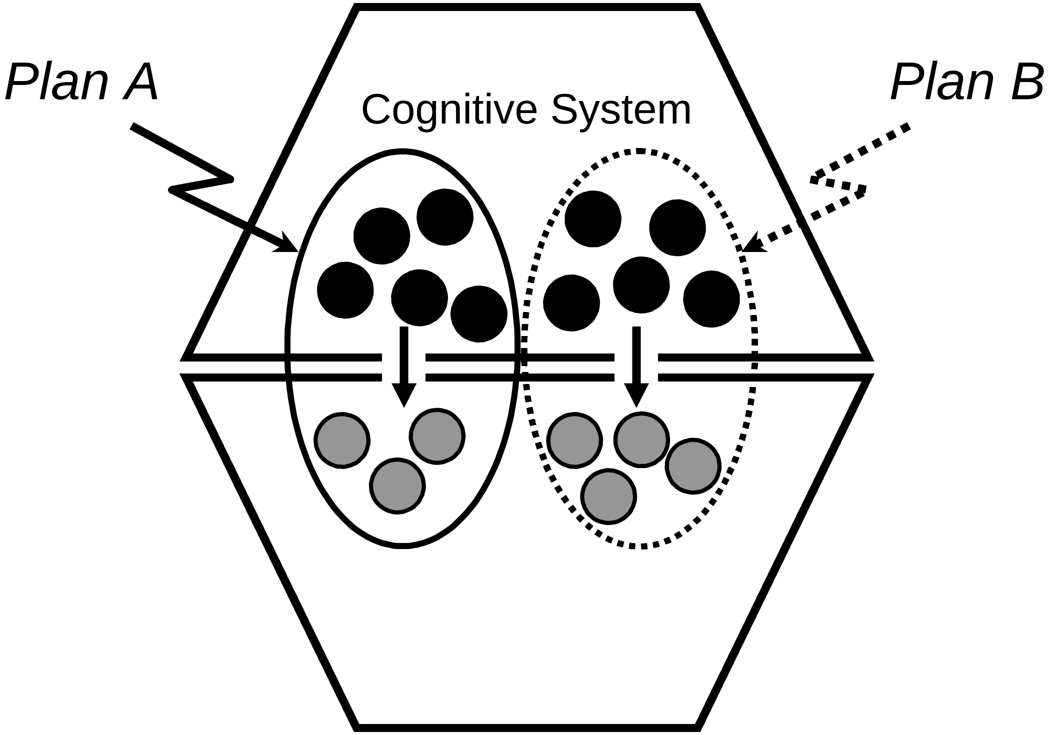

Stimulus preprocessing
Stimulus identification
Response Selection
Response Execution
Working Memory
Long Term Memory

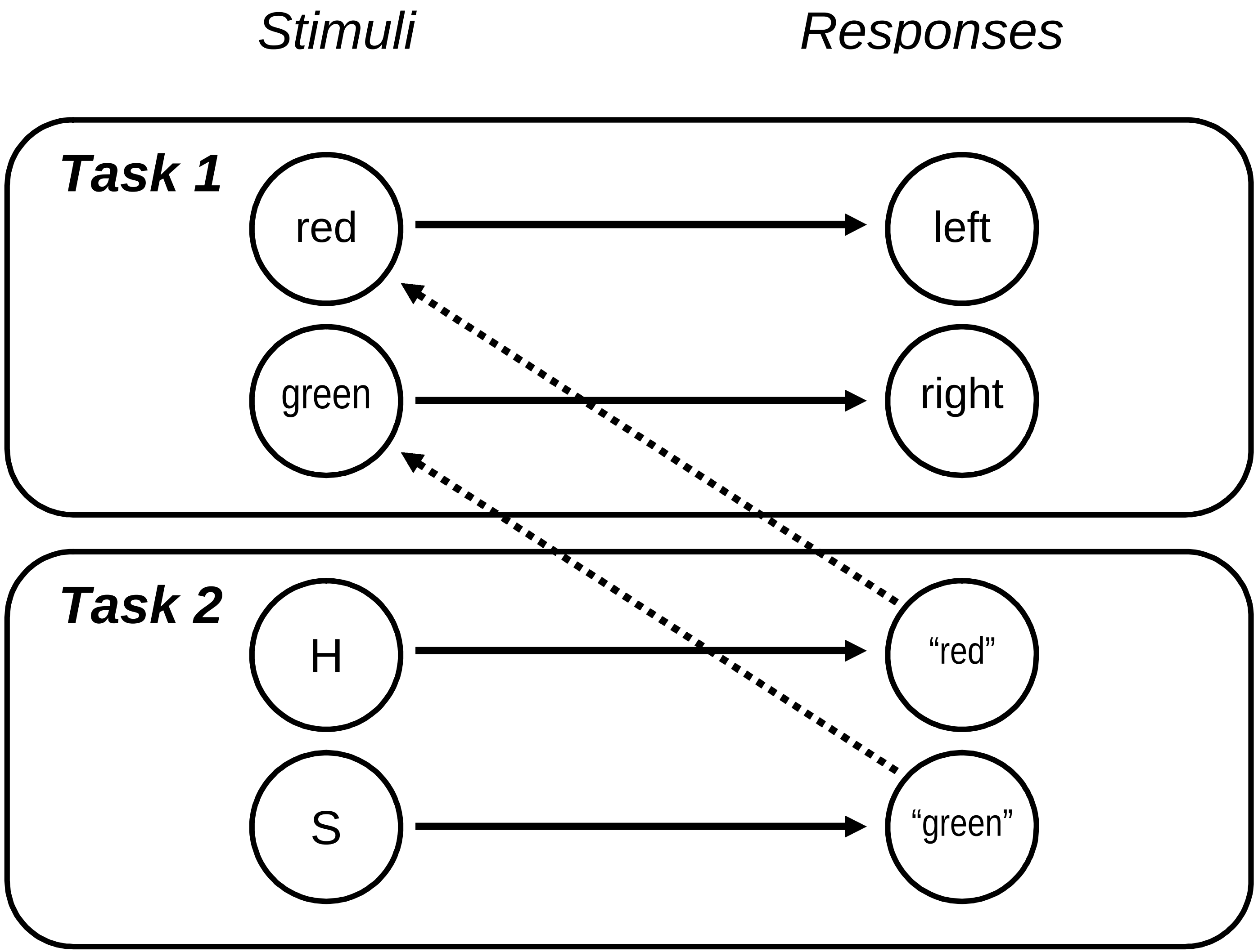


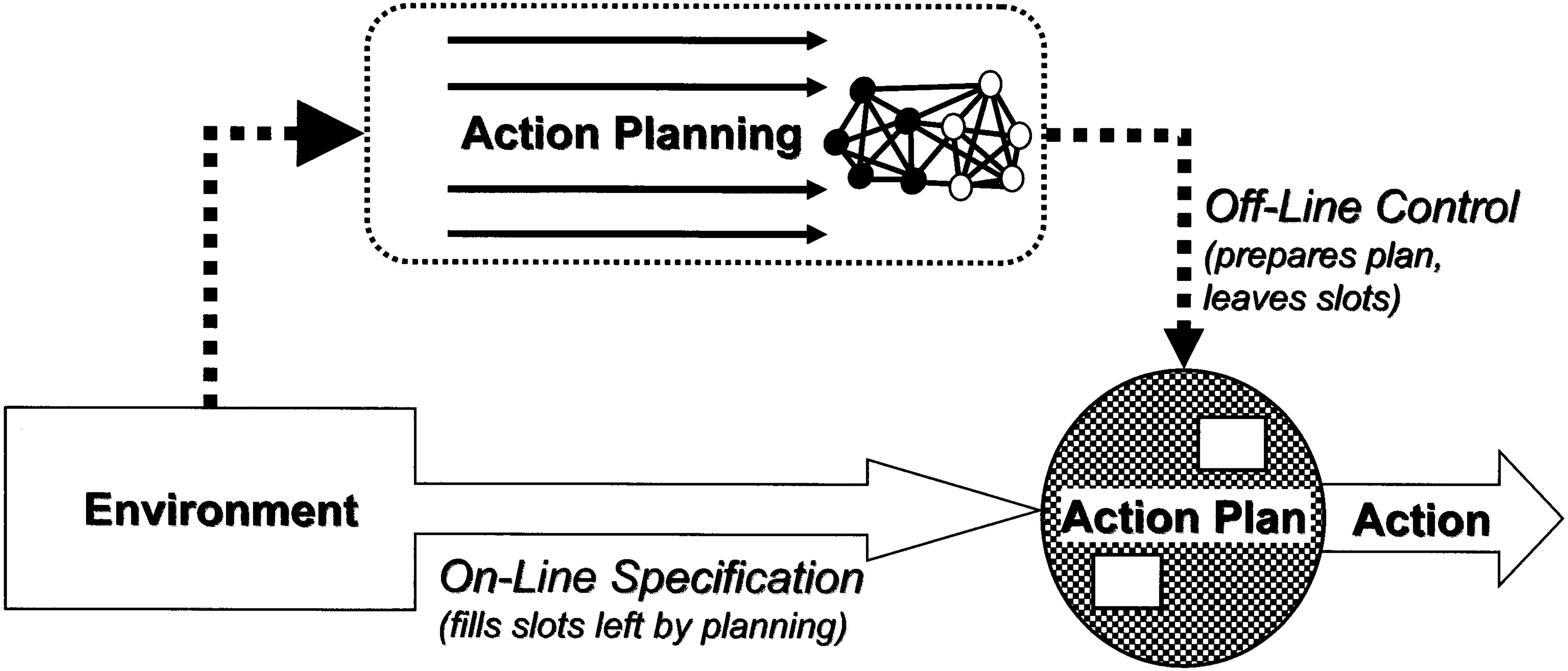

Acquisition
Use
Cognitive System
Cognitive System




Single Action
Action Overlap
Cognitive System
Cognitive System


Plan A
Cognitive System
Plan B


Stimuli
Responses
Task 1
red
left
green
right
Task 2
H
"red"
S
"green"


Action Planning
Off-Line Control
(prepares plan,
leaves slots)
Environment
On-Line Specification
(fills slots left by planning)
Action Plan
Action