Theoretical Issues in Stimulus-Response Compatibility
B. Hommel and W. Prinz (Editors)

Toward an Action-Concept Model of Stimulus-Response Compatibility

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This chapter highlights the importance of the problem of action coding, that is, the cognitive representation of action, for theories of S-R compatibility. An action-concept model of S-R compatibility is presented, based on considerations of Lotze and Harleß on the emergence of voluntary action. It assumes that the cognitive code of any perceivable, movement-contingent event—hence, action effect—is associated with the motor pattern producing it. Accordingly, the cognitive system can, and actually does, use these action-effect codes to choose between actions and to address motor patterns for action generation. That is, action-effect codes serve for perception as well as for action control, and are thus called *action concepts*. The explanatory power of the action-concept model is demonstrated for a considerable number of findings from compatibility research. It is argued that such a model could close a theoretical gap in understanding S-R compatibility and the perception-action relationship in general.

1 Introduction: The Problem of Action Coding

Whenever a certain combination of, or mapping between, stimuli and responses allows for better performance than another, this is a demonstration of stimulus-response (S-R) compatibility. Over the decades, numerous cases of S-R compatibility have been discovered and investigated, mostly by means of choice-reaction-time tasks. To mention a few examples: Choosing a left- against a right-hand response is faster if this is signaled by a left- rather than a right-side stimulus (e.g., Broadbent & Gregory, 1962), even if stimulus location is irrelevant to the task (Simon & Rudell, 1967); verbal responding is faster to words naming the response than to pictures representing it (Cattell, 1885); numerals can be identified faster by naming them rather than by pressing an assigned response key (Alluisi & Martin, 1958); and a color stimulus is responded to more quickly by pressing a same-color rather than a different-color button (Hedge & Marsh, 1975).

Compatibility phenomena often come as no surprise: Almost anybody would expect that, if there is a mapping effect at all, left- rather than right-side stimuli facilitate left-hand responses and that reading a word is easier than naming a picture. This ease of predicting reaction time effects of only a few milliseconds obviously has to do with similarity. Actually, we simply see (or hear or feel) which stimulus fits to which response: Left-side stimulus and left-hand response fit together because they are both on the left side or have something to do with the feature LEFT. And, in fact, most stimulus and response sets that give rise to compatibility effects show some kind of similarity or feature overlap. Consequently, the concept of stimulus-response similarity plays a crucial role in so-called coding accounts of compatibility (Kornblum, Hasbroucq, & Osman, 1990; Nicoletti, Umiltà, & Ladavas, 1984; Prinz, 1990; Wallace, 1971). Usually, these accounts hold that if there is similarity between stimulus and response sets, the cognitive representations or codes of these sets will overlap. With S-R similarity, this may facilitate S-R translation or produce automatic activation of the correct response. With dissimilar S-R pairs, S-R translation may be delayed due to the additional requirement to recode the stimulus information and/or because the incorrect response is activated automatically.

Despite the wide acceptance of the notion that compatibility phenomena arise from a match of stimulus and response codes, little is known about what kinds of codes are critical, according to which criteria they are formed, and where they come from. With respect to spatial stimulus codes, one can ask, for instance, when and under which circumstances a stimulus is coded as LEFT or RIGHT. Recent approaches have suggested a variety of solutions: Stimulus position codes may be formed in reference to the current focus of attention (Nicoletti & Umiltà, 1989), to the direction of the attentional shift toward the stimulus (Stoffer, 1991), or to other reference frames (Hommel, 1993a; Hommel & Lippa, 1995; Lamberts, Tavernier, & d'Ydewalle, 1992).

Another question concerns the number of stimulus dimensions that are, or can be, coded at a time. For instance, Nicoletti and Umiltà (1984; Nicoletti, Umiltà, Tressoldi, & Marzi, 1988) found that, if tested separately, spatial compatibility effects occur in the vertical and in the horizontal dimension. However, if both dimensions are varied in one experiment, only the horizontal dimension produces an effect. This led Nicoletti and Umiltà to assume a limited capacity to process spatial information, so that information about only one dimension can be processed at a time. Although this assumption can be doubted on both theoretical and empirical grounds (Hommel, 1996a), the more general questions raised by Nicoletti and Umiltà's work, namely whether coding underlies certain capacity limitations and which aspects of a stimulus are coded, are far from being settled.

If too little is known about mechanisms and conditions of stimulus coding, even less is known about response or action codes. Usually, coding accounts of S-R compatibility take it for granted that actions have features and that these are represented in the cognitive system, but there is little theory and even less evidence on what counts as an action feature. It is indeed obvious that pressing a left versus right key by moving the left- versus right-hand index finger may be coded as a LEFT versus RIGHT response. However, even this simple form of response coding can be affected by practice in discriminating between left and right effectors (Castiello & Umiltà, 1987). How exactly does this work?

And there are many more questions. For example, what about nonspatial characteristics of a response, like the speed or duration of a finger movement or a keypress? On a motor level, these and other parameters are likely to be specified, but are they also coded at the highest control level, the cognitive system? And what about more complicated cases, such as a duel with pistols, when the index finger of the right hand is moved toward the body to produce an outcome at 20 meters from the actor? Which spatial aspect or feature of the movements involved will be coded? Only spatial features? And will those codes relate only to the actual movement or are, say, movement goals considered as well?

Unfortunately, we lack not only convincing answers to questions of this sort, but also a principled way to look for them. This chapter tries to contribute to changing this situation. In the following section, I shall present a preliminary model that, though far from providing a complete theory at this stage, may be helpful in organizing available evidence, guiding further research, and as a framework for a theory of action coding in general and S-R compatibility in particular. It is based on very early considerations on the problem of action representation by Lotze (1852) and Harleß (1861), whose work received some wider recognition in the psychological literature in the guise of James' ideomotor theory (see Greenwald, 1970a; Prinz, 1987, for a historical overview). However, I shall argue that some modification and extension of this approach is needed to account for S-R compatibility effects. The outcome of this modification and extension, called the action-concept model, elaborates on ideas and considerations developed in the Munich group (Eimer, Hommel, & Prinz, 1995; Hommel, 1993b, in press a; Müsseler & Hommel, in press; Prinz, 1990; Prinz, Aschersleben, Hommel, & Vogt, 1995; Prinz & Hommel, 1995).

At first glance, the action-concept model may look very similar to other accounts of compatibility. In fact, it shares some processing assumptions with the dimensional-overlap model of Kornblum et al. (1990; Kornblum, 1994); its basic idea of a common representation of stimuli and responses is borrowed from the common-coding model of Prinz (1990, 1992); and by stressing the close relationship and mutual dependency between perception and action, it bears an obvious resemblance to the ecological approach followed by Michaels and Stins (1996). However, in contrast to previous models, the present approach focuses explicitly on—and provides an explanation for—how actions are (and become) represented in the cognitive system.

After having demonstrated that the action-concept model provides a reasonable account for standard S-R compatibility effects, I shall use the third section to show that, and how, it also permits the prediction of in part surprising new effects and novel phenomena. Among others, the model will be used to predict effects of compatibility between the imperative stimulus and a response-contingent stimulus event, compatibility effects under response certainty, and effects of response selection on stimulus processing—phenomena that other models have little, if anything, to say about. Furthermore, I shall report and discuss several recent findings that have helped to refine the model, predominantly to specify its temporal dynamics in more detail. In the fourth and concluding section, I shall summarize the model's basic assumptions and the theoretical elaborations suggested by the available evidence. But let us first go back more than a century.

2 An Action-Concept Approach to S-R Compatibility

2.1 Lotze, Harleß, and the *Effektbild*

Lotze (1852) and Harleß (1861) were concerned with the question of how an actor can learn to bring about a willed action or, in more modern terms, how cognitive control of motor activity can be acquired. Interestingly, this question reverses the perspective usually taken in compatibility research and, more generally, in psychological information-processing approaches: The issue is not how a given stimulus is translated into a response, but rather how an intended stimulus event (i.e., the action goal) is produced by coordinated muscle activity.

Lotze and Harleß proceed on the assumption that there is a motor system (*motorium* in Harleß' words), comprising all those neural structures that produce muscle activity, and a sensory system (*sensorium*), responsible for registering incoming stimulation. They ask how the will (i.e., the cognitive system) can be educated to modulate sensorimotor coordination in a way that allows for intentional movements to occur. In the newborn (or even unborn) child, they reason, motor activity may be produced by external factors, such as stimuli activating direct (inbuilt) sensorimotor connections, or by internal factors, such as a certain emotion or a curiosity drive. Although Lotze and Harleß admit that these kinds of movements are likely to be random and erratic, they nevertheless consider them to represent the building blocks of voluntary action. In particular, they assume that in order to gain voluntary control over a certain movement, the perceiver/actor needs to run through the following sequence of experiences:

First, a particular movement must be carried out in a completely involuntary fashion. Thus, as shown in Figure 1 (Connection 1), there is some motor pattern m formed by chance (or produced by one of the factors mentioned above) that produces an overt response R. Performing R produces several effects on the sensory system, be it the immediate kinesthetic stimulation during an arm movement or the more remote auditory effect of a baby's babbling. However, if a particular movement is really carried out for the first time, one cannot know what effects it will produce, and it is this fact that makes it involuntary. Thus, as James (1890, p. 487) pointed out, "if, in voluntary action properly so-called,

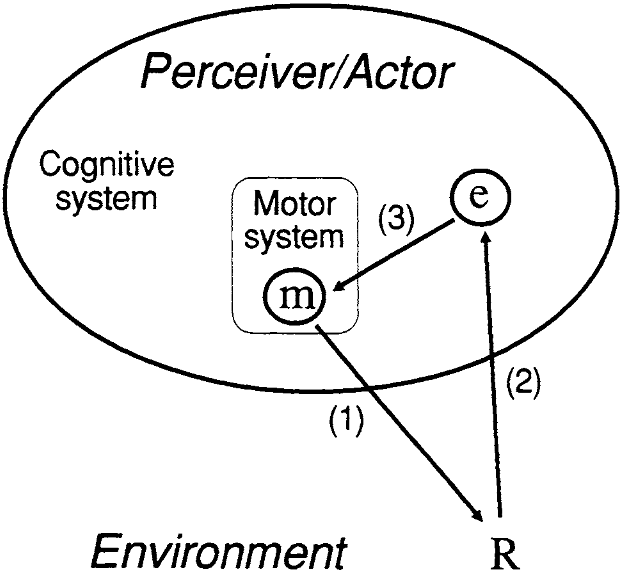

Figure 1. An illustration of the Lotze-Harleß model of the emergence of movement control. Chance activation of motor pattern m produces overt movement R (1), whose perceivable effects are coded by e (2). Co-occurrence of m and R leads to simultaneous activation of m and e, this fostering an association between the two (3).

the act must be foreseen, it follows that no creature not endowed with divinatory power can perform an act voluntarily for the first time." Without having performed a movement before, its effects cannot be known. Without knowing these effects, they cannot be anticipated and intended. But without intending its effects, a movement would not be voluntary by definition.

Second, to experience a self-performed movement at all, the perceiver/actor must form an internal code or image of its effects, an *Effektbild*, as Harleß calls it. That is, as shown in Figure 1 (Connection 2), the overt response R must have produced effects that are registered in the sensory system and coded (as e) within the cognitive system.[1] The resulting code or codes are assumed to cognitively represent these effects in terms of possible, intendable movement goals.

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[1] It should be noted that Lotze and Harleß as well as James were very much concerned with the conscious experience of action effects, which would suggest distinguishing between sensory, motor, and *conscious* systems. However, while one may agree that sensory and motor states or processes cannot be represented consciously, one may very well doubt that all the remaining (i.e., nonsensory and nonmotor) states and processes are necessarily conscious. Therefore, I prefer the more neutral distinction between sensory, motor, and *cognitive* systems, the latter comprising all those structures and processes that mediate perception and action, that is, serve to interpret sensory stimulation and control motor activity.

Third, if movement and effect are highly correlated and if this correlation is somehow registered, the motor activity producing the movement is conditioned to the internal code of the effect, hence the *Effektbild.* The emerging association between effect code and motor pattern (see Fig. 1, Connection 3) provides a means to activate the motor pattern m by activating the associated cognitive code e, that is, to bring motor activity under cognitive control.

Fourth, if all of this has happened, the actor is prepared to act voluntarily, that is, to produce intended effects by performing planned movements. Thus, the actor is not only able to anticipate movement effects before executing the movement, but he or she can also select among possible movements by choosing among codes of the effects they would produce. In other words, the cognitive control of voluntary action can be understood as choosing between and selectively activating codes of intended action effects.

From this view, action coding is a result of self-perception. Actors are assumed to perceive what they are doing and what follows from that. Only by observing these movement-effect relationships are they able to condition their own motor system, to bring it under voluntary control. So, the flow of information from central commands to peripheral muscle activity is not direct, but is mediated by codes of former movement outcomes.

2.2 An Action-Concept Model

Obviously, the Lotze-Harleß approach provides a promising start for a theory of action coding and, thus, a firm base for coding accounts of S-R compatibility effects. However, there are a number of important points to be clarified first. For one thing, it is important to specify what a movement effect is meant to be. In their examples, Lotze, Harleß, and James referred to movement-produced sensory feedback only. In the same vein, Greenwald's (1970a, 1970b) extension of James' ideomotor theory was restricted to auditory effects of speech or graphical effects of drawing and writing movements, and the like; hence, to what Salmoni, Schmidt, and Walter (1984) have called *intrinsic* feedback. Does that mean that effect codes can only represent immediate re-afferent information? Are they, or do they form, mere movement codes instead of real action codes?

If this were true, the Lotze-Harleß approach would be of a rather limited value for building a comprehensive action-related theory. After all, only few intended actions are carried out just to move an effector or to produce immediate sensory feedback. On the contrary, most action goals refer to more remote effects, or *extrinsic* feedback (in terms of Salmoni et al., 1984), like when switching on a light, reaching for a glass, or stepping on a car's brake. So, a comprehensive approach to action coding should take this into its scope. Accordingly, I assume that action codes may refer to *any kind* of perceivable action outcome, and thus be made up of several effect codes of varying abstractness or complexity. That is, actions may well be coded in terms of movement parameters, such as effector, location, speed, or distance. But an action code may also comprise information about the category and function of the movement and any event that, in the actor's perception, is contingent on that particular movement—be it the approaching waiter I called or the broken nose of the boxing champ's opponent.

Thus broadly conceived, even a single effect code may serve several functions. First, it may refer to, and thus represent, a sensory as well as a motor event. On the one hand, this means serving a perceptual function, inasmuch as the code is activated by, and thus refers to, a perceived action outcome, hence information afforded to the sensory system. On the other hand, effect codes are assumed to be involved in the process of action selection and action planning, thereby representing their associated motor pattern.[2] This view resembles that of Adams (1968) or Schmidt (1975), who distinguished between a *memory trace*, which is the learned motor pattern itself, and a *perceptual trace*, which is a representation of the (to-be-)expected sensory consequences of a pattern. However, in Adams' and Schmidt's theories, perceptual traces are used only for an evaluation of the already performed movement, whereas I assume that the cognitive system also uses perceptual traces to select and control memory traces. That is, these traces mediate perception as well as action planning, which is insufficiently expressed in calling them "perceptual."

A different—but related—example of how effect codes serve different functions refers to the time scale of the represented events. On the one hand, such a code may represent a movement-produced event that already happened. On the other hand, however, it is also used for planning an action and anticipating its likely outcome. That is, effect (or action) codes refer to both effected (or perceived) and to-be-effected (or to-be-perceived) events (Prinz, 1992; Prinz et al., 1995).

To sum up, effect (or action) codes may refer to (i.e., code) any kind of movement- or action-contingent event in the world or in the perceiver/actor's body (i.e., the cognitive system's closest environment), as far as this is perceptually discriminable and actually noticed. Effect codes are both perceptual *and* action-related cognitive entities, and thus form the building blocks of intentional action. As most actions will produce more than one discriminable effect on the environment, they will be represented by integrated structures of several effect codes. I will refer to these entities as *action concepts*, both to express the differ-

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[2] At this point of theoretical development, a more precise definition of what "motor patterns" are and a description of how exactly they are linked to effect codes seems premature. Motor theorists (e.g., Schmidt, 1975) may think of a linkage between a generalized motor program and its cognitive retrieval cue, whereas action theorists (e.g., Greene, 1982) may consider effect codes as cognitive constraints of sensorimotor coordination.

ent janus-faced functions they serve and to emphasize that they may comprise sensory and motor as well as more abstract information, such as the meaning of a movement forming a gesture or a symbolic act.

It is important to note that it would be inadequate to classify action concepts as cognitive structures *or* processes. On the one hand, they are activated by registering incoming information and associated with output-producing motor patterns, which may well qualify them as representational cognitive structures. On the other hand, however, their activation does not only mean that a certain informational state is established, but also has a direct impact on action selection and action control, which may characterize an activated concept as a cognitive process. Moreover, speaking of a particular code or concept does not mean that this is a rigid and stable thing. On the contrary, action concepts are very likely to change over time and through practice. Effects produced in one particular situation, such as an echo in the mountains, will not be reproducible in others, and some events that once occurred at the same time an action was performed may turn out not to be causally dependent on that action. That is, with increasing repetition of an action, codes of accidental effects will vanish, so that action concepts become more and more reliable and valid representations of the to-be-expected action outcomes. This also means that action concepts will become increasingly context-sensitive, so that situational dependencies are more and more taken into account in selecting actions and anticipating their consequences.

As pointed out, action concepts are assumed to mediate and be active in action perception as well as action production and to represent anything an action perceptually leads to. If we take this assumption seriously, a further—admittedly radical—theoretical step presents itself. If one accepts that action concepts code stimuli as well as responses, one can ask whether there is any need for a further, distinct class of cognitive codes, such as pure perceptual codes. Dewey (1896) and Gibson (1979), in their more general approaches, or Wolff (1984), with special regard to eye-movement control, have emphasized that any perception is an achievement of an actively behaving observer. In the case of touch, hardly any meaningful perception is possible without moving the sensing organ across the object to be perceived. Visual perception of an object requires the coordination of trunk, head, and eyes to orient the perceiver to the object's location; and auditory, olfactory, or gustatory perception often presupposes similar behavior. So, perceiving understood as a temporally extended act of information acquisition, rather than as receiving a certain amount of sensory input at a point in time, comprises action and must thus accompany action control. The emergence of action concepts with their dual perception-action function would not only seem a natural consequence of this intertwined relationship between acting and perceiving, but also provide an appropriate structure for controlling both. From this view, a distinct class of perceptual codes is unnecessary. That is, perceiving and acting are not merely alternating modes or functions but, in some sense, one and the same thing.

2.3 Applying the Action-Concept Model

After having characterized the basic elements of the action-concept model, I shall now examine how it may be applied to a standard choice reaction time task. Figure 2 shows how a particular act in a certain trial might be represented. In the environment of the perceiver/actor, there is stimulus S, say, a red light flashing on the left side, and the observable response R, say, a left-hand keypress. S has several features: It might be round, red, have a certain intensity, and so forth. Although some information may get lost during its way through the sensory systems, many features will get coded in the cognitive system by activating their corresponding codes, say, s_1, s_2, and s_3.[3]

Let us now assume that the task requires responding to s_2 only (the red color) by performing R. To perform that response, motor pattern m needs to be activated. According to the action-concept model, this cannot be done directly, for example, by linking s_2 and m, because motor structures can be addressed only via action concepts or the effect codes forming them. That is, s_2 needs to be linked to an action concept or effect code that is associated with m. In the example, response R produces an effect with three perceivable (or actually perceived) features, say, an audible click, a kinesthetic sensation in the left index finger, and a visible accuracy feedback on the screen, coded by r_1, r_2, and r_3, respectively. As carrying out R will usually be accompanied by all these three events or event features, their codes—which form the action concept—will be associated with m, the responsible motor pattern. This means that activating any of these codes will increase the activation of and eventually launch m, thereby effecting R. Which of the three possible effect codes will actually be selected and used in a given task for producing R will depend on both previous practice and task instruction (Hommel, 1993b; Prinz, 1996). Whichever is selected, say, r_2, is then temporarily linked to the relevant stimulus feature, such as s_2 in the present example.[4]

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[3] It is important to note that my distinction between *stimulus codes* (s_1, ..., s_n) and *response codes* (r_1, ..., r_n) is not meant to reintroduce two different kinds or classes of codes. Actually, both stimulus and response codes are effect codes (or integrated effect-code structures, hence action concepts), the first being functional in acquiring information about S, the second used to access the motor pattern producing R. That is, stimulus and response codes differ in the role they play in a task, not in the way they work.

[4] This is, of course, a simplification. There is evidence that, at least in complex choice tasks, performance does not necessarily rely on direct S-R associations but on S-R translation rules (e.g., Duncan, 1977, 1978). However, the theoretical conclusions presented here do not depend on this issue.

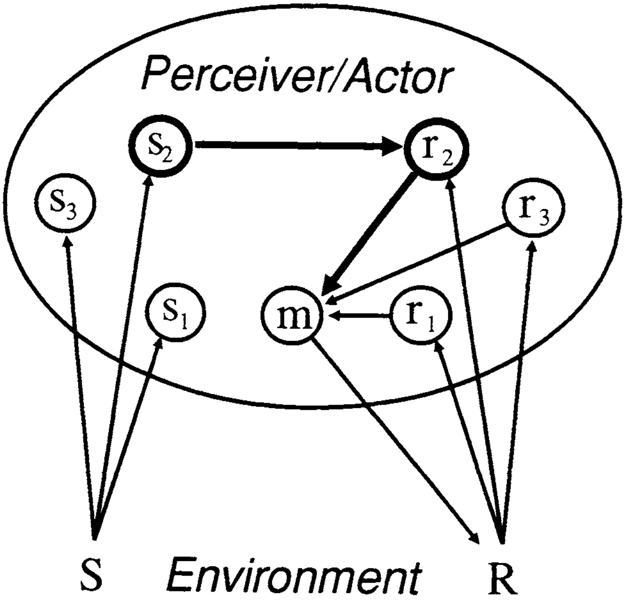

Figure 2. An illustration of the activation flow in a typical choice-reaction task as seen from an action-concept perspective. The features of stimulus S are coded by s_1, s_2, and s_3, and the effects of response R are coded by r_1, r_2, and r_3. Relevant stimulus feature s_2 is temporarily associated with relevant reponse feature (i.e., intended action effect) r_2, through which m, the motor pattern producing R, is accessed.

Apart from its role in the acquisition of external information (i.e., perceptual activities), an effect code or action concept can be activated via four routes: First, activation may come from purely endogenous sources, like in the course of action planning. Second, registering effects of a self- or other-performed action may also lead to an activation of effect codes. Third, overlearning of a particular S-R pairing, say, a red traffic light and stepping on a car's brake pedal, may lead to an enduring association between the respective stimulus (feature) code (i.e., the action concept or the part of it representing the red light) and a response (feature) code (i.e., the action concept or the part of it representing the braking movement), so that activation of the respective stimulus code may lead to some automatic activation of the associated response code.

Fourth, and most important for explaining compatibility phenomena, effect codes may be activated by stimuli that share features with action effects. In a choice task, response selection is carried out by activating particular effect codes or whole action concepts, that is, codes of intended action effects. Let us assume that the actor chooses between a left- and a right-hand keypress. As being left or right is the main difference between the two response alternatives, relative response position is likely to be coded in the action concepts controlling the appropriate motor patterns. However, as action concepts not only control motor activity but also serve perceptual functions, any incoming information about horizontal position will tend to activate the corresponding action concept, provided the concept is not refractory at this time (see 3.5.2). For example, because a left-hand response will produce left-side effects, a LEFT effect code will be included in the response's action concept. However, the LEFT code does not exclusively code left-hand keypressing events in a certain task; it simply stands for the fact that something has the feature of being LEFT. In other words, this LEFT code will be part of any action concept referring to left-side events. As a consequence, it will necessarily be activated by any incoming information about leftness, be it stimulus-related information or response-related information.

2.4 Accounting for Basic Effects

Let us now take a closer look at how phenomena of S-R compatibility could be explained from an action-concept view. Because of their relative simplicity, I will concentrate on spatial compatibility effects, although other effects could be accounted for in a similar way. One of the most basic effects in the spatial domain is produced by manipulating S-R mapping. Assume that subjects are presented with stimuli appearing randomly on the left or right side, and they respond by pressing a left- versus right-hand key. There are two possible mappings of responses upon stimuli: left response to left stimulus and right response to right stimulus, or left response to right stimulus and right response to left stimulus. As one would expect, the first mapping is much more compatible (i.e., allows for better performance) than the second (e.g., Broadbent & Gregory, 1962).

The left panel of Figure 3 represents the example of a response to a left-side stimulus with a compatible and an incompatible mapping. With a compatible mapping, the correct left-hand response is performed by activating m_1, whereas the incompatible mapping calls for a right-hand response, performed by activating m_2. However, motor patterns cannot be accessed directly, but only via associated action concepts. With spatially defined responses, these concepts are likely to comprise codes referring to response location, which are represented in the example by l and r. Independent of the mapping, the left-side stimulus will always activate l, hence the action concept of the left-hand response. This means that with a compatible mapping nothing else must be done after stimulus coding—just the movement corresponding to the activated pattern has to be carried out. With an incompatible mapping, however, a selection problem arises. Whereas m_1 will be activated by the stimulus via l, the correct response actually requires activation of m_2, which can only be accessed via the alternative action

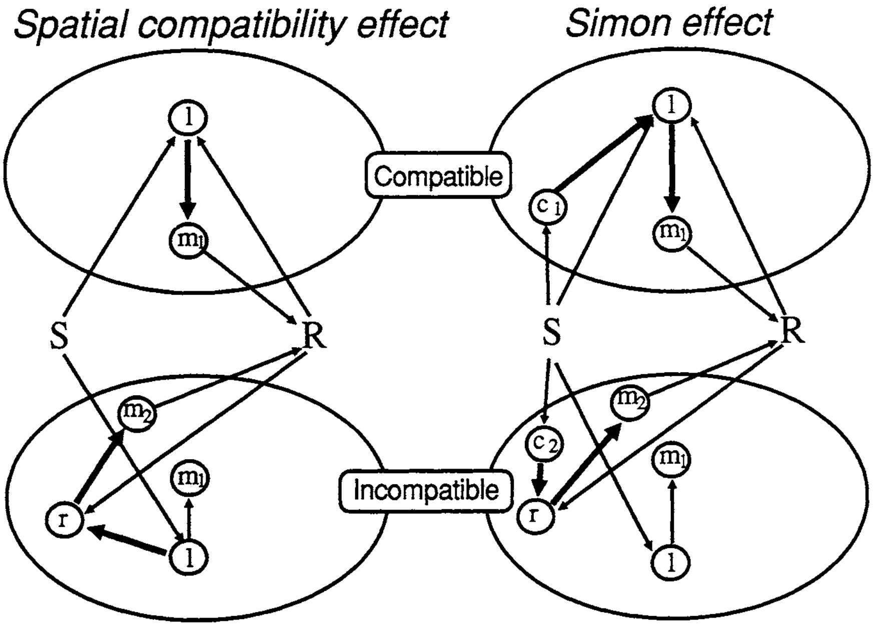

Figure 3. An illustration of the hypothetical activation flow in a spatial compatibility task with compatible and incompatible stimulus-response mapping (left panel), and in a Simon task under compatible and incompatible conditions (right panel). Left-side stimulus S activates its corresponding effect code l that is associated with motor pattern m_1. In compatible conditions, activating m_1 via l produces the correct left-hand response, whereas in incompatible conditions a right-hand response is required, produced by activation of m_2 via r. In the spatial compatibility task, the relevant stimulus feature is stimulus location (coded by l). In the Simon task, the relevant feature is color (coded by c_1 and c_2, which are linked to l and r, the effect codes representing the relevant response features of the left- and right-hand response, respectively).

concept r. This means that, first, an additional translation step (l → r) will be necessary to activate the correct (but incompatible) response, and, second, that this activation process is counteracted by stimulus-induced activation of the incorrect (but compatible) response. Thus, an incompatible mapping will yield slower responses than a compatible one.

As already mentioned, spatial S-R correspondence affects reaction time even if stimulus location is irrelevant to the task. Assume that subjects respond to a nonspatial stimulus attribute, such as color, by pressing a left- versus right-hand key. Even if the stimulus location is varied randomly, and is thus completely uninformative, responses are faster and more often correct if the stimulus appears on the same side or relative position as the response it signals (e.g., Simon & Rudell, 1967). This is called the *Simon effect*. The right panel of Figure 3 represents the example of a response to a left-side stimulus in a Simon task. In the compatible condition, hence with S-R correspondence, stimulus color c_1 (red, say) calls for a left-hand response, produced by motor pattern m_1 via action concept l. As the stimulus appears on the left side, l receives activation from the stimulus via two routes: direct input from the stimulus-location information and indirect input from the color code. Consequently, the required activation threshold will be reached faster than without spatial S-R correspondence. In the incompatible condition, stimulus color c_2 (green, say) calls for a right-hand response, produced by m_2 via r. However, the left-side stimulus will again activate l, thus producing response competition. As a consequence, responses will be slower in the incompatible than in a compatible or neutral condition.

Up to this point, the compatibility story told from an action-concept point of view does not sound too different from that of other views. In fact, apart from terminology, the action-concept account of standard compatibility effects comes very close to the original coding model of Wallace (1971) or the dimensional-overlap model of Kornblum et al. (1990). However, crucial differences will be found in the details. In the following, the action-concept model will be applied to several recent observations in the compatibility field, mostly from Simon tasks. As we shall see, an action-concept approach provides a rather natural account for most of these findings, whereas alternative models often have problems in coming up with any explanation. However, we shall also see that the action-concept model in its current shape is far from being complete. So far, the discussion was mainly concerned with assumptions regarding the emergence and the basic characteristics of effect codes and action concepts. As already pointed out, these assumptions are completely sufficient to account for basic compatibility effects and, as the following sections will show, they allow for a successful prediction of several novel and surprising compatibility phenomena. Yet, I shall also point out that precise predictions regarding more subtle aspects of data patterns, such as relative effect sizes or reaction time distributions, will require a bit more detail with regard to the temporal characteristics of code or concept activation. Fortunately though, recent findings discussed below permit the elaboration of at least some important characteristics.

3 Testing and Refining the Action-Concept Model

3.1 Action Effects and Action Goals

According to the action-concept approach, actions need not or need not only be coded in terms of movement parameters or sensory movement effects. Even remote events produced by a particular action may be coded as action effects, integrated into an action concept, and thus represent the action in the cognitive system. First support for such an idea in the spatial compatibility field came from the studies of Guiard (1983) and Riggio, Gawryszewski, and Umiltà (1986).

Guiard's (1983) subjects rotated a steering wheel in response to the pitch of a stimulus tone. Independent of how the hands were positioned and in which direction they had to be moved, left-hand turns were faster if signaled by a left-side tone and right-hand turns were faster with a right-side tone compared with conditions involving noncorrespondence between stimulus and direction of rotation. Thus, insofar as the correspondence effect was due to a match of stimulus and response codes, the response codes did not, or not only, refer to hand position or movement, but to the direction of wheel rotation; hence, the intended action effect or action goal. That is, the action goal must have been represented in the response code or action concept.

In the experiment of Riggio et al. (1986), subjects operated response keys with sticks that were crossed or held in parallel. Irrespective of the active hand or its location, responses were faster with spatial correspondence between stimulus and response key, that is, end location of the stick. Again, the results show that correspondence of stimulus and action goal was important, suggesting that the code representing the action goal was an integral part of the action concept.

Action goals can be defined as that portion of perceivable action effects that are actively anticipated and intended by the actor (Hommel, 1993b; Prinz, 1996). That is, what counts as an action goal should mainly depend on the actor's intention. Consequently, manipulating intention should have an impact on how or to which degree an action effect is coded and represented in the action concept. In fact, there is some evidence for a critical role of intention:

In a Simon task, Hommel (1993b: Exp. 1) had subjects respond to the pitch of a left- or right-side tone by pressing a left versus right key. Pressing a certain key produced a light flash on the opposite side (see Fig. 5 of Prinz, this volume, for an illustration). This was the critical manipulation because it introduced two different and conflicting compatibility relations. Whereas correspondence between stimulus and key implied noncorrespondence between stimulus and light, stimulus-key noncorrespondence meant stimulus-light correspondence. The question was which relation would be more important or, more precisely, whether the importance of a particular relationship would depend on the action goal of the subjects. So, one group of subjects was asked to "press the left/right key" in response to the pitch, whereas another group should "flash the right/left light" in response to pitch. That is, both groups performed the same movements in response to the same stimuli, but their intention referred to different events located on different sides. As it turned out, the groups behaved quite differently: Whereas the key group was faster with tone-key correspondence than with noncorrespondence, the light group was better with tone-light correspondence, although this meant tone-key noncorrespondence. In other words, performance was best with correspondence between stimulus and intended action effect.

Although these findings suggest a dominant role of intended action effects, later experiments showed that nonintended effects are also integrated into action concepts. For instance, if the spatial correspondence between stimulus and anatomically defined hand, stimulus and hand position, and stimulus and action goal (light flash) is varied orthogonally, each relationship contributes an effect of its own (Hommel, 1993b: Exp. 2). In another study (Hommel, in press a: Exp. 1), subjects responded to color stimuli randomly appearing on the left or right side. In one half of the session, each keypress produced a tone on the side opposite to the key, so that each action had both left- and right-side effects. Although subjects received a key-related instruction, the presence of the tone reduced the effect of stimulus-key correspondence. In other words, correspondence between the stimulus and a task-irrelevant, but hardly ignorable auditory action effect diminished the facilitative effect of stimulus-key correspondence (and/or the interfering effect of stimulus-key noncorrespondence).

The finding that learned, artificial action effects and manipulations of the actor's action goal influence the speed of response selection provides strong support for the proposed extension of the Lotze-Harleß approach. As expected from the action-concept model, action codes are not restricted to referring to body-related, sensory feedback. In contrast, they also include information about body-unrelated effects, insofar as these are "produced" by, that is, are dependent on a particular movement. Moreover, the selection between alternative effects is clearly mediated by the intention to act. This means that action codes or concepts are more than mere movement codes in integrating information about a movement's end, hence the action goal. Although such a finding does not stand in opposition to other coding theories, it is hardly predicted by any of them. So, the action-concept approach provides at least a reasonable extension of other models.

3.2 Creating Novel Compatibility Effects

The action-concept model does not account only for the modification of standard compatibility effects by artificial action effects, it can also be used to predict the emergence of novel S-R compatibility effects. Imagine a response set that has no feature overlap with the stimulus set, such as pressing a central button one versus two times in response to the color of a left or right stimulus. As the responses do not vary on the horizontal dimension, the spatial position of the stimulus is not expected to affect the two response alternatives differently, and the same should hold for color. But assume that, say, the single response produces (i.e., is associated with) a left-side tone, whereas the double press produces a right-side tone. According to the action-concept model, the tone positions should be coded as action effects and thus be integrated into the action concepts controlling the single and the double keypress. Then there is overlap between an irrelevant stimulus feature and an irrelevant response feature, hence stimulus and response (-effect) location. According to the model, compatibility effects are expected: If stimulus and response-contingent tone correspond, responses should be faster than with noncorrespondence.

And in fact, in an experiment using such a design, responses producing left-side tones were faster if the stimulus also appeared on the left side, whereas responses producing right-side tones were facilitated by right-side stimulus presentation (Hommel, in press a). A similar effect was observed with single versus double or left- versus right-hand keypressing responses to color stimuli, when one response was paired with a high-pitched tone and the other with a low-pitched tone. After some practice in "tone production," a further tone was presented along with the visual stimulus. As expected, responses were faster when the pitch of this tone matched the auditory action effect of the correct response (Hommel, in press a).

Together with the results reported in the preceding section, these findings provide ample evidence that even irrelevant action effects are integrated into something like action concepts and thus play some role in response selection. There seems to be little difference between response features that are intrinsic to the performed movement and those that are not, just as expected from an action-concept point of view. Considering this may help to clarify the relationship between compatibility effects that are currently thought to be of a different kind. For instance, Simon, Sly, and Vilapakkam (1981) distinguish between effects of spatial compatibility, such as those discussed here, and effects of symbolic compatibility. As an example for the latter they refer to the observation that color stimuli are responded to faster if assigned to same-colored response keys (e.g., red stimulus → red key, green stimulus → green key) rather than to alternate-colored keys (e.g., red stimulus → green key, green stimulus → red key; cf. Hedge & Marsh, 1975; Simon & Sudalaimuthu, 1979). Although people would agree that the color of a response key is, in a sense, not as intrinsic to a response as the spatial location of the finger, there is, however, no available theory that would allow us to tell whether this is a crucial difference or not. Therefore, it is hardly surprising that some researchers have drawn a line between the more and the less intrinsic cases (e.g., Nicoletti & Umiltà, 1984; Simon et al., 1981), whereas others have not (e.g., Kornblum et al, 1990; Lu & Proctor, 1994).

The action-concept model does not only provide a firm theoretical basis for predicting that less intrinsic response (or response-contingent) features or events can have the same effects as the more intrinsic ones, it also explains why: If even irrelevant response-contingent features, like the tones in Hommel's (in press a) experiments, are integrated into action concepts, relevant features should be integrated all the more. Consequently, action concepts including "red" effect codes are activated by red stimuli and those with "green" codes by green stimuli, which facilitates response selection with the same-color mapping, but hampers selection with alternate mapping. Of course, the integration of response-contingent events will strongly depend on intentional and attentional factors (Hommel, 1993b) as well as on the salience of those features (Barber & O'Leary, 1996; Weeks & Proctor, 1990), so that intended, attended, and salient response-contingent effects will be likely to produce larger compatibility effects than those that lack all these qualities. However, consistent with the action-concept model, the available evidence does not suggest any qualitative difference between compatibility effects associated with response- or movement-intrinsic features and those owing to more extrinsic response-contingent events or features. Consequently, the distinction between spatial and symbolic compatibility lacks empirical support and is not really needed.

On a general level, demonstrating effects of compatibility between irrelevant stimulus features and irrelevant action effects does not directly contradict other coding models. The most obvious theoretical move would be to simply assign the status of a regular response feature to an action's effect and then account for the findings by referring to similarity between stimulus and response sets. In fact, this is exactly the interpretation of the action-concept approach. However, unlike the action-concept model, available coding models do not explain where response features come from and *why* stimulus-response similarity produces compatibility effects. And as long as this is so, they can offer explanations after the fact only.

3.3 The Role of Response Uncertainty

One of the most salient characteristics of the action-concept model is that, unlike other models, it does not locate stimulus codes and response codes in two different domains or systems. Although, in a given task, one code may represent the imperative stimulus whereas another represents the associated action, neither code has a particular property qualifying it as a stimulus or response code independent of the task. In other words, though individual codes or whole action concepts may play task-specific roles, there is no "receptive-only" or "productive-only" code or concept. Accordingly, stimulus coding and response coding, or stimulus selection and response selection, take place within one common representational system (Prinz, 1990; Prinz et al., 1995).

An important implication of this basic assumption is that stimulus processing and response processing are allowed to overlap in time and, thus, may affect each other as long as they are not completed. Whereas the following sections will draw on this implication in one way or another, this section focuses on which predictions it suggests concerning the role of response uncertainty in compatibility effects. In most compatibility theories, response uncertainty plays a major role—implicitly or explicitly. And it seems to make sense: As S-R compatibility effects are usually attributed to problems arising at a response-selection stage, no such effects are expected without response uncertainty. If a response can be selected before the imperative stimulus appears, so the argument goes, the selection process cannot be affected by the stimulus, hence by the S-R relationship (e.g., Anzola, Bertoloni, Buchtel, & Rizzolatti, 1977; Berlucchi, Crea, Di Stefano, & Tassinari, 1977).

Interestingly, this "preselection logic" is not shared by the action-concept model. Its view is that response selection is accomplished by activating the correct response's action concept or, more precisely, those codes of the action concept that represent the relevant response feature(s). Of course, there is no reason to doubt that this can be done before the imperative stimulus arrives, just as traditional models assume. Yet, this does not preclude compatibility effects. As stimulus and response processing take place within the same system, preselecting a response code cannot protect it against influences from (e.g., spatial) stimulus coding on principle. That is, as long as the response is not carried out, any response-congruent or conflicting stimulus information may facilitate or hamper responding. Consequently, response uncertainty should not play a major role from an action-concept point of view.

At first sight, the empirical evidence available so far clearly favors the traditional view. In fact, simple reaction time tasks (i.e., tasks with random left- and right-side stimuli and blocked left- or right-hand responses) yielded no or only very small S-R correspondence effects. Small effects (≤ 5 ms) are commonly not considered to be real compatibility effects but are ascribed to the additional time needed for interhemispherical transmission when stimulus hemifield and responding hand do not correspond (for reviews see Bashore, 1981; Hasbroucq, Kornblum, & Osman, 1988; Marzi, Bisiacchi, & Nicoletti, 1991). So, response certainty, hence the absence of response selection, seems to eliminate compatibility effects.

However, while these findings apparently support the preselection logic following from traditional models, there are other reasons why compatibility effects may not occur in simple reaction time tasks. First, just like a stimulus dimension tends to be ignored if it does not vary between alternative stimuli (Olson, 1970), a response may not be spatially coded in the absence of a valid spatially defined alternative (Nicoletti et al., 1984). Consequently, its action concept would not include a spatial (effect) code that could be activated by a spatially corresponding stimulus. Second, simple reactions may be carried out too quickly to be affected by spatial stimulus information. Usually, simple reactions are much faster than choice reactions (e.g., Teichner & Krebs, 1972), probably because both stimulus identification and response selection processes do not contribute to reaction time (Theios, 1973). If we assume that the critical stimulus feature (e.g., a certain energy increment) can be coded and responded to before the stimulus is spatially coded, at least in a considerable number of trials, the lack of a stimulus location effect would have found a trivial explanation. That is, the mere absence of compatibility effects in simple reaction time tasks as such does not evidence a critical role of response uncertainty.

Recent observations actually suggest that the importance of response selection and response uncertainty has been overstated by traditional models. In an experiment of Hommel (1995a: Exp. 1), subjects performed a Go-Nogo task with responses varying randomly between trials. In each trial, a response cue that preceded the imperative stimulus of about 1 sec would signal which of two (left- vs. right-hand) response keys, operated by the left and right index finger, was valid. The imperative stimulus was a green Go signal or a red Nogo signal that indicated whether the precued response should be carried out or suppressed. Critically, these signals appeared randomly on the left or right side of the screen, so that there were conditions with correspondence between Go signal and response and some without. As the correct response was known in advance, response selection should have been completed long before the Go (or Nogo) signal appeared. Consequently, traditional models of S-R compatibility would predict the absence of compatibility effects. There was, however, a very large effect: Responses were 43 ms faster with correspondence than with noncorrespondence. A further experiment (Hommel, in press b: Exp. 1) showed that the same effect is obtained with 100% Go trials, which rules out the argument that the Go-Nogo manipulation may have precluded sufficient response preparation. Other experiments (Hommel, in press b) used more conventional, simple reaction time tasks, that is, tasks in which response uncertainty was eliminated by blocking response location (thus, the responding effector) over a number of trials. Nevertheless, in most cases, significant compatibility effects between 4 and 20 ms were observed. The fact that reliable effects even occurred when two fingers of the same hand were used as response alternatives ruled out an account in terms of anatomical connectivity.

We can conclude that consistent with the action-concept model but not with traditional accounts, compatibility effects do not depend on response uncertainty. But then why are these effects so small or even absent with simple reactions? As annoted, one reason may be the lack of any necessity to discriminate between left and right response, and another may have to do with the temporal relationship between coding the relevant stimulus information and coding stimulus location. There is actually evidence that both factors play a role. Evidence for the first one was found in an experiment of Hommel (in press b), in which subjects performed a simple reaction time task with a slight modification. The main task was to press a predetermined (i.e., blocked) left- or right-hand key in response to a green patch randomly appearing on the left or right side. In a few trials, however, a red "catch signal" was presented centrally immediately after a response. In one group of subjects, this meant to press the response key a second time, whereas in another group, the alternate key had to be pressed. That is, only one response was to be held in preparation in the first group, but two in the second. Although the response to the catch signal was not a valid response alternative to the blocked simple reaction, holding two responses in preparation alone should require a discrimination between them, and hence foster spatial response coding. Consequently, according to the discrimination hypothesis, spatial S-R correspondence should yield larger effects in the second than in the first group, which is exactly what was found. So, the need for response discrimination seems to be an important factor in predicting compatibility effects under response certainty.

Evidence for an effect of the second possible factor, the relative speed of spatial stimulus coding, is available as well. As pointed out, processing the relevant information in a simple reaction time task can be assumed to be faster than processing spatial information. With very rapid responses of a given subject or group, this would mean that the response is carried out even before a spatial code is formed, so that, for trivial reasons, no effect of spatial S-R correspondence occurs. With the slower responses, however, it is more and more likely that spatial coding is completed at the time of response selection, so that an effect is expected. That is, when comparing the faster and the slower portion of reaction time distributions, correspondence effects may show up in the slower, but not the faster portion. In fact, this is observed in simple reaction time tasks (Hommel, in press b) as well as in Go-Nogo tasks with prepared responses (Hommel, 1995a: Exp. 1, in press b: Exp. 1): Whereas the correspondence effect is hardly detectable with fast responses, it increases the longer responding takes. That is, the absence of a reliable correspondence effect in reaction time averages does not necessarily mean that no effect at all is obtained; it may simply be restricted to the slower portions of the reaction time distribution.

To sum up, these demonstrations of compatibility effects under response certainty represent a major challenge for most compatibility theories. This is especially true for perceptual theories claiming that compatibility effects arise from problems with stimulus identification (Hasbroucq & Guiard, 1991; Stoffels, van der Molen, & Keuss, 1989). While one may argue that some degree of identification is necessary in Go-Nogo tasks, this is much less convincing with simple reactions. But, as already discussed, response-selection accounts hardly fare any better. Although the action-concept approach also assumes that compatibility effects reflect problems having to do with response selection, its assumptions that action concepts serve a dual perception-action function and that stimulus and response processing take place in the same system provide a reasonable theoretical escape. Like other models, an action-concept model would assume that blocking or precueing a response affords and motivates the preactivation and maintenance of the action concept controlling the appropriate motor pattern. However, preactivating an action concept does not prevent it from being activated by stimulus information, nor does it preclude stimulus-induced activation of a competing action concept. Thus, competition between actions and/or stimulus-induced action tendencies does not end with response selection, but only with execution.

3.4 Temporal Dynamics of Compatibility Effects

Most approaches to S-R compatibility that have been presented over the decades are more or less static (see, e.g., Fitts & Seeger, 1953; Simon, 1968; Wallace, 1971). Their explanatory goals were restricted to accounting for the difference between compatible and incompatible mappings or conditions in reaction time, but there was little attempt to explicate interactions between compatibility-inducing factors, such as spatial correspondence, and other experimental factors or of other measures and data than reaction time means. On the contrary, if compatibility effects were found to interact with factors unrelated to the response-selection stage (where "compatibility" is usually "located"), such as in the Stanovich and Pachella (1977) study, this was dismissed by claiming it was a special case (e.g., Sanders, 1980). However, recent studies have demonstrated a considerable number of those interactions, interactions that are very difficult to interpret from the classical additive-factors point of view (Sanders, 1980; Sternberg, 1969) on which stage models of information processing are usually based. Actually, the available evidence suggests that interactions of this kind are less likely to indicate a certain processing-stage architecture, as additive-factors logic would imply, but rather point to certain temporal characteristics that cognitive codes seem to possess. I shall discuss two of them: the automatic decay of codes representing irrelevant information and the active maintenance of those that code relevant information. Subsequently, I shall point out that although the hypothesis of decay and maintenance of cognitive codes as such is not bound to a particular theory, combining it with the action-concept model has certain theoretical advantages that do not emerge from other combinations.

3.4.1 Automatic Decay of Irrelevant Information

As mentioned, effects of spatial S-R compatibility can be shown to interact with a multitude of non-response-related factors. It is interesting that the available data show two regularities: First, interactions seem to be associated with manipulations of irrelevant S-R correspondence only, such as in the Simon effect. Second, the form of the interactions is mostly underadditive, that is, the size of the compatibility effect decreases with increasing level of the other factor, hence with task difficulty. In contrast, which other factor is varied seems to play a minor role: Underadditive interactions have been found with factors that presumably affect sensory processes, such as retinal eccentricity, stimulus quality, or stimulus contrast (Hommel, 1993c), as well as with more identification-related factors, such as stimulus discriminability (Hommel, 1994a, 1994b; Lu & Proctor, 1994), and even with "later" factors, such as memory-set size (Hommel, 1995b) or single-versus-dual task manipulations (Hommel, 1996b; McCann & Johnston, 1992).

Interactions of this sort are a surprising finding from an additive-factors perspective, because it would localize the compatibility effect at a number of very different processing stages at the same time. However, there is another interpretation (Hommel, 1993c, 1994a) that fits well into the action-concept framework. It rests on the observation that responses to spatial location can usually be carried out faster than those to other stimulus features, such as form (e.g., Hommel, 1993c: Exp. 3), suggesting that spatial information is available quite early. This has implications for Simon-type tasks. If we assume that relevant and irrelevant stimulus information is processed independently and in parallel, as the action-concept model implies (see Fig. 3, right panel), the earlily available spatial information would activate its corresponding action concept some time before the correct concept is activated by the outcome of stimulus discrimination or identification. What happens to this activation during the time in which the relevant stimulus information is being processed? Hommel (1993c, 1994a) reasoned that it would make little sense if it stayed for very long, the less so as it represents irrelevant information. He thus claimed that automatically induced activation spontaneously decays over time. Provided that the decay is sufficiently rapid, this means that spatial stimulus information should have less impact the longer the relevant information is processed, hence the more time it has to decay. Therefore, any manipulation delaying the processing of the relevant stimulus information should diminish the size of the correspondence effect, hence produce an underadditive interaction.

The assumption of quickly decaying spatial information (or of codes representing it) accounts not only for underadditive interactions between irrelevant S-R correspondence and other, response-unrelated factors, but also for underadditive effects between correspondence and relative response speed *within* a given condition (De Jong, Liang, & Lauber, 1994). In an analysis of reaction time distributions, De Jong et al. as well as Grice, Boroughs, and Canham (1984) found that correspondence effects were mainly associated with fast responses, but continuously decreased with increasing reaction time. In a reanalysis of Hommel's (1993c) data, similar patterns were obtained (see Eimer et al., 1995) corroborating this finding. A typical pattern taken from this study (Hommel, 1993c: Exp. 2) is shown in Figure 4. In this experiment, the effect of spatial S-R correspondence was measured under low, medium, and high retinal eccentricity of the visual stimulus, represented by the three pairs of curves. Each curve shows the group means of the individually determined quintiles, that is, the means of the first to fifth 20% of the rank-ordered reaction times in a condition. The decay of spatial codes is indicated by two effects. First, as reported by Hommel (1993c), the overall compatibility effect decreases from low to high eccentricity, hence with increasing reaction time level. Second, similar to De Jong et al.'s (1994) and Grice et al.'s (1984) findings, within a particular eccentricity condition, the compatibility effect decreases continuously from the first to the fifth quintile, hence from fast to slow responses.

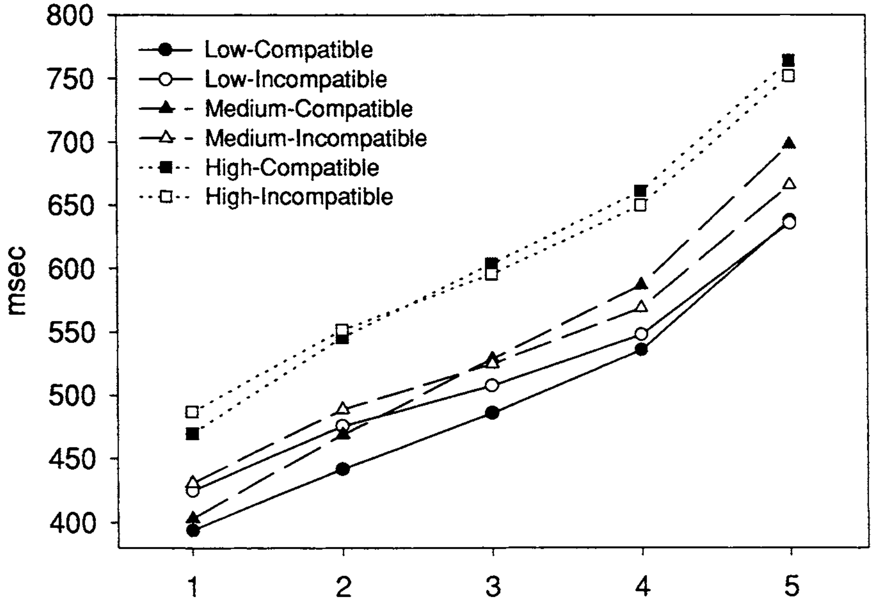

Figure 4. Group quintiles for compatible (C) and incompatible (IC) conditions as a function of retinal stimulus eccentricity (low, medium, or high) in Hommel's (1993c) Experiment 2.

Besides showing up in interactions with other experimental variables and with relative response speed within a particular condition, decay-type effects have also been observed with manipulations of stimulus-onset asynchrony, that is, with direct variations of the temporal relationship between relevant and irrelevant stimulus information. Consistent with the decay hypothesis, Hommel

(1993c) found a decreased Simon effect (relative to the standard condition) when the imperative stimulus built up gradually on the screen, so that its position was visible about 200 ms before its identity. Likewise, Kornblum (1994) or Stoffer and Yakin (1994) observed a decreased Simon effect when the side on which the stimulus was to appear was cued in advance. But not only Simon tasks produce decay effects: As reported by Lu and Proctor (1996) or Sugg and McDonald (1994), and summarized by Lu (1996), preexposing the irrelevant information can also reduce the size of the Stroop effect (i.e., interference due to incongruence between two stimulus features like color and meaning of color words, or location and meaning of locatory words). That is, the decay of code activation resulting from irrelevant information seems to be a rather general phenomenon.

According to Hommel's (1993c) approach, the decay of cognitive codes happens spontaneously, not due to a particular inhibitory strategy or the like. First evidence for this assumption was reported by Hommel (1994a). In this study, S-R discriminability was varied in a Simon task to delay the processing of the relevant stimulus information relative to that of the irrelevant location information. Consistent with the decay assumption, the effect of irrelevant S-R correspondence decreased from high to low discriminability. A further manipulation concerned the frequency of trials involving S-R noncorrespondence, hence the likelihood that irrelevant stimulus location and response location would not match. In a 50:50-block, noncorrespondence trials occurred as often as correspondence trials, as in the standard paradigm. However, in a 25:75-block, noncorrespondence trials were three times as frequent as—thus more likely than—correspondence trials. As expected, the Simon effect was much smaller with a high percentage of noncorresponding trials, hence in the 25:75-block, an effect that was successfully replicated with slightly different ratios in the Hommel (1994a) study and by Toth et al. (1995). It indicates that subjects were able to make use of the fact that left-side stimuli were likely to precede right-hand responses, and vice versa, by preparing the response opposite to the stimulus. Interestingly, however, the frequency manipulation did not modify the impact of discriminability on the correspondence effect. This means that, if the decreased correspondence effect with decreasing discriminability reflects code decay, the decay rate is not affected by frequency. Yet, with increasing frequency of noncorrespondence trials, (fast) decay would become more useful. So, if decay is under strategical influence, one would expect faster decay with higher frequency. As this is not observed, decay seems to occur automatically.

3.4.2 Active Maintenance of Relevant Information

With regard to irrelevant stimulus information, spontaneous decay of code activation does not provide any problem for a perceiver/actor: What is lost is not needed anyway. Yet, if a code represents relevant information, hence information needed to solve a given task, decay is a problem indeed. For instance, if subjects were to report the stimulus location after each trial in a Simon task, as in the study of Simon (1982), the spontaneous decay of spatial stimulus information would seriously conflict with the task requirements. Still, as Simon's findings show, subjects can easily solve a task like this without committing too many errors. This suggests that subjects are able to counteract information decay by actively maintaining code activation, similar to the maintenance of word material in working memory (Baddeley, 1986).

Some implications of this maintenance hypothesis were examined in a study of Hommel (1996b). It was motivated by the observation of different outcomes for each of the three prior attempts to investigate the impact of secondary-task performance on the Simon effect: Adding a second task increased the correspondence effect in Simon's (1982) study, decreased it in McCann and Johnston's (1992: Exp. 2) study, and had no impact in Fagot and Pashler (1992: Exp. 5 and 6). From a decay/maintenance point of view, this empirical divergence can be accounted for easily if only the order and the type of tasks is considered:

Task order is important because it is likely to affect the decay of spatial codes. Assume that, after the stimuli for both the secondary and the Simon task are presented, the secondary task is carried out first. During secondary-task performance, there is ample time for spatial codes to decay, so that no effect of S-R correspondence should show up in the Simon task. As McCann and Johnston (1992) used this type of task order, their findings can be taken as another demonstration of automatic code decay—consistent with the authors' own interpretation. However, with a reversed task order, as in Fagot and Pashler's (1992) experiments, adding a secondary task does not delay response selection in the Simon task and should thus not affect the correspondence effect.

The type of task can be important as well. In McCann and Johnston's experiments and those of Fagot and Pashler, the secondary task was unrelated to the location of the stimulus, unlike the study of Simon (1982), in which subjects had to verbally name the location. Here, subjects need the spatial stimulus information and, according to our reasoning, must actively maintain the activation of the corresponding code. As a consequence, the code does not decay. On average, this would produce an increased correspondence effect, which is consistent with Simon's finding.

In order to test this reinterpretation, Hommel (1996b) ran an experiment including an orthogonal variation of the type of secondary task and task order. That is, there was a manual task with the S-R correspondence manipulation (i.e., a Simon task), and another, verbal task, requiring either the naming of stimulus location (position-related) or of stimulus color (position-unrelated). If the secondary task was unrelated to stimulus location, there was an underadditive interaction of task order and correspondence. That is, the effect of irrelevant S-R correspondence in the manual task was of a normal size when this task was performed first, but absent with the reversed task order. This replicates the findings of McCann and Johnston (1992) and of Fagot and Pashler (1992), and supports an interpretation in terms of code decay. However, if the secondary task was related to stimulus location, an overadditive interaction of task order and correspondence occurred. That is, the manual correspondence effect obtained when the manual task was carried out first was even increased with the reversed task order. Moreover, in contrast to the usual finding in Simon-type tasks, it did not depend on relative response speed, that is, it was present with both fast and slow responses. So, as predicted, there was no indication of decay. Rather, the activation of the spatial code increased over time, suggesting that bottom-up activation was not only maintained but even supplemented by activation from top-down sources.

3.4.3 Temporal Code Dynamics and the Action-Concept Model

All taken together, the assumption of spontaneous decay of (codes coding) irrelevant information and of active maintenance of (codes coding) relevant information accounts quite successfully for the temporal dynamics of S-R compatibility effects. In the present context, however, the crucial question is whether these assumptions have particular theoretical implications. Most important, can these assumptions be combined with the action-concept model and, if so, does this combination work better than with other models? Or is the decay/maintenance hypothesis indifferent to this issue?

At first sight, it seems that virtually any model that somehow refers to cognitive codes may be equipped with a decay function and thus be used to predict the interactions just discussed. For instance, perceptual models that attribute the Simon effect to a conflict between stimulus meaning and stimulus location (Hasbroucq & Guiard, 1991) may simply assume that meaning and location are first processed independently and then somehow matched, so that a hypothetical decay of the location code would be the more pronounced the longer it takes to process the meaning.

At second sight, however, at least purely stimulus-related interpretations can be discarded. The major piece of counterfactual evidence comes from Simon studies using lateralized readiness potentials (LRPs) as measures of (hand-) specific response preparation (De Jong et al., 1994; Leuthold & Sommer, 1996; Sommer, Leuthold, & Hermanutz, 1993). A consistent finding in these studies is that presenting irrelevant spatial stimulus information produces an automatic preparation of the corresponding response, independently of whether it is correct or not. Moreover, Eimer (1995) observed that responses are activated by corresponding stimuli even if no immediate response is necessary at that time, and Zachay (1991) was able to track automatic stimulus-induced activations as far as to subthreshold motor activity in the corresponding, but wrong, hand. So, it is not (or not only) stimulus information that decays but response activation. This also means that, theoretically, a decay function alone does not suffice; one also needs a processing architecture that allows for parallel activation of correct and incorrect response codes by (codes of) different (and differently relevant) features of a stimulus.

The action-concept model is equipped with such a multiple-path architecture. In addition to the activation flow along the short-term link between relevant stimulus code and relevant response code, an unlimited number of action concepts can be activated automatically by stimulus information, if only one of the four activation conditions (see 2.3) are met. Yet, although this distinguishes it from several other compatibility models—most notably (re-)coding or translation models of the sort suggested by Fitts and Seeger (1953) or Wallace (1971), the multiple-path assumption as such is by no means unique to this model. In fact, the notion of multiple routes from perception to action is becoming increasingly popular, and especially dual-route models have been drawn on it in many different areas (e.g., De Jong et al., 1994; Frith & Done, 1986; Kornblum et al., 1990; Los, 1994; Stoffels, 1996; Van Duren & Sanders, 1988). However, there is evidence that, whereas a multiple-route architecture is necessary for dynamic interactions to occur, it is by no means sufficient:

A further essential assumption is that of a temporal overlap of stimulus processing and response processing (Hommel, 1993c), including the asynchronous processing of different features of the imperative stimulus (Miller, 1988; Toth et al., 1995), an assumption embodied by the action-concept model's processing architecture. According to the model, stimulus and actions are not represented by single, unitary codes, but by codes of their features, even though these may be interconnected to form an action concept. Consequently, different features of the same stimulus may activate their corresponding codes at different points in time, whether these codes belong to the stimulus' or the response's action concept. This implies that response-activation processes can happen anytime, irrespective of whether stimulus processing is completed or not. The relevance of this temporal-overlap notion becomes clear when we consider the consequences of dropping it. Let us assume that response-related processes must wait until all stimulus-related processes including localization and identification are completed, as actually claimed by Kornblum's dimensional-overlap model (1994). If so, decay-type interaction effects could arise only because, first, the location code decays the longer stimulus processing takes, so that, second, the degree of stimulus-induced automatic activation decreases from fast to slow stimulus processing. Note that this account implies response-locked, not stimulus-locked, response activation: If responding slows down due to prolonged stimulus processing, automatic response activation should also be late. Yet, automatic response activation as measured by early LRPs turns out to be stimulus-locked, not response-locked (Leuthold & Sommer, 1996). That is, as implied by the action-concept model, stimulus information activates corresponding response codes as soon as it is available.

Altogether, the empirical evidence available so far suggests that spatial stimulus information activates corresponding response codes automatically in parallel with, and independently of, the activation flow from relevant stimulus to response codes. If stemming from irrelevant information, this automatically induced activation decays spontaneously over time, but it is maintained if the information is relevant. Although the assumptions of a decay function and of a maintenance process are not basic ingredients of the action-concept model, they fit well into its context. And what is even more important, only the action-concept model, by embodying the temporal-overlap notion of Hommel (1993c) and De Jong et al. (1994), seems to provide a processing architecture that can be combined with the decay/maintenance hypotheses in a way that allows for a consistent and comprehensive account of the findings.

3.5 Interactions Between Stimulus Selection and Response Selection

Owing to the common assumption that compatibility effects arise from response selection problems, models of S-R compatibility usually do not address the issue of stimulus selection. In particular, problems due to stimulus-stimulus (S-S) incongruence, that is, to conflicting information from different features or elements of a stimulus or stimulus compound, are rarely dealt with. Even if those problems are discussed, as in the model of Kornblum et al. (1990; Kornblum, 1994), it is assumed that they do not affect S-R compatibility effects at all.

The action-concept model, in contrast, strongly suggests interactions between stimulus and response processing and, in particular, between stimulus selection and response selection. There are at least three reasons for this. First, as broadly discussed, stimulus and response processing may often overlap in time, which is a necessary precondition for interactions. Second, stimulus and response codes are members of the same representational system, which gives ample opportunity for interactions. Third, as both stimulus codes and response codes are of the same kind (i.e., are action concepts), stimulus selection and response selection processes should at least work in the same way, or may even be the same. Therefore, it should be possible to demonstrate that compatibility effects not only interact with stimulus-related factors in general, as reported above, but with stimulus selection in particular. Moreover, it should also be possible to demonstrate specific effects of response selection on stimulus selection, if only both processes have some temporal overlap. As the next two sections will show, there is evidence substantiating both predictions.

3.5.1 Stimulus Selection and Response Selection

Considering the empirical findings discussed in Section 3.4.1, we can safely rule out the assumption of a general independence between stimulus-related effects and S-R compatibility effects. We have seen that delayed processing of the relevant stimulus information yields a decreased Simon effect, which demonstrates at least some impact of stimulus-related processes on response selection. Although this runs counter to the implications of even the most flexible and comprehensive compatibility model to date, the dimensional-overlap model of Kornblum (1994; Kornblum et al., 1990), this model is not mainly concerned with—and is thus not very specific about—stimulus processing in general. Therefore, one may argue that the interactions already discussed do not challenge this model, but only demonstrate its silence regarding some particularities of stimulus processing. In fact, Kornblum and colleagues have not explicitly excluded *any* interaction between stimulus-related and response-related effects, but only those between S-S congruency and S-R compatibility. So, it is worth examining whether such interactions can be found.

A first inspection of the available evidence is disappointing from an action-concept perspective: Most results from studies involving an orthogonal variation of congruency and compatibility are consistent with the dimensional-overlap model's independence assumption. Combining a Simon with a Stroop task (i.e., responding to the color of color words), Simon, Paullin, Overmyer, and Berbaum (1985), Simon and Berbaum (1990), Kornblum (1994), and Hommel (1996c) all found additive effects of (irrelevant) spatial S-R correspondence and S-S congruency. Likewise, Stoffels and van der Molen (1988: Exp. 1), who manipulated S-S congruency by varying the relationship between a central letter target and irrelevant letter flankers, failed to find an interaction with correspondence. If we take the action-concept model's temporal-overlap assumption for granted and combine it with the decay hypothesis outlined above, this is a surprising outcome. As S-S incongruence should delay processing the relevant information the same way as, say, stimulus discriminability or a large memory set, the spatial information should be more decayed with incongruent than with congruent stimuli, thus producing an underadditive interaction.

However, the five studies did not provide a promising context for interactions to occur: Congruency main effects were either small or even absent (27 ms, 30 ms, n.s., 20 ms, and 56 ms, for the five experiments), and the situation was even poorer with spatial correspondence (n.s., n.s., 36 ms, 27 ms, and 14 ms). As already discussed in the Hommel (1993c) paper, effects of that size are unlikely to produce a significant statistical interaction even if the empirical interaction were real. Moreover, especially the temporal dynamics of the Stroop effect may obscure a real interaction. Both De Jong et al. (1994) and Hommel (1996c) found that Stroop effects are associated with slow rather than fast reaction times. This means that, due to the automatic decay of location-induced information, the correspondence effect shows up most in that part of the reaction time distribution that is least affected by the Stroop effect, and vice versa. A robust interaction can surely not be expected under these conditions.

Nevertheless, interactions are not impossible to find. De Jong et al. (1994: Exp. 3) observed a decrease of correspondence effects from congruence to incongruence of spatial Stroop stimuli (i.e., responses to the vertical position of words denoting vertical position). Likewise, correspondence and flanker-target congruence produced an underadditive interaction in a study of Hommel (1996c). In the same study, a similar interaction occurred between correspondence and between-level congruence of Navon (1977) letters (i.e., large letters made up of small letters). So, it is doubtful that stimulus selection processes are unable to affect response selection. Rather, it seems that S-S incongruence slows down the processing of the relevant stimulus information and thus allows for a more advanced decay of response activation induced by irrelevant stimulus information, at least if associated with a considerable main effect. Whereas this view stands in opposition to the assumptions of Kornblum (1994), it is in full accordance with the approach defended here.

Delaying the processing of the relevant information is only one way in which stimulus selection processes may affect response selection. A more direct impact was revealed in a recent study (Hommel, 1996d) motivated by findings of Proctor and Lu (1994). Proctor and Lu used a modified Simon task, in which each imperative stimulus (the letter S or H) was accompanied by a neutral distractor (the letter Y). The target appeared randomly on the left or right, whereas the distractor occupied the opposite location. An interesting outcome of this study was that the distractor had little influence on the Simon effect (i.e., of target-response correspondence) when it was of another color than the target, but produced an increased effect if it had the same color. According to the decay/maintenance logic, such a finding might indicate maintenance processes. As pointed out by Proctor and Lu, the presence of a same-color distractor creates a stimulus-selection problem, inasmuch as the possibility to discriminate between target and distractor is largely reduced as compared to the different-color condition. If so, additional attentional processes become necessary, processes that are known to operate on the basis of spatial location (Schneider, 1995; Treisman, 1988; Van der Heijden, 1992). This means that stimulus location is made relevant to the task, a situation that can be assumed to foster the maintenance of spatial information. Maintenance should be reflected by the absence of decay effects, suggesting that the usual decrease of correspondence effects with increasing reaction time should be absent if target and distractor are of the same color. In fact, this is what was found: Whereas a decrease can be observed in different-color conditions, the size of the correspondence effect is constant from fast to slow responses in the same-color condition (Hommel, 1996d).

So, stimulus-selection processes may affect response selection not only by delaying it—and thus making it less susceptible to spatial information, but also by making active use of information that, from a cursory view, would be considered task-irrelevant. Again, this is evidence against the common assumption of distinct stimulus and response systems or stages, but consistent with the action-concept model's notion that stimulus processing and response processing overlap in time and take place within a common representational system.

3.5.2 Response Selection and Stimulus Selection

An intriguing implication of the action-concept model does not concern the impact of stimulus-related on response-related processes, but effects in the opposite direction, hence from response- to stimulus-related processes. Recall the assumption that action concepts are used for, and are thus involved in, perceptual as well as action-planning processes. As pointed out, this has implications for S-R compatibility, which is explained by the (partial) overlap of codes representing the stimulus event and codes representing a to-be-performed action. But what about R-S compatibility? Assume that a stimulus is presented and perceived during ongoing action planning. According to the action-concept model, perceiving this stimulus should be facilitated if it is similar to the action currently planned. That is, feature overlap between stimulus and response should not only facilitate response-related processes but also stimulus-related processes.

This hypothesis was tested in a study of Hommel and Schneider (1996), who used a dual-task paradigm introduced by Pashler (1991). In each trial, subjects carried out a speeded manual two-choice task in response to the pitch of a tone. With a variable stimulus-onset asynchrony, a briefly masked search display was presented during the tone task. The display consisted of four letters occupying the corners of an imaginary square, with one letter marked by a bar. After carrying out the manual task, subjects reported the identity of the marked letter at leisure. As it turned out, the reports were more often correct when the relative position of the manual response corresponded to the relative position of the target letter in the search display. That is, as an action-concept perspective predicts, stimuli are perceived more easily when they share features with a currently planned response. Moreover, the larger the actual temporal overlap was between manual response selection and selecting the target from the search display (manipulated by varying tone-display onset asynchrony), the slower was the manual reaction time. This suggests that stimulus selection and response selection processes do not only exhibit crosstalk under certain conditions, but may actually share processes or mechanisms, just as the action-concept notion would lead one to expect.

Müsseler and Hommel (in press) investigated a further implication of the notion that stimuli and responses are coded and processed within a common representational system. They considered what might happen if a perceiver/actor perceives the effects of an intended and executed action. If, for instance, a left-hand key has been pressed, this should lead to registering and cognitively coding LEFT events. This again implies activating action concepts comprising effect codes that refer to the fact of being left, and these should include the one just used to produce the left-hand effects. In principle, this could produce a reverberatory loop, as activated effect codes will tend to activate the corresponding motor pattern, which again produces effects to be coded, and so forth. That is, the concept just used would be activated a second time, which—given a certain activation level—may produce the LEFT effects a second time, and so forth. Following earlier considerations of MacKay (1986), Müsseler and Hommel reasoned that one solution of this theoretical (and practical) problem would be provided by (the notion of) a brief refractory period of action concepts immediately after use. That is, after an action is planned and already under execution, the action concept involved may automatically enter a refractory phase and, thus, become temporarily insensitive to activation from incoming information about corresponding action effects. In other words, action concepts may be temporarily "blind" to stimulus events that share features with the action just planned.

The refractoriness notion strongly suggests a rather counterintuitive hypothesis: If a stimulus is presented immediately after an action is planned, hence during or directly following execution, stimuli compatible with the action should be perceived *less* accurately than action-incompatible stimuli. Müsseler and Hommel (in press) tested this hypothesis in a series of experiments by using a modified version of a task designed by Müsseler (1995). Their subjects performed a preprepared sequence of two manual keypressing responses with the index and middle finger of their right hand. The first response was neutral in that it always required pressing the two keys simultaneously. It triggered a briefly masked stimulus, which was a centrally presented arrow pointing to the left or right. Subjects were asked to judge the arrow's direction at leisure about one second after completing the response sequence. The second manual response required pressing the left or right key only. As the response sequence was highly prepared, the masked stimulus triggered by the first response should fall into the execution phase of the second response. If so, the compatibility relationship between the second response and the stimulus should matter. In particular, perception of response-compatible arrows (i.e., spatial correspondence between response key and pointing direction) should be *inferior* to the perception of response-incompatible arrows. This is what was found: Independent of whether a manual or verbal judgment was required, subjects consistently misjudged compatible arrows more often than incompatible ones. So, as predicted by the action-concept model, response-related processes can affect stimulus-related processes in a way other models do not anticipate.

4 Summary and Conclusions

The purpose of this chapter was to present a first outline of an action-concept model of S-R compatibility. Unlike other models, this model explicitly focuses on the problem of action coding, that is, on the cognitive representation of action. Its development was motivated by the appraisal that a really comprehensive account of S-R compatibility in particular, and of the relationship between perception and action in general, requires an understanding of how actions are cognitively represented and where these representations come from. Yet, although response codes play a major role in compatibility theories, a principled approach to the question of action coding has been lacking so far.

I have argued that the general approach of Lotze (1852) and Harleß (1861), especially their claim that movements are represented by codes of their perceived effects, provides an appropriate starting point for developing an action-coding theory. However, I have pointed out the necessity of some qualifications and extensions. In particular, unlike previous interpretations of the Lotze-Harleß approach by James (1890) and Greenwald (1970a), I have defended a broad definition of action effects that includes any perceivable event that is produced by (i.e., is contingent on) a given movement or movement pattern. Consequently, the cognitive codes produced by perceiving a movement and its effects do not merely refer to the movement per se, but to action, the action's goal, and to its consequences as well. That is, these codes are not mere movement codes but action concepts. Action concepts emerge from the actor's perception of his or her own movements and the movement-produced events. Once formed, they also serve to control the movement and thus the events the movement brings about. So, action concepts are for perception as well as for action and form—as envisioned by Prinz (1990)—a "common-coding system," in which codes of both perceived events and to-be-produced events are formed and stored in a commensurable format.

The studies conducted so far have provided considerable support for the basic architecture of the action-concept model. The model supplies a reasonable theoretical account for, and successfully predicts, the impact of artificial action effects (i.e., response-contingent events) on S-R compatibility as well as the emergence of a novel kind of compatibility effect: compatibility between stimulus and action effect. It also allows us to shed new light on the role of response uncertainty and on the interplay between stimulus and response processing. Last but not least, the model makes new and surprising predictions about the mutual relationship between stimulus-selection and response-selection processes.

The present studies have also suggested and successfully tested a few nonessential, but useful refinements of the model: First, the activation level of action concepts raised by irrelevant information decreases over time. Second, this spontaneous decay can be counteracted by maintenance processes if the encoded information is task-relevant, that is, useful or necessary for stimulus or response selection. Third, action concepts exhibit refractory behavior after having been used for action selection or other functions. These three supplementary assumptions concerning the temporal dynamics of action concepts were most useful in accounting for the interaction of stimulus and response factors or the form of the reaction-time distributions in Simon tasks. Nevertheless, as they are not intimately tied to the model's theoretical core, it is important to distinguish between the assumption's and the model's contribution to the success of empirical predictions.

Of course, the decay of information or the refractoriness of codes as such do not imply a particular theory or model and may thus be postulated in any theoretical context. Yet, I tried to make clear that this does not mean that all combinations of theory and assumptions are equally successful. Without allowing for piecemeal transmission of stimulus information and temporal overlap of stimulus and response processing, the decay notion does not permit a consistent account of the available evidence. Without claiming some kind of common coding of stimuli and responses and some relationship between stimulus and response selection, the assumption of maintenance alone would be of little help in explaining why making stimulus selection more difficult should affect the size of compatibility effects. And without granting at least some functional identity between spatial stimulus codes and spatial response codes, the refractoriness assumption hardly allows for predicting the"action-effect blindness" phenomenon demonstrated by Müsseler and Hommel (in press). Thus, even though the three additional assumptions presented here are logically separable from the action-concept model's architecture, their empirical success is not.

On the one hand, the model proposed here already provides a valuable tool in predicting and explaining phenomena other models have very little to say about. On the other hand, however, there are also some findings and phenomena left unexplained. For instance, the present version of the model is more or less silent about how exactly the relevant stimulus information is selected and linked to the action concept of the correct response, an issue other models have dealt with in some more detail (e.g., Duncan, 1977; Hasbroucq, Guiard, & Ottomani, 1990; Kornblum et al., 1990). As a consequence, it does not contribute to understanding processes like stimulus recoding, which seems to play a decisive role in the reversal of S-R compatibility under certain instructions (Arend & Wandmacher, 1987; De Jong et al., 1994; Hedge & Marsh, 1975; Lu & Proctor, 1994). It also has little to say about coding strategies and about why and how stimulus or response features differ in salience (Barber & O'Leary, 1996; Weeks & Proctor, 1990), hence, in their likelihood of being integrated into action concepts. In other words, the action-concept model is not yet a complete model of compatibility phenomena. So, while it may well be that a later version covers more empirical observations, it would not yet be a sensible move to argue for it to replace available accounts. For the time being, however, the action-concept model may well function to call more attention to the problem of the cognitive representation of action, to afford provisional guidance for further empirical research, and to provide a framework for the development of more advanced theoretical solutions. In this way, it may contribute to closing a theoretical gap in the understanding of S-R compatibility and, more generally, the relationship between perception and action.

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References

Adams, J. A. (1968). Response feedback and learning. *Psychological Bulletin, 70,* 486-504.

Alluisi, E. A., & Martin, H. B. (1958). An information analysis of verbal and motor responses to symbolic and conventional arabic numerals. *Journal of Applied Psychology, 42,* 79-84.

Anzola, G. P., Bertoloni, G., Buchtel, H. A., & Rizzolatti, G. (1977). Spatial compatibility and anatomical factors in simple and choice reaction time. *Neuropsychologia, 15,* 295-302.

Arend, U., & Wandmacher, J. (1987). On the generality of logical recoding in spatial interference tasks. *Acta Psychologica, 65,* 193-210.

Baddeley, A. D. (1986). *Working memory.* Oxford: Oxford University Press.

Barber, P. J., & O'Leary, M. J. (1996). The relevance of salience: Towards an activational account of irrelevant stimulus-response compatibility effects. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility* (pp. 135-172). Amsterdam: North-Holland. (this volume)

Bashore, T. R. (1981). Vocal and manual reaction time estimates of interhemispheric transmission time. *Psychological Bulletin, 89,* 352-368.

Berlucchi, G., Crea, F., Di Stefano, M., & Tassinari, G. (1977). Influence of spatial stimulus-response compatibility on reaction time of ipsilateral and contralateral hand to lateralized light stimuli. *Journal of Experimental Psychology: Human Perception and Performance, 3,* 505-517.

Broadbent, D. E., & Gregory, M. (1962). Donders' B- and C-reactions and S-R compatibility. *Journal of Experimental Psychology, 63,* 575-578.

Castiello, U., & Umiltà, C. (1987). Spatial compatibility effects in different sports. *International Journal of Sport Psychology, 18,* 276-285.

Cattell, J. M. (1885). Über die Zeit der Erkennung und Benennung von Schriftzeichen, Bildern und Farben. *Philosophische Studien, 2,* 635-650.

De Jong, R., Liang, C. C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial S-R correspondence. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 731-750.

Dewey, J. (1896). The reflex arc concept in psychology. *Psychological Review, 3,* 357-370.

Duncan, J. (1977). Response selection errors in spatial choice reaction tasks. *Quarterly Journal of Experimental Psychology, 29,* 415-423.

Duncan, J. (1978). Response selection in spatial choice reaction. Further evidence against associative models. *Quarterly Journal of Experimental Psychology, 30*, 429-440.

Eimer, M. (1995). Stimulus-response compatibility and automatic response activation: Evidence from psychophysiological studies. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 837-854.

Eimer, M., Hommel, B., & Prinz, W. (1995). S-R compatibility and response selection. *Acta Psychologica, 90*, 301-313.

Fagot, C., & Pashler, H. (1992). Making two responses to a single object: Implications for the central attentional bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 1058-1079.

Fitts, P. M., & Seeger, C. M. (1953). S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology, 46*, 199- 210.

Frith, C. D., & Done, D. J. (1986). Routes to action in reaction time tasks. *Psychological Research, 48*, 169-177.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.

Greene, P. H. (1982). Why is it easy to control your arms? *Journal of Motor Behavior, 14*, 260-286.

Greenwald, A. G. (1970a). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review, 77*, 73-99.

Greenwald, A. G. (1970b). A double stimulation test of ideomotoric theory with implications for selective attention. *Journal of Experimental Psychology, 84*, 392-398.

Grice, G. R., Boroughs, J. M., & Canham, L. (1984). Temporal dynamics of associative interference and facilitation produced by visual context. *Perception & Psychophysics, 36*, 499-507.

Guiard, Y. (1983). The lateral coding of rotations: A study of the Simon effect with wheel-rotation responses. *Journal of Motor Behavior, 15*, 331-342.

Harleß, E. (1861). Der Apparat des Willens. *Zeitschrift für Philosophie und philosophische Kritik, 38*, 50-73.

Hasbroucq, T., & Guiard, Y. (1991). Stimulus-response compatibility and the Simon effect: Toward a conceptual clarification. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 246-266.

Hasbroucq, T., Guiard, Y., & Ottomani, L. (1990). Principles of response determination: The list-rule model of SR compatibility. *Bulletin of the Psychonomic Society, 28*, 327-330.

Hasbroucq, T., Kornblum, S., & Osman, A. (1988). A new look at reaction time estimates of interhemispheric transmission time. *Cahiers de Psychologie Cognitive/ European Bulletin of Cognitive Psychology, 8*, 207-221.

Hedge, A., & Marsh, N. W. A. (1975). The effect of irrelevant spatial correspondences on two-choice response-time. *Acta Psychologica, 39*, 427-439.

Hommel, B. (1993a). The role of attention for the Simon effect. *Psychological Research/Psychologische Forschung, 55*, 208-222.

Hommel, B. (1993b). Inverting the Simon effect by intention: Determinants of direction and extent of effects of irrelevant spatial information. *Psychological Research/Psychologische Forschung, 55*, 270-279.

Hommel, B. (1993c). The relationship between stimulus processing and response selection in the Simon task: Evidence for a temporal overlap. *Psychological Research/Psychologische Forschung, 55*, 280-290.

Hommel, B. (1994a). Spontaneous decay of response code activation. *Psychological Research/Psychologische Forschung, 56*, 261-268.

Hommel, B. (1994b). Effects of irrelevant spatial S-R compatibility depend on stimulus complexity. *Psychological Research/Psychologische Forschung, 56*, 179-184.

Hommel, B. (1995a). Stimulus-response compatibility and the Simon effect: Toward an empirical clarification. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 764-775.

Hommel, B. (1995b). Conflict versus misguided search as explanation of S-R correspondence effects. *Acta Psychologica, 89*, 37-51.

Hommel, B. (1996a). No prevalence of right-left over above-below spatial codes. *Perception & Psychophysics, 58*, 102-110.

Hommel, B. (1996b). *Decay and maintenance of spatial codes under dual-task conditions*. Manuscript submitted for publication.

Hommel, B. (1996c). *Interactions between stimulus-stimulus congruence and stimulus-response compatibility effects*. Manuscript submitted for publication.

Hommel, B. (1996d). *Visual noise and spatial stimulus coding*. Manuscript submitted for publication.

Hommel, B. (in press a). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research/Psychologische Forschung*.

Hommel, B. (in press b). S-R compatibility effects without response uncertainty. *Quarterly Journal of Experimental Psychology, 49A*.

Hommel, B., & Lippa, Y. (1995). S-R compatibility effects due to context-dependent spatial stimulus coding. *Psychonomic Bulletin & Review, 2*, 370-374.

Hommel, B., & Schneider, W. X. (1996). *Visual attention and the selection of manual responses*. Manuscript submitted for publication.

James, W. (1890). *The principles of psychology* (Vol. 2). New York: Dover Publications.

Kornblum, S. (1994). The way irrelevant dimensions are processed depends on what they overlap with: The case of Stroop- and Simon-like stimuli. *Psychological Research/Psychologische Forschung, 56*, 130-135.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for S-R compatibility—a model and taxonomy. *Psychological Review, 97*, 253-270.

Lamberts, K., Tavernier, G., & d'Ydewalle, G. (1992). Effects of multiple reference points in spatial stimulus-response compatibility. *Acta Psychologica, 79*, 115-130.

Leuthold, H., & Sommer, W. (1996). *Spatial S-R compatibility and Simon effect: Response competition as common underlying mechanism*. Manuscript submitted for publication.

Los, S. A. (1994). Procedural differences in processing intact and degrades stimuli. *Memory & Cognition, 22*, 145-156.

Lotze, R. H. (1852). *Medicinische Psychologie oder die Physiologie der Seele*. Leipzig: Weidmann'sche Buchhandlung.

Lu, C.-H. (1996). Correspondence effects for irrelevant information in choice-reaction tasks: Characterizing the stimulus-response relations and the processing dynamics. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility* (pp. 85-117). Amsterdam: North-Holland. (this volume)

Lu, C.-H., & Proctor, R. W. (1994). Processing of an irrelevant location dimension as a function of the relevant stimulus dimension. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 286-298.

Lu, C.-H., & Proctor, R. W. (1996). *Effects of ideomotor compatibility and relative timing on the processing of multidimensional stimuli.* Manuscript submitted for publication.

MacKay, D. G. (1986). Self-inhibition and the disruptive effects of internal and external feedback in skilled behavior. In H. Heuer & C. Fromm (Eds.), *Generation and modulation of action patterns* (pp. 174-186). Berlin: Springer-Verlag.

Marzi, C. A., Bisiacchi, P., & Nicoletti, R. (1991). Is interhemispheric transfer of visuomotor information asymmetric? Evidence from a meta-analysis. *Neuropsychologia, 29,* 1163-1177.

McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 471-484.

Michaels, C. F., & Stins, J. F. (1996). An ecological approach to stimulus-response compatibility. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility* (pp. 333-360). Amsterdam: North-Holland. (this volume)

Miller, J. (1988). Discrete and continuous models of human information processing: Theoretical distinctions and empirical results. *Acta Psychologica, 67,* 191-257.

Müsseler, J. (1995). *Wahrnehmung und Handlungsplanung: Effekte kompatibler und inkompatibler Reize bei der Initiierung und Ausführung von Reaktionssequenzen.* Aachen: Shaker.

Müsseler, J., & Hommel, B. (in press). Blindness to response-compatible stimuli. *Journal of Experimental Psychology: Human Perception and Performance.*

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9,* 353-383.

Nicoletti, R., & Umiltà, C. (1984). Right-left prevalence in spatial compatibility. *Perception & Psychophysics, 35,* 333-343.

Nicoletti, R., & Umiltà, C. (1989). Splitting visual space with attention. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 164-169.

Nicoletti, R., Umiltà, C., & Ladavas, E. (1984). Compatibility due to the coding of the relative position of the effectors. *Acta Psychologica, 57,* 133-143.

Nicoletti, R., Umiltà, C., Tressoldi, E. P., & Marzi, C. A. (1988). Why are left-right spatial codes easier to form than above-below ones? *Perception & Psychophysics, 43,* 287-292.

Olson, D. R. (1970). Language and thought: Aspects of a cognitive theory of semantics. *Psychological Review, 77,* 257-273.

Pashler, H. (1991). Shifting visual attention and selecting motor responses: Distinct attentional mechanisms. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 1023-1040.

Prinz, W. (1987). Ideo-motor action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 47-76). Hillsdale, NJ: Erlbaum.

Prinz, W. (1990). A common coding approach to perception and action. In O. Neumann & W. Prinz (Eds.), *Relationships between perception and action* (pp. 167-201). Berlin: Springer-Verlag.

Prinz, W. (1992). Why don't we perceive our brain states? *European Journal of Cognitive Psychology, 4,* 1-20.

Prinz, W. (1996). Why Donders has led us astray. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility* (pp. 247-267). Amsterdam: North-Holland. (this volume)

Prinz, W., Aschersleben, G., Hommel, B., & Vogt, S. (1995). Handlungen als Ereignisse. In D. Dörner & E. van der Meer (Eds.), *Das Gedächtnis: Trends, Probleme, Perspektiven* (pp. 129-168). Göttingen: Hogrefe.

Prinz, W., & Hommel, B. (1995). Über die kognitive Repräsentation von Handlungen. In K. Pawlik (Ed.), *Bericht über den 39. Kongreß der Deutschen Gesellschaft für Psychologie in Hamburg 1994* (pp. 684-688). Göttingen: Hogrefe.

Proctor, R. W., & Lu, C.-H. (1994). Referential coding and attention shifting accounts of the Simon effect. *Psychological Research/Psychologische Forschung*, *56*, 185-195.

Riggio, L., Gawryszewski, L., & Umiltà, C. (1986). What is crossed in crossed-hand effects? *Acta Psychologica*, *62*, 89-100.

Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin*, *95*, 355-386.

Sanders, A. F. (1980). Stage analysis of reaction processes. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior I* (pp. 331-354). Amsterdam: North-Holland.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, *82*, 225-260.

Schneider, W. X. (1995). VAM: A neuro-cognitive model for visual attention control of segmentation, object recognition, and space-based motor action. *Visual Cognition*, *2*, 331-375.

Simon, J. R. (1968). Effect of ear stimulated on reaction time and movement time. *Journal of Experimental Psychology*, *78*, 344-346.

Simon, J. R. (1982). Effect of an auditory stimulus on the processing of a visual stimulus under single- and dual-tasks conditions. *Acta Psychologica*, *51*, 61-73.

Simon, J. R., & Berbaum, K. (1990). Effect of conflicting cues on information processing: The 'Stroop effect' vs. the 'Simon effect'. *Acta Psychologica*, *73*, 159-170.

Simon, J. R., Paullin, C., Overmyer, S. P., & Berbaum, K. (1985). Reaction time to word meaning and ink color of laterally-presented Stroop stimuli: Effects of handedness and sex. *International Journal of Neuroscience*, *28*, 21-33.

Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*, 300-304.

Simon, J. R., Sly, P. E., & Vilapakkam, S. (1981). Effects of compatibility of S-R mapping on reactions toward the stimulus source. *Acta Psychologica*, *47*, 63-81.

Simon, J. R., & Sudalaimuthu, P. (1979). Effects of S-R mapping and response modality on performance in a Stroop task. *Journal of Experimental Psychology: Human Perception and Performance*, *5*, 176-187.

Sommer, W., Leuthold, H., & Hermanutz, M. (1993). Covert effects of alcohol revealed by event-related potentials. *Perception & Psychophysics*, *54*, 127-135.

Stanovich, K. E., & Pachella, R. G. (1977). Encoding, stimulus-response compatibility, and stages of processing. *Journal of Experimental Psychology: Human Perception and Performance*, *3*, 411-421.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica, 30,* 276-315.

Stoffels, E.-J. (1996). On stage robustness and response selection routes: Further evidence. *Acta Psychologica*, *91*, 67-81.

Stoffels, E.-J., & Van der Molen, M. W. (1988). Effects of visual and auditory noise on visual choice reaction time in a continuous-flow paradigm. *Perception & Psychophysics*, *44*, 7-14.

Stoffels, E.-J., Van der Molen, M. W., & Keuss, P. G. J. (1989). An additive factor analysis of the effect(s) of location cues associated with auditory stimuli on stages of information processing. *Acta Psychologica, 70,* 161-197.

Stoffer, T. H. (1991). Attentional focussing and spatial stimulus-response compatibility. *Psychological Research, 53,* 127-135.

Stoffer, T. H., & Yakin, A. R. (1994). The functional role of attention for spatial coding on the Simon effect. *Psychological Research/Psychologische Forschung, 53,* 127- 135.

Sugg, M. J., & McDonald, J. E. (1994). Time course of inhibition in color-response and word-response versions of the Stroop task. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 647-675.

Teichner, W. H., & Krebs, M. J. (1972). Laws of the simple visual reaction time. *Psychological Review, 79,* 344-358.

Theios, J. (1973). Reaction time measurements in the study of memory processes: Theory and data. *The Psychology of Learning and Motivation, 7,* 43-85.

Toth, J. P., Levine, B., Stuss, D. T., Oh, A., Winocur, G., & Meiran, N. (1995). Dissociation of processes underlying spatial S-R compatibility: Evidence for the independent influence of what and where. *Consciousness and Cognition, 4,* 483-501.

Treisman, A. M. (1988). Features and objects: The fourteenth Bartlett memorial lecture. *Quarterly Journal of Experimental Psychology, 40A,* 201-237.

Van der Heijden, A. H. C. (1992). *Selective attention in vision.* London: Routledge.

Van Duren, L. L., & Sanders, A. F. (1988). On the robustness of the additive factors stage structure in blocked and mixed choice reaction designs. *Acta Psychologica, 69,* 83-94.

Wallace, R. J. (1971). S-R compatibility and the idea of a response code. *Journal of Experimental Psychology, 88,* 354-360.

Weeks, D. J., & Proctor, R. W. (1990). Salient-features coding in the translation between orthogonal stimulus and response dimensions. *Journal of Experimental Psychology: General, 119,* 355-366.

Wolff, P. (1984). Saccadic eye movements and visual stability: Preliminary considerations towards a cognitive approach. In W. Prinz & A. F. Sanders (Eds.), *Cognition and motor processes* (pp. 121-137). Berlin: Springer.

Zachay, A. (1991). *Diskrete und kontinuierliche Informationsverarbeitungsmodelle zur Erklärung von Reiz-Reaktions-Inkompatibilitäten: Evidenz für einen Antwortkonflikt beim Simon-Effekt.* Unpublished master's thesis, Tübingen, Germany.