

The Prepared Reflex: Automaticity and Control in Stimulus-Response Translation

Bernhard Hommel

ABSTRACT This chapter reviews a number of empirical and theoretical approaches to the translation of stimulus information into action in choice reaction tasks. Abundant evidence shows that stimulus-response (S-R) translation does not always conform to people's intentions, which rules out the notion that it is a highly selective control (or intentionally controlled) operation. This has led to the conception of dual-route models, which view action control as the outcome of a competition between intentional and automatic S-R translation processes. Although these conceptions have many advantages, they also have their limitations. In particular, there is evidence for more than two routes from perception to action; intention-related S-R translation can shown to be triggered automatically; and effects attributed to "automatic translation" often depend on the actor's intentions. An alternative view conceives of intentional and automatic processes, not as being different in kind, but rather as taking place at different points in time, with intentional processes setting the stage for automatic S-R translation.

Higher organisms exhibit an enormous flexibility in responding and adapting to immediate changes in environmental conditions. Their behavior is not only controlled by direct and persistent input-output connections but mediated by internal states and modified through experience. A wealth of cognitive processes is involved in transforming sensory inputs into observable muscle contractions. This chapter will focus on a central stage in the transformation process—the interface between perceptual processing and action selection—emphasizing the role intentional and automatic processes play in translating stimulus information into response activation.

Theories of human information processing commonly deal with this interface under the heading of "stimulus-response translation" (or "S-R translation"), "response determination," "response identification," or "response selection." Although most models include a box carrying one of these labels surprisingly little is known about how stimulus information is actually translated into action plans. However, to speak of S-R translation at least two requirements need to be met.

First, there has to be some indication, whatever the level of analysis—that response-related functional codes or brain structures are activated, at least to some degree. These indications may be relatively direct, such as the increase in activation of some part of the motor cortex in a brain-

imaging study; or indirect, such as a reaction time pattern revealing competition between alternative responses. The consequences of S-R translation differ widely between situations, ranging from the unobservable activation of a mild response tendency, overcome within a few milliseconds, to the actual execution of the activated response; clearly, these differences are of great theoretical and practical moment. Yet, in this chapter, all that counts is whether there is any indication of response activation under particular stimulus conditions and task instructions.

The second requirement is that the measured arousal of response tendencies, be systematically related to the present stimulus conditions. Obviously, merely observing that some situations induce response tendencies or increase the likelihood of responding does not yet allow one to assume that some kind of stimulus information was translated into a corresponding response. To be sure that S-R translation actually took place requires one to predict which response tendency was aroused as a function of which stimulus information. Its logical dependency on available stimulus information already puts some constraints on the temporal and functional locus of S-R translation in the sequence of stages in human information processing. Indeed, most authors (e.g., De Jong 1993; Frith and Done 1986; Kornblum, Hasbroucq, and Osman 1990; Meyer and Kieras 1997; Pashler 1994) locate the S-R translation or response selection stage in between what is commonly called the "perceptual" or "stimulus identification" stage and those stages having to do with "response initiation" and "response execution." Although some stimulus processing is required before the processed information can be translated into a response, this does not mean that S-R translation has to await full processing or identification of a stimulus. For instance, Miller (1988) and others have argued that perceptual stages may pass partial output to response stages before stimulus identification is complete. For our present purposes, any specific, stimulus-related activation of response-related codes or structures will count as evidence that S-R translation has taken place, irrespective of the type of the corresponding stimulus information and the degree to which it is processed.

Authors have characterized intentional and automatic processes in many different ways (for overviews, see Neumann 1984; Schweickert and Boggs 1984): intentional translation processes have been characterized as controlled (by whatever state or mechanism), working serially (implying only one translation at a time), capacity limited, effortful, conditional (on intentions), and conscious, whereas automatic processes have been characterized as uncontrolled, working in parallel (implying more than one translation at a time), capacity unlimited, effortless, unconditional, and unconscious. However, most of the data to be discussed here speak only to the issue of whether, or how much, translation processes depend on the perceiver's or actor's intentions, apart from some preliminary hints

about whether these processes work serially or in parallel (thus being capacity limited or unlimited).¹

From a phenomenological perspective, it may seem odd to ask whether S-R translation depends on intentions. We commonly feel that we perceive an environmental event, think about it, and then deliberately select an appropriate action without further ado. This view, which has so obviously motivated many stage models of information processing, strongly suggests that S-R translation is a more or less direct reflection of the perceiver's or actor's intentions. There is increasing empirical evidence, however, for stimulus-induced and unwanted response activation, which challenges the idea of S-R translation being under direct, immediate intentional control.

11.1 THE DEMONSTRATION OF AUTOMATIC STIMULUS-RESPONSE TRANSLATION

Under normal circumstances, we do not have the slightest doubt that the actions we perform originate within ourselves, that we are the causal agents in the process of transforming mere willing into actual moving. Accordingly, many early psychological approaches to action control, especially those based on the theorist's introspection, assumed that human action was guided and controlled by human will.

A well-known proponent of such an intentional view was Donders (1868), who attributed the responsibility of translating perceptual information into movement to an "organ of will" (*wilsorgaan*). To measure how long this organ would need to make a decision, Donders manipulated S-R uncertainty in a number of ways. In one experiment, subjects responded to the electrical stimulation of their left or right foot by moving their left or right hand, respectively. It turned out that subjects were faster to respond correctly if they knew in advance which stimulus would occur than when they did not, and Donders took this difference in reaction time as an estimate for the combination of stimulus discrimination and "determination of the will." To further disentangle these two processes, Donders employed a go/no-go task that required a selective response to a specified subset of the stimulus set, pairing stimulus uncertainty with response certainty. He reasoned that such a task would not require any further will determination processes (assuming that the response could be selected in advance), so that their duration could then be estimated by subtracting the go/no-go reaction time from that obtained in conditions requiring a response decision. He calculated will determination to take 36 msec.

The outdated expression "will determination" easily translates into the more fashionable "S-R translation" or "response selection" (Gottsdanker and Shragg 1985). Indeed, despite marked changes in terminology, some

information-processing models (e.g., Hasbroucq, Guiard, and Ottomani 1990; Pashler 1994; Sanders 1980; Teichner and Krebs 1974; Welford 1968) are still based on the (sometimes implicit) idea of S-R translation as a process that exclusively serves to realize the actor's intention. Conceived this way, S-R translation represents a control operation by means of which the "will," or some functional equivalent, decides what to do by selecting one stimulus and activating the corresponding response. Fitting well into this picture are claims (e.g., Pashler 1994; Welford 1952) that S-R translation draws heavily on mental resources and thus constitutes a rather fixed, structural bottleneck in the flow of information through the cognitive system. On the other hand, a number of robust empirical findings cast doubt on whether an account of S-R translation as purely intentional is tenable. These findings fall into four categories, each suggesting a different type of nonintentional and sometimes even counter-intentional S-R translation.

Compatibility: Effects of Stimulus-Response Similarity

Since the classical work of fitts and Seeger (1953), it is known that the speed of S-R translation depends not only on the stimulus or the response but also on the relationship or mapping between stimuli and responses.² If stimuli and responses vary on the same dimension, such as with left- and right-hand responses to left- and right-side stimuli, then responses to stimuli having the same value on the respective dimension (e.g., left response to left stimulus) can be initiated faster than responses that do not (e.g., left response to right stimulus).

Of greater interest for our purposes is that feature overlap between stimulus and response affects performance even if this overlap is irrelevant to the task, as convincingly demonstrated by the Simon effect (Simon and Small 1969; for an overview, see Lu and Proctor 1995). This is observed when people make a spatial response, such as a left versus a right keypress, to a nonspatial stimulus attribute, such as color. If the location of the stimulus varies randomly, and if it does so on the same spatial dimension as the response, performance is better if the stimulus spatially corresponds to the response than if it does not. Importantly, this is true not only for absolute spatial S-R correspondence, but also when left and right stimuli appear within the same visual hemifield (Nicoletti and Umiltà 1989; Umiltà and Liotti 1987) or when subjects respond with two fingers of the same hand (Arend and Wandmacher 1987; Heister, Ehrenstein, and Schroeder-Heister 1987). That is, anatomical linkage between hemifield and hand is insufficient to account for the Simon effect.

If S-R translation exclusively reflected the instructed S-R mapping rules, stimulus location would have no effect. The location of the stimu-

lus is obviously processed, however, which leads to at least partial activation of the spatially corresponding response. Presenting a left or right stimulus can be shown to activate the corresponding response even when the relevant stimulus feature calls for the alternate response—whether response activation is assessed by means of lateralized readiness potentials (De Jong, Liang, and Lauber 1994; Sommer, Leuthold, and Hermannutz 1993), electromyographical recordings (Zachay 1991), or registration of subthreshold movements (Zachay 1991). Even symbolic stimuli with a spatial meaning, such as left- or right-pointing arrows, can under certain conditions automatically activate the corresponding response (Eimer 1995). Clearly, these findings provide strong evidence against S-R translation being purely under the control of intentions, all the more so because the critical spatial stimulus feature is evidently not relevant for the task at hand.

One might argue that, for some reason, the wrong stimulus feature is “intentionally” translated into response activation, perhaps because the (nonspatial) relevant stimulus dimension is sometimes confused with the (spatial) relevant response dimension. Or S-R translation might always need to take into account all the features of a relevant stimulus, so that irrelevant features cannot be excluded. However, these attempts to save the intentional translation notion are inconsistent with the observation of Simon-type effects in tasks that, on a given trial, do not require any translation between attributes of the critical stimulus and the appropriate response. For instance, if subjects are signaled to prepare a left- or right-hand keypress in advance of a go/no-go signal—so that all relevant S-R translations can be completed before that signal appears—performance is still better with spatial correspondence between go signal and response (Hommel 1995a, exp. 1). Correspondence effects show up even with 100% go- signal probability, that is, in simple reactions, and even when responses are blocked over 80 consecutive trials (Hommel 1996).

Altogether, these findings clearly undermine the idea that the translation of stimulus location into response activation is wholly under the control of intentional processes. There is more evidence from nonspatial tasks. The best known example is the Stroop effect (Stroop 1935; for an overview, see MacLeod 1991), which occurs when people verbally name the color of ink in which color words are written. Performance is better if the color word denotes the color of ink to be named (e.g., “RED” written in red ink) than if it refers to another color (e.g., “GREEN” written in red ink). On the one hand, the occurrence of the Stroop effect can be taken to show that the meaning of the stimulus word cannot be ignored but is automatically translated into a (congruent or incongruent) response.³ On the other, requiring subjects to name or respond to the color of the word clearly introduces color as a task-relevant dimension, and it may be exactly this task relevance that makes the word so difficult to ignore.

Habits: Effects of Overlearned Stimulus-Response Associations

From everyday life, we know how difficult it is to escape bad habits, that is, to change or inhibit overlearned responses to particular stimuli (Ouellette and Wood 1998). In what appears to be the first empirical study of the interplay between will and habits, Ach (1910) argued that human will can be studied best when opposed by overlearned habits that need to be overcome. In his “combined method,” he first had subjects acquire particular S-R associations by asking them, for instance, to produce a rhyme to a stimulus syllable (e.g., “zup” → “tup”). After extensive practice, he presented the same stimuli but asked for another response, such as reading the syllable backward (e.g., “zup” → “puz”; cf. Hommel 2000). According to Ach, practice leads to direct associations between stimuli and responses, so that presenting a stimulus later on will automatically activate the corresponding response. If this response is not the correct one, it is up to the will to counteract the now dysfunctional habit and to make sure that the intended response is made. This extra demand should show up in two measures: (1) increased reaction time to stimuli previously associated with a different response; and (2) increased occurrence of what Ach called “intended errors,” that is, production of the previously associated but now incorrect response.

Although the methodological standards of experiments in these early days certainly do not meet today’s expectations—especially the lack of inferential statistics and the small number of subjects per study—both increased reaction times and increased frequency of “intended errors” after the task switch were replicated many times by Ach and several of his students (summarized in Ach 1935). According to Ach, these findings indicate that a stimulus event not only provokes an intentional translation into an appropriate response; it may also, and at the same time, automatically retrieve a previously acquired S-R association, thereby activating the previously associated response.

In a better-controlled study, MacLeod and Dunbar (1988) followed the same logic as Ach in trying to manipulate the relative strength of S-R associations through differential practice (cf., Stroop 1935 for a very similar approach). They first trained their subjects to give verbal color word responses to the shapes of polygons. Then colored polygons were presented, and subjects either named the color (color → color word, shape being irrelevant) or responded to the shape (shape → color word, color being irrelevant). In congruent conditions, stimulus color and shape called for the same response, and in incongruent conditions the implied responses were different. As it turned out, testing after only a little practice produced substantial effects of congruence on shape naming but not on color naming, suggesting that the associations between stimulus colors and color word responses were stronger than those between the shapes and the just acquired color word responses. However, after more

practice, congruence also affected color naming; after even more practice, incongruent shapes had a stronger effect on color naming than incongruent colors had on shape naming. Obviously, then, the relative impact of irrelevant stimuli on response selection varies with the relative strength of S-R associations, which suggests that the speed or likelihood of automatic S-R translation, or both, can be affected by learning.

A similar conclusion might be drawn from the findings of Proctor and Lu (1999). Their subjects practiced a spatial compatibility task for three sessions with either a compatible S-R mapping (left stimulus → left response; right stimulus → right response) or an incompatible mapping (left stimulus → right response; right stimulus → left response) before performing a standard Simon task requiring left-right responses to letter stimuli. After compatible mapping practice, a Simon effect of normal size was obtained, but an inverted effect was observed after incompatible mapping practice. Possibly, learning an incompatible mapping leads to the formation of S-R associations that are then automatically activated in the Simon task, too, and thus cancel out, and even overwrite the usual benefits of spatial correspondence.

Rules: Effects of Involuntary Application of the Mapping-Rule

Thus far, the evidence for automatic S-R translation discussed has been restricted to S-R pairs that were either compatible or highly overlearned. However, indications of automatic translation have also been observed in single-session experiments (with no opportunity for extensive S-R learning) using arbitrary S-R mappings. In none of these studies were the translation-inducing stimulus attributes really task irrelevant, nor was the translation completely unrelated to the task or the subject's intentions. Nevertheless, the translation indicated by the results was involuntary and inappropriate, either translating the wrong stimulus or occurring at the wrong time—the right rules used in a wrong way.

If people make a discriminative response to a visual target, their reaction time is strongly affected by irrelevant stimuli surrounding the target. For instance, if a left versus right keypress is made to the centrally presented letters *H* and *S*, which are flanked by other letters, performance is better if target and flankers look the same (e.g., *H* flanked by *Hs*) than if the flankers resemble the other, alternative target (e.g., *H* flanked by *Ss*; Eriksen and Eriksen 1974). This is not just an effect of visual similarity or distraction. If two dissimilar letters are assigned to each response, flankers assigned to the same response as (but different from) the present target produce better performance than flankers assigned to the alternate response (Miller 1991). Such an effect suggests that both flankers and target are processed and activate their corresponding responses. Indeed, incongruent flankers activate their assigned (incorrect) response to the extent that the activation can be observed in the lateralized readiness

potential (LRP; Coles et al. 1985), or in electrophysiological activity (Eriksen et al. 1985) and overt, subthreshold movements of the wrong hand (St. James 1990).

The flanker effect demonstrates that stimuli are not translated into response activation only in strict conformity with the actor's intention and thus indicates some kind of automatic processing.⁴ It is also true, however, that the incorrectly selected and translated flanker stimuli in a flanker task are not completely irrelevant; after all, they are valid targets that merely appear at a wrong location. On the one hand, S-R translation in a flanker task is intentional in the sense that it realizes the intention to respond to stimuli in a particular way. On the other, it seems that not every aspect of the resulting translation can be controlled, so that, somewhat paradoxically, intended S-R rules are automatically applied.

A very similar picture emerges from studies on task-switching performance: moving from one task to another does not switch off the previously used S-R mapping rules completely. Consider, for instance, Sudevan and Taylor 1987, whose subjects responded to single digits ranging from 2 to 9 by pressing a left or right key. There were two different S-R mapping rules, varying randomly from trial to trial, that were signaled by a letter cue preceding the stimulus. According to one rule, odd digits were assigned to one response key and even digits to the other, while the alternate rule assigned low digits (2–5) to one key and high digits (6–9) to the other. Obviously, such mappings introduce conditions of rule or intertask S-R congruence and incongruence, inasmuch as some stimuli require the same response under either S-R assignment (e.g., "3" if "odd" and "low" stimuli were assigned the same key), while other stimuli imply different responses (e.g., "2"). In fact, intertask congruence had a strong impact on performance, with response-congruent stimuli (i.e., stimuli that in the alternate task would require the same response) speeding up performance even if the mapping rule was precued as early as four seconds before the stimulus set in. Similar effects have been observed in Rogers and Monsell 1995, in Meiran 1996, and in several experiments in our lab, suggesting that cross talk between tasks is a reliable phenomenon (cf., Allport and Wylie, chap. 2, this volume). As observed by Otten et al. (1996), this cross talk can have far-reaching consequences, with stimuli belonging to the currently invalid task triggering their associated response up to a level of response-related LRPs.

Note that cross talk between different tasks can occur only if the mapping rules of these tasks are concurrently applied to translate the stimulus into response activation. In fact, participants in task-switching studies seem not so much confused about what to do as uncertain about which (of the simultaneously applied) rules to follow. For instance, Meiran and Daichman (forthcoming) had people switch between tasks under high time pressure, so that many errors were made. Analyses and simulations showed that the types of errors made were not random but rather

reflected the correct use of the incorrect S-R mapping rule, which fits well with the (commonly less pronounced) error patterns observed in other task-switching studies. Obviously, then, we have here the same kind of interplay between intentional and automatic processes as seen before. On the one hand, we find evidence of S-R translation that is neither needed nor helpful, which indicates a high degree of automaticity even in the absence of extensive practice and S-R similarity. On the other, the outcomes of these automatic processes do not seem erratic or habitlike, but rather are strongly related to the actor's intentions.

The same conclusion can be drawn from Hommel 1998a. Subjects performed two tasks in a row (response order was strictly controlled), a manual left-right keypressing response (R_1) to the color (S_1) of a stimulus, followed by a verbal color name response (R_2) to the form (S_2) of the same stimulus. As often found in such double tasks, the second response was delayed relative to the first by a half second or more, hence there was a "psychological refractory period" (PRP) effect (Telford 1931). However, the type of R_2 strongly affected reaction time in the primary manual task. If the meaning of R_2 corresponded to the color of S_1 (e.g., $S_1 = \text{red}$; $R_2 = \text{"red"}$) the response to S_1 was much faster than if R_2 and S_1 did not match (e.g., $S_1 = \text{red}$; $R_2 = \text{"green"}$). This could only happen if R_2 was activated before the primary task was completed, which again implies that (at least some) S_2 - R_2 translation must have taken place with or even before the processing of S_1 and R_1 . Obviously, then, S-R translation is unlikely to be the "structural bottleneck" that is widely believed to be responsible for dual-task costs and PRP effects (e.g., Pashler 1994, chap. 12, this volume; Welford 1952). Whatever or wherever this bottleneck may be, it does not seem to prevent different stimuli from being translated into response activation at about the same time. Indeed, the application of arbitrary S-R translation rules seems to be so automatic that it occurs even if it or its timing produces unintended and inappropriate results.

Integration: Aftereffects of Stimulus-Response Binding

The previous examples show that extensive learning may promote, but is not always necessary to bring about, automatic S-R translation. Even single-trial learning can produce stimulus-triggered response activation. Hommel (1998b) used a task that required two responses (R_1 and R_2) to two stimuli (S_1 and S_2) on each trial. Participants were presented with a response cue that signaled the identity of R_1 (e.g., left versus right key-press). R_1 was prepared but not performed until S_1 was presented. Although S_1 varied randomly in shape, color, and location (e.g., green versus red; X versus O; top versus bottom position), R_1 did not depend on or covary with any of the features of S_1 . About 1 sec later, S_2 appeared; it varied on the same dimensions as S_1 , with one feature (shape, say) sig-

naling R_2 . That is, the already prepared, simple R_1 was made to the mere onset of S_1 , and the binary forced-choice discrimination R_2 was made to the relevant feature of S_2 . For example, a left-pointing arrow might cue a left-hand response, which is then prepared and performed at S_1 onset, independent S_1 being, say, a red X in the top position. After 1 sec, S_2 would appear (e.g., a green X at the bottom position), with its shape signaling a left-hand response. (Note that this example implies repetition of stimulus shape and response, and alternation of stimulus color and location.)

One might expect several kinds of repetition effects with a task like this, such as better performance if a stimulus feature or the response is repeated. Indeed, repetition effects were obtained, although not very reliably so and only in task versions with very short intervals between S_1 and S_2 (Hommel forthcoming-a). Much more interesting, however, is the consistent observation that stimulus- and response-related repetition effects interacted. In particular, repeating stimulus shape or location was beneficial *only* if the response was also repeated; if not, shape or location repetition yielded interference instead (Hommel 1998b). Apparently, a single co-occurrence of S_1 and R_1 resulted in an association or binding of stimulus (features) and response (features). As a consequence, presenting the same stimulus (feature) reactivated the associated response, which caused a problem if this response was not the correct one, that is, if the repeated stimulus required a new response. That automatic response activation is indeed involved is also suggested by experiments in which the forced-choice R_2 was replaced by a free-choice response to S_2 . Even if urged to avoid any strategy and produce random behavior, participants tend to repeat R_1 if S_1 is also repeated (Hommel forthcoming-b). Being unintended, unwanted, and unhelpful, these S-R binding effects fulfill the most common criteria for automaticity and hence represent a case of automatic S-R translation. Interestingly, however, they clearly do not result from practice or S-R compatibility, or from applying S-R rules in an inappropriate way.

Automaticity: Types versus Degrees

The foregoing examples making the case for automatic translation stem from a broad range of tasks and paradigms and may therefore seem to indicate very different kinds of automaticity. However, it is tempting to try ordering them on a common dimension, such as the length of the learning history involved. Binding effects, which result from experiencing a single S-R co-occurrence, clearly have the shortest history, followed by effects indicating inappropriate rule use, which can be measured after only 50 trials or less. Then we have effects of S-R associations that seem to take several sessions of practice to emerge and, finally, effects of S-R compatibility, which are sometimes attributed to extreme overlearning

of S-R relationships (cf. Umiltà and Zorzi 1997). Indeed, the available demonstrations of automatic S-R translation may differ only with respect to the strength of the underlying S-R associations and thus indicate merely different degrees or states, not different types of automaticity.

Although such an account is attractively parsimonious, it is not supported by the (still few) findings that speak to this issue. First, there is no evidence available as to whether binding effects increase with the number of consistent S-R occurrences, so that it is not clear whether binding is the first stage of S-R associative learning or only a temporary phenomenon. Second, there is no indication that effects of inappropriate rule use would increase over practice. On the contrary, whereas Hommel (1998a) found no systematic relationship between effects of automatic, inappropriate rule use and practice within a single session, Sudevan and Taylor (1987) observed a general decrease of such effects over 20 sessions of task-switching practice. Third, whereas there is strong evidence for the impact of task-irrelevant S-R associations on performance increasing with practice (MacLeod and Dunbar 1988), the studies on automatic rule use (Hommel 1998a; Sudevan and Taylor 1987) have found no evidence of such a relationship, suggesting that the two kinds of effect are of different origin.

Fourth, up to now there is no convincing evidence that S-R compatibility effects are due to S-R learning. Of course, testing this assumption is difficult—if we are talking about lifelong experience (e.g., responding with the right hand to objects on the right side or verbally responding to objects with their name), it would be unethical to prevent subjects from having this experience and impractical to experimentally induce an equivalent number of (counter-) practice trials. Nevertheless, several studies have investigated whether S-R compatibility effects could be eliminated through extensive practice. For instance, Fitts and Seeger (1953) found better performance with spatially compatible than with incompatible S-R mappings even after 32 sessions of practice. Later studies all showed the same pattern of results. During the very first trials, subjects have much more difficulty getting into the task with an incompatible than with a compatible mapping, but then the difference between compatible and incompatible conditions stabilizes very quickly and is more or less unaffected by further practice (e.g., Brebner, Shephard, and Cairney 1972; Dutta and Proctor 1992; Morin and Grant 1955). A similar pattern has been observed in Simon tasks. Although Simon, Craft, and Webster (1973) did find a reduction during 5 sessions of 216 trials each, a pronounced Simon effect was still observed in the final session (see also Proctor and Lu 1999). Even 30 sessions of 210 trials each do not suffice to eliminate the effect, as demonstrated by the performance of a single, heroic subject in Hommel 1995b.

To sum up, the available findings do not support the assumption of a single dimension of automaticity or associative S-R strength on which the

observed phenomena could be easily ordered. However, given that some relationships between significant phenomena have not yet been investigated and that some of these relationships are difficult to investigate in any meaningful way, it would be premature to draw definitive conclusions.

11.2 MULTIPLE ROUTES FROM STIMULUS TO RESPONSE

We have seen substantial evidence against the intuitive, but perhaps naive idea that S-R translation is a control operation that realizes the intentions of a perceiver or actor, thereby shielding the action system against unwelcome stimulus-induced action tendencies. The insight that S-R translation is only partially under intentional control has led to the formulation of several models that assume both an intentional and an automatic route from perception to action. I shall review some of the most influential dual-route models, considered state-of-the art in many domains of information-processing psychology, pointing out limitations that need to be overcome if we are to achieve a comprehensive model of S-R translation.

Dual-Route Models

Part of the reasoning behind today's dual-route models can already be found in Ach 1910, which distinguished between will, a capacity-limited mechanism in charge of S-R translation and action control, and habits, S-R associations that result from and become stronger with S-R learning. Habits are assumed to lead to fully automatic S-R translation, that is, to the activation of the response most often associated with the given stimulus in the past. If the outcome of this translation is in agreement with (i.e., functional for reaching) the intended action goal, only minimal effort (or will power) needs to be applied, and execution is facilitated. If an existing habit activates a counterproductive tendency, however, this needs to be overcome by an increase in effort deployed.

Although current dual-route models are often more specific as to the processes involved and the conditions that need to be fulfilled, the general idea that habit and will compete for action control is still alive—even if habitual S-R translation is now called “automatic” or “unconditional” and willed translation referred to as “intentional” or “conditional.” A model that has much in common with Ach's has been suggested by Logan (1988), who assumes that each experience of a S-R episode leaves a memory trace of an “instance.” Attended stimulus events necessarily retrieve the instances associated with them and, through that retrieval, activate the associated response. The more S-R co-occurrences experienced in the past, the more instances retrieved; the more instances

retrieved, the more likely it is that the corresponding response will be activated, which then will compete with intentional, rule-governed S-R translation processes for action control. Although the two models implement habits in different ways—through the strengthening of single S-R associations (Ach) and through a separate trace for each experience (Logan)—the general way they characterize the relationship between intentional and automatic S-R translation is very similar.

Perhaps the most general of dual-route models, Kornblum, Hasbroucq, and Osman's "dimensional overlap model" (1990) attributes S-R compatibility effects to a competition between automatic response activation and voluntary S-R translation. If, and only if, a stimulus event shares features with a response, such as with spatial S-R correspondence in a Simon task, the stimulus activates the corresponding response automatically and in parallel to the controlled translation of the relevant stimulus feature into the correct response. If the automatically activated response happens to be appropriate, response execution is faster and performance better. If not, the system must suppress the misleading response tendency before the correct response can be issued—a time-consuming process. This basic architecture is shared by other, less general models of S-R compatibility (e.g., De Jong, Liang, and Lauber 1994; Hommel 1993a; Lu 1997; Virzi and Egeth 1985).

In the last decade, computational parallel distributed processing (PDP) or neural network models of S-R compatibility have spelled out the dual routes in increasing detail, often implementing intentional and automatic routes in very similar ways. Typically, stimulus feature codes are assumed to be permanently connected to codes of responses they share features with, such as a left stimulus code and a left response code (e.g., Barber and O'Leary 1997; Kornblum et al. 1999; Zorzi and Umiltà 1995). Consequently, registering and coding a stimulus leads to a spreading of activation to the feature-overlapping response, hence to automatic S-R translation. In contrast, intentional translation is modeled by introducing temporary, short-term associations connecting codes of the relevant stimulus feature or features and the respective response. These associations are task specific and intention dependent and may be taken to represent something like S-R rules temporarily stored in working memory.

The notion of dual routes from perception to action has advanced our basic understanding of S-R compatibility and motivated a wealth of empirical investigations. It has played a crucial role in explaining, among other things, the consistent observation that the Simon effect decreases with increasing task difficulty (De Jong, Liang, and Lauber 1994; Hommel 1993a) and the dependence of spatial compatibility effects on task preparation (De Jong 1997; Shaffer 1965). There are several reasons, however, why the basic idea and architecture of dual-route models may fail to fully capture the essence and diversity of S-R translation. I shall discuss three.

Multiple Routes to Action

Constructed to serve rather specialized purposes, such as accounting for practice effects or effects of S-R compatibility, existing dual-route models emphasize one particular type of automaticity and neglect others. Inasmuch as there is more than one type or cause of automatic S-R translation, however, none of the available models seems sufficiently developed to serve as a comprehensive model of S-R translation. Such a model would need more than two routes or pathways from perception to action. To model such multiple pathways, we need to understand the relationships between the various phenomena indicative of automatic translation.

First, we need to know whether S-R binding is only a process for short-term temporary integration or whether it also represents the mechanism that forms long-term S-R associations—what Logan (1988) has called “instances.” Second, we need to know when, how, and why S-R rules, stored in working memory to guide current behavior, can be accessed and used by other, inappropriate or irrelevant stimuli to activate the corresponding responses, and what roles short-term binding and long-term learning play in this context. Third, we need to know more clearly what the relationship is between habits or overlearned S-R associations and S-R compatibility. Take, for instance, MacLeod and Dunbar’s finding (1988) that practicing at naming shapes with color words results in Stroop-like interference with naming colors. If this effect indicates some kind of acquired compatibility between irrelevant stimulus shape and response (which are defined on nonoverlapping dimensions), this would seem to argue against, say, the dimensional overlap model of Kornblum, Hasbroucq, and Osman (1990). Alternatively, if the effect is assumed to be mediated by different mechanisms and simply to mimic compatibility effects, we need to specify these mechanisms and how they differ from those mediating compatibility effects. This in turn requires compatibility models to be specific as to *why* similarity between stimulus and response sets lead to automatic S-R translation—an issue commonly neglected in dual-route models (but see Eimer, Hommel, and Prinz 1995; Hommel 1997).

Automaticity of Intentional Translation

Obviously, people can respond to the same stimulus in many different ways, depending on the task or context and, most important, depending on their intentions and strategies. To account for this enormous degree of flexibility in S-R translation, dual-route models have been equipped with “intentional” or “controlled” pathways, that is, with perception-action links that are under full control of the perceiver’s or actor’s intentional states. On the other hand, we have already seen that intentional or con-

trolled translation is not always as intended and controlled as it should be: irrelevant flankers activate arbitrarily assigned responses, and task-specific S-R rules are inappropriately applied while performing another task. This means that stimuli can activate responses automatically not only via the automatic pathway proposed by dual-route models but also by the intentional route. If so, it cannot be the *process* of S-R translation that is under intentional control, but rather the *implementation* of the underlying S-R rules. That is, although intentional states may determine which rules are selected, formed, and implemented, once they are established, stimuli seem to have direct and uncontrolled access to these rules, leading to automatic translation via intentional routes.

This conclusion has important theoretical implications. First, as far as S-R translation is concerned, it shifts the time point of intentional control from the interval between stimulus perception and response selection to the beginning of a task. In a sense, such a view stands in contrast to Donders's idea (1868) that "will determination" follows perception—an idea that has made its way into many modern information-processing models. In fact, if the preconditions for S-R translation are already set before a stimulus comes up, at least part of the will has already been determined in advance, a consideration I will develop in the section 11.3.

Second, if intentional S-R translation is really as automatic as the available findings suggest, it is unlikely to represent the processing bottleneck that has always been associated with it by single-channel models of dual-task performance since Welford 1952. Obviously, if more than one stimulus at a time can be translated into a response, there is no reason why costs observed in dual-task performance should have something to do with S-R translation. Rather, it may be the automaticity of intentional translation, not the lack of it, that causes the trouble. If more than one stimulus at a time is translated into its response, the system may need to find out which response belongs to which stimulus, and in what order the responses are to be carried out. This may be called a problem of "response selection," but not one of S-R translation (Hommel 1998a).

Intentionality of Automatic Translation

Although exact criteria for automaticity are still under debate (e.g., Bargh 1989; Hasher and Zacks 1979; Neumann 1984), dual-route models explicitly or implicitly share the definition of Kornblum, Hasbroucq, and Osman (1990, 261) that the automatic route can "under some conditions be attenuated or enhanced" but "under no conditions ... ignored or bypassed," and that, accordingly, people "whether instructed to use or to suppress an automatized process would therefore produce evidence of its operation in their performance." There are reasons to believe, however, that automatic S-R translation is not independent of the task at hand and the instructions given to acting participants. In particular, it has been

shown that the occurrence of effects attributed to automatic translation depends on attention (i.e., the way stimuli are selected and coded), intention (i.e., the way responses are prepared and coded), and on task-specific strategies.

Attention and Stimulus Coding A first demonstration of the impact of instructions on “automatic” S-R translation comes from the observation that the Simon effect occurs not only with unilateral, but also with symmetrical, bilateral stimulation. That is, even when people are presented with a left and a right stimulus at the same time, with the relevant one defined by its form (Grice, Boroughs, and Canham 1984), color (Hommel 1993b; Proctor and Lu 1994), or meaning (O’Leary and Barber 1993), they are faster if the relevant stimulus comes up on the same side as the required response. Thus it is not the spatial correspondence between any stimulus and the response that matters for the Simon effect, but the spatial relationship between the *attended* stimulus of a display and the response (Stoffer and Umiltà 1997). Given that the task instruction specifies which stimulus to attend to, this implies that there is no Simon effect without specific task instructions, at least when more than one stimulus is presented at a time. Inasmuch as the Simon effect is attributed to automatic S-R translation, this kind of translation cannot be completely independent from the task.

There are more challenging findings. Consider, for example, Eimer’s observation (1995) that response-irrelevant arrows automatically activate corresponding responses, a finding consistent with dual-route models of S-R compatibility. In a recent lateralized readiness potential study, Eimer and Schlaghecken (1998) showed that even subliminal (i.e., not consciously perceivable) arrowheads preceding a target arrow activated the corresponding response. However, as soon as the relevant arrow stimuli were replaced by letters without any spatial meaning, arrow primes no longer produced “automatic activation.” Obviously, the translation of stimulus information into the activation of spatially congruent responses can depend critically on what relevant information a perceiver or actor intends to translate—hence automatic translation depends on intentions.

A very similar conclusion is suggested by the findings of Cohen and Shoup (1997), who modified the standard flanker task by manipulating targets and distractors on two dimensions: color and orientation. For instance, one response key could be assigned to a red vertical line and a blue right diagonal line and the other key to a green vertical line and a blue left diagonal line. If target and flankers were defined on the same dimension (e.g., red vertical line flanked by red vertical lines versus green vertical lines), the standard flanker effect was obtained, that is, congruent flankers produced better performance than incongruent flankers. If, however, target and flankers were defined on different dimensions (e.g., red vertical line flanked by blue right diagonal lines versus blue left diagonal

lines), there was no congruence effect—an observation also made by Fournier, Eriksen, and Bowd (1998) in a speeded feature judgment task. It seems that, although incongruent flankers are unintentionally translated into corresponding response activation, the probability of this translation is strongly determined by what is defined and identified as target, that is, by task-specific, attentional and intentional processes. This fits nicely with the results of Bauer and Besner (1997), who showed that Stroop words affect keypressing responses only if participants classify the ink of the words, but not if they judge whether a given color is present or absent (even if RT levels are comparable). Obviously, automatic processes are (or at least can be) task dependent.

Intention and Response Coding Evidence for a role of response sets in S-R translation comes from Hommel's 1996, study on spatial S-R compatibility in simple, prepared responses. One major outcome was that effects of S-R compatibility are not restricted to situations involving response uncertainty, as commonly believed (e.g., Berlucchi et al. 1977), but also occur if a completely prepared response is made to a spatially compatible or incompatible go stimulus. It also turned out that the size of the compatibility effect depended strongly on the task relevance of the responses. For instance, if the same (left- or right-hand) response was used throughout a long block of trials, the effect of spatial correspondence between response and go signal was very small and often insignificant. Interestingly, though, much larger and more reliable correspondence effects showed up when another spatial (i.e., right- or left-hand) response was used in a secondary task performed in between the trials of the compatibility task. Apparently, the overlap of stimulus and response features is not a sufficient predictor of automatic S-R translation. Whether a particular response possesses a particular feature and whether this feature overlaps with those of the stimulus are of little consequence if the task at hand does not require use of the response feature to discriminate the response from another one. In other words, similarity between a stimulus and a response produces "automatic" S-R translation only (or at least mainly) if the respective feature dimension is important to the given task context.

If this is so, one should be able to manipulate the kind of "automatic" S-R translation by asking the participant to attend more to some response features than to others. This is what Hommel (1993c) did in a version of the Simon task, where people responded to the pitch of a tone heard randomly on the left or right side by pressing a left- or right-hand key. Pressing a particular key flashed a light on the opposite side, so that each response had two spatial features: the location of the finger or key and the location of the action-contingent light. When subjects were instructed, as in a standard Simon task, to "press the left/right key in response to the low/high pitch," left-hand keypresses were faster to left-side tones and

right-hand keypresses were faster to right-side tones—a standard Simon effect. When, however, subjects were instructed to “flash the right/left light in response to the low/high pitch,” left-hand keypresses were faster to right-side tones and right-hand keypresses were faster to left-side tones. Obviously, the instruction not only had a strong impact on automatic S-R translation; it actually determined its outcome. Merely describing the task in terms of keypressing led the participants to code their responses with respect to the locations of the response keys, whereas describing the very same task in terms of light flashing persuaded them to code their responses with respect to the locations of the lights. If we attribute the Simon effect to automatic S-R translation, this is further evidence that automatic translation is not independent of how participants interpret the task and how they intend to solve it.

Strategies and Implementation of Stimulus-Response Rules Apart from stimulus- and response-related factors, automatic translation can also be affected by task-specific strategies and expectations. Evidence for this comes from variations of the relative frequency or likelihood of stimulus-stimulus-congruent or stimulus-response-compatible trials in Stroop tasks (Logan 1980; Logan and Zbrodoff 1979), flanker tasks (Gratton, Coles, and Donchin 1992), and Simon tasks (Hommel 1994; Toth et al. 1995), that is, from manipulations of the utility of irrelevant, but response-related information. Whatever the task, increasing the frequency of congruent or compatible trials increased, and decreasing the frequency decreased or even eliminated, the effect. In the same vein, Proctor, Lu, and Van Zandt (1992) found that the Simon effect gets larger if the likely response is precued and can be prepared in advance. Clearly, these observations suggest that the degree and outcome of automatic translation is modified by, and sometimes even depends on, task-specific strategies and preparatory processes.

Further evidence for a role of task preparation has been reported by Valle-Inclán and Redondo (1998), who measured response activation in a Simon task by means of LRPs. The relevant S-R mapping was not fixed in this study, but varied randomly from trial to trial, as did the temporal order in which mapping and stimulus were presented. When the mapping was presented before the stimulus, the stimulus immediately activated the spatially corresponding response, independently of which response was correct. That is, there was evidence of automatic S-R translation. On the other hand, when the stimulus appeared before the S-R mapping, automatic response activation was no longer observed. Apparently, although automatic S-R translation did not follow the relevant S-R rules, it required their implementation or at least, as Valle-Inclán and Redondo suggest, some degree of readiness to react. Whatever the correct answer may be, it seems clear that automatic routes proposed by dual-route models can be “ignored or bypassed,” which stands in contradiction to how these routes are typically defined and characterized.

11.3 PROSPECTS: STIMULUS-RESPONSE TRANSLATION AS PREPARED REFLEX

The abundant evidence for several kinds of automatic access of stimuli to action control calls for a translation model with more than just one, highly controlled pathway from perception to action. As a consequence, several dual-route models have been developed to account for different aspects of the available evidence, and these models are quite successful in their respective empirical domains. On the other hand, if we want a comprehensive S-R translation model not restricted to particular experimental effects, we still have some way to go.

I have sketched three major theoretical problems that need to be solved. First, a comprehensive model is likely to comprise more than two routes. There is evidence of at least four kinds of automatic S-R translation, and the ways they differ do not suggest that they originate in the same type of process. It thus seems insufficient to distinguish just one intentional and one automatic route. We need more complex, multiroute models. Second, observations of inappropriate rule use suggest that the intentional route from perception to action is not very tightly controlled, but can be automatically accessed by task-related stimuli. This raises doubts about the usefulness of distinguishing between controlled and uncontrolled routes, or at least requires that we specify exactly when and how control is exerted. Third, phenomena that current dual-route models attribute to automatic S-R translation strongly depend on attentional set and action intentions, suggesting that the supposedly automatic route is not uncontrollable. Thus, all in all, there are reasons to doubt that the roles of, and the interplay between, control and automaticity in S-R translation are best captured by the distinction between intentional and automatic routes.

A more suitable approach to the control-automaticity relationship might be derived from consideration of Exner 1879. On the basis of his introspections in "reaction time" experiments (a term he had introduced to psychology six years earlier), Exner explicitly rejected the notion that intentional control (or the will) intervenes between stimulus and response—a notion that seemed quite natural to Donders and that still does to his followers. Exner argued that preparing for a task is accomplished by setting oneself, long before the first stimulus comes up, into a state that ensures that responses are carried out efficiently and as intended. Although evoking that state is a voluntary act requiring attention, once the state is created, the response is actually involuntary, that is, no further effort of will is needed to translate the upcoming stimulus into the response. In fact, stimuli trigger their respective response unless the mediating state is actively deactivated or inhibited. According to this conception, intentional processes do not actually carry out S-R translation, but only configure the cognitive system to do so automatically, once the defined target stimulus arrives—that is, as a "prepared reflex"

(Woodworth 1938). Interestingly, the old idea of theoretically distinguishing between intentional set implementation and set-dependent, but automatic S-R translation is currently experiencing a revival (see the overview by Monsell 1996), and recent models such as those of Cohen and Huston (1994) or Meyer and Kieras (1997; Kieras et al., chap. 30, this volume) can be viewed as first, systematic attempts to implement the major aspects of this distinction into a computational framework.

From a prepared reflex perspective, it is not so surprising to find evidence of both automaticity of intended S-R translation and intentional control of automatic routes. Obviously, a prepared cognitive reflex is neither exclusively automatic nor exclusively voluntary. On the one hand, it is implemented as a consequence of, and does express a voluntary decision to perform an action under particular circumstances in a particular way and thus necessarily depends on task and intention. If so, the resulting task set is likely to reflect the way the task is understood and interpreted by the perceiver or actor, and hence determines how stimuli are coded (e.g., which stimulus features are attended and linked to response features), how responses are coded (e.g., which response features are attended and linked to stimulus features), when stimulus information is expected, and when actions are prepared and issued. As we have seen, all these decisions have a strong impact on the occurrence of automatic processes, and therefore can be regarded as both implementing arbitrary, transient S-R connections (the intentional route) and directly or indirectly enabling learning- or compatibility-related S-R associations (the automatic route).

Once a task set is implemented (and automatic routes enabled), however, the whole system is prepared to act in an automatic fashion—and this may sometimes produce undesirable side effects. It is certainly an advantage that the cognitive system is able to automatize itself, so to speak, so that the onset of a stimulus immediately triggers the corresponding prepared action without (much) further ado. On the other hand, the price to pay for this economical solution is that unwanted information will sometimes lead to troublesome consequences, especially if an irrelevant stimulus fits the internal description of the triggering stimulus, such as in flanker or Stroop tasks, or in task-switching experiments. Nevertheless, even unhelpful and misleading S-R translations of this sort strictly depend on, and thus in some sense represent, the actor's intention.

Such a prepared reflex view may be helpful in developing a comprehensive theory of S-R translation. Indeed, it complements and extends recent attempts at computational modeling of S-R translation processes in compatibility and related tasks. Take, for instance, the models of Barber and O'Leary (1997) and of Zorzi and Umiltà (1995), which distinguish between transient S-R associations reflecting the instructed S-R mapping and permanent links that can be hard-wired or acquired through learn-

ing. Although this distinction maps onto that of intentional and automatic routes, once the transient links are implemented, they work in a purely stimulus-triggered fashion like their permanent counterparts. That is, the two types of pathway differ only in history and durability, not in automaticity. The same can be said of the model proposed by Cohen, Dunbar, and McClelland (1990) and Cohen and Huston (1994), who went one step further in attempting to deal with the process of route implementation itself (also treated in Meyer and Kieras 1997). To do so, task demand representations are postulated, the activation of which (e.g., through presenting task instructions) can directly modify the flow of information from stimulus to response codes. In this case, S-R links differ neither in permanence nor automaticity, but in task-specific strength only. Although it is clear that more work needs to be done to understand and model in greater detail how S-R associations are acquired in the first place, how stimulus and response coding can affect the implementation or use of S-R links, and how the preparation to act influences the likelihood of automatic S-R translation, current modeling attempts are very much in line with the idea of S-R translation as a prepared cognitive reflex.

To summarize, we have seen that S-R translation is not just a direct expression of human will, nor is it satisfactorily sketched as a competition between fully automatic, stimulus-triggered processes and autonomous control operations representing an on-line realization of task intentions. S-R translation is almost always modulated by the intentions of the perceiving or acting person. Rather than directly intervening between stimulus perception and response selection, and thus actually performing the translation, intentional processes seem merely to set the stage for later S-R translation and to leave the rest to the dynamic interplay between intentionally implemented and nonintentionally enabled automatic processes. Even though this kind of interplay may sometimes produce unwanted side effects, we must not forget that intentions usually refer to behavioral outcomes, not to processes realizing them. Therefore, the functionality of our intentionally controlled automatic processes should be judged in terms not of reaction times but of behavioral outcome. Given that, with sufficient time, no subject in a Stroop task would ever name the color word, this surely provides a much brighter perspective on our capacity for self-control.

NOTES

1. Some evidence pertaining to the relationship between conscious awareness and the control of manual pointing and grasping is reviewed by Milner (chap. 9, this volume), although the distinction made there between processing streams for conscious perception and for visuomotor control does not easily map onto the distinction between intentional and automatic S-R translation discussed here.

2. In this chapter, the terms *compatible* and *incompatible* refer to the relationship or mapping between stimuli and responses, whereas the terms *congruence* and *incongruence* refer to the relationship between stimuli or between responses.
3. The Stroop effect has also been observed with manual keypressing responses (e.g., in the absence of S-R feature overlap; Keele 1972), which might be taken to suggest a contribution of stimulus-stimulus (in)congruence to the overall Stroop effect (e.g., Kornblum 1994). Even if this were so, however, the robust finding that switching from manual to verbal responses substantially increases the effect (e.g., Redding and Gerjets 1977) shows that S-R compatibility makes an important contribution of its own.
4. Note that this conclusion in no way depends on the actual cause of the flanker effect. Whether the effect is due to a conflict between target- and flanker-activated responses (Eriksen and Schultz 1979) or to interactions between target- and flanker-coding processes (Kornblum et al. 1999)—implying that response activation only reflects, but does not produce, the flanker effect—it is clear that (1) flanker information is translated into response activation and (2) this particular translation is not intended.

REFERENCES

- Ach, N. (1910). *Über den Willensakt und das Temperament*. Leipzig: Quelle and Meyer.
- Ach, N. (1935). *Analyse des Willens*. In E. Abderhalden (Ed.), *Handbuch der biologischen Arbeitsmethoden*. Vol. 4, Berlin: Urban and Schwarzenberg.
- Arend, U., and Wandmacher, J. (1987). On the generality of logical recoding in spatial interference tasks. *Acta Psychologica*, 65, 193–210.
- Barber, P. J., and O'Leary, M. J. (1997). The relevance of salience: Towards an activation account of irrelevant stimulus-response compatibility effects. In B. Hommel and W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility*, pp. 135–172. Amsterdam: Elsevier.
- Bargh, J. A. (1989). Conditional automaticity: Varieties of automatic influence in social perception and cognition. In J. S. Uleman, and J. A. Bargh (Eds.), *Unintended thought*, pp. 3–51. London: Guilford Press.
- Bauer, B., and Besner, D. (1997). Processing in the Stroop task: Mental set as a determinant of performance. *Canadian Journal of Experimental Psychology*, 51, 61–68.
- Berlucchi, G., Crea, F., Di Stefano, M., and 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.
- Brebner, J., Shephard, M., and Cairney, P. (1972). Spatial relationships and S-R compatibility. *Acta Psychologica*, 37, 93–106.
- Cohen, A., and Shoup, R. (1997). Perceptual dimensional constraints in response selection processes. *Cognitive Psychology*, 32, 128–181.
- Cohen, J. D., Dunbar, K., and McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, 97, 332–361.
- Cohen, J. D., and Huston, T. A. (1994). Progress in the use of interactive models for understanding attention and performance. In C. Umiltà, and M. Moscovitch (Eds.), *Attention and Performance XV: Conscious and nonconscious information processing*, pp. 453–476. Cambridge, MA: MIT Press.

- Coles, M. G. H., Gratton, G., Bashore, T. R., Eriksen, C. W., and Donchin, E. (1985). A psychophysiological investigation of the continuous flow model of human information processing. *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 529–553.
- De Jong, R. (1993). Multiple bottlenecks in overlapping task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 965–980.
- De Jong, R. (1997). Compatibility effects on performance and executive control in dynamic task settings. In B. Hommel and W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility*, pp. 223–239. Amsterdam: Elsevier.
- De Jong, R., Liang, C.-C., and Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 731–750.
- Donders, F. C. (1868). Over de snelheid van psychische processen. *Onderzoekingen, gedaan in het fysiologisch laboratorium der Utrechtsche hoogeschool*, series 2, vol. 2, pp. 92–120.
- Dutta, A., and Proctor, R. W. (1992). Persistence of stimulus-response compatibility effects with extended practice. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*, 801–809.
- 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., and Prinz, W. (1995). S-R compatibility and response selection. *Acta Psychologica*, *90*, 301–313.
- Eimer, M., and Schlaghecken, F. (1998). Effects of masked stimuli on motor activation: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1737–1747.
- Eriksen, B. A., and Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception and Psychophysics*, *16*, 143–149.
- Eriksen, C. W., Coles, M. G. H., Morris, L. R., and O'Hara, W. P. (1985). An electromyographic examination of response competition. *Bulletin of the Psychonomic Society*, *23*, 165–168.
- Eriksen, C. W., and Schultz, D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception and Psychophysics*, *25*, 249–263.
- Exner, S. (1879). Physiologie der Grosshirnrinde. In L. Hermann (Ed.), *Handbuch der Physiologie*, vol. 2, part 2, pp. 189–350. Leipzig: Vogel.
- Fitts, P. M., and Seeger, C. M. (1953). S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, *46*, 199–210.
- Fournier, L. R., Eriksen, C. W., and Bowd, C. (1998). Multiple-feature discrimination faster than single-feature discrimination within the same object? *Perception and Psychophysics*, *60*, 1384–1405.
- Frith, C. D., and Done, D. J. (1986). Routes to action in reaction time tasks. *Psychological Research*, *48*, 169–177.
- Gottsdanker, R., and Shragg, G. P. (1985). Verification of Donders' subtraction method. *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 765–776.
- Gratton, G., Coles, M. G. H., and Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General*, *121*, 480–506.

- Grice, G. R., Boroughs, J. M., and Canham, L. (1984). Temporal dynamics of associative interference and facilitation produced by visual context. *Perception and Psychophysics*, *36*, 499–507.
- Hasbroucq, T., Guiard, Y., and Ottomani, L. (1990). Principles of response determination: The list-rule model of SR compatibility. *Bulletin of the Psychonomic Society*, *28*, 327–330.
- Hasher, L., and Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General*, *108*, 356–388.
- Heister, G., Ehrenstein, W. H., and Schroeder-Heister, P. (1987). Spatial S-R compatibility with unimanual two-finger choice reactions: Effects of irrelevant stimulus location. *Perception and Psychophysics*, *42*, 195–201.
- Hommel, B. (1993a). The relationship between stimulus processing and response selection in the Simon task: Evidence for a temporal overlap. *Psychological Research*, *55*, 280–290.
- Hommel, B. (1993b). The role of attention for the Simon effect. *Psychological Research*, *55*, 208–222.
- Hommel, B. (1993c). Inverting the Simon effect by intention. *Psychological Research*, *55*, 270–279.
- Hommel, B. (1994). Spontaneous decay of response code activation. *Psychological Research*, *56*, 261–268.
- 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). Unpublished study reported in W. Prinz, G. Aschersleben, B. Hommel, and S. Vogt, *Handlungen als Ereignisse*. In D. Dörner and E. van der Meer (Eds.), *Das Gedächtnis: Trends, Probleme, Perspektiven*, pp. 129–168. Göttingen: Hogrefe, 1995.
- Hommel, B. (1996). S-R compatibility effects without response uncertainty. *Quarterly Journal of Experimental Psychology*, *49A*, 546–571.
- Hommel, B. (1997). Toward an action-concept model of stimulus-response compatibility. In B. Hommel and W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility*, pp. 281–320. Amsterdam: Elsevier.
- Hommel, B. (1998a). Automatic stimulus-response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1368–1384.
- Hommel, B. (1998b). Event files: Evidence for automatic integration of stimulus-response episodes. *Visual Cognition*, *5*, 183–216.
- Hommel, B. (2000). Intentional control of automatic stimulus-response translation. In Y. Rossetti and A. Revonsuo (Eds.), *Interaction between dissociable conscious and nonconscious processes*, pp. 223–244. Amsterdam: John Benjamins Publishing Company.
- Hommel, B. (Forthcoming-a). Time course of feature binding.
- Hommel, B. (Forthcoming-b). Single stimulus-response co-occurrences affect subsequent free-choice behavior.
- Keele, S. W. (1972). Attention demands of memory retrieval. *Journal of Experimental Psychology*, *93*, 245–248.
- 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*, *56*, 130–135.

- Kornblum, S., Hasbroucq, T., and Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—a model and taxonomy. *Psychological Review*, 97, 253–270.
- Kornblum, S., Stevens, G., Whipple, A., and Requin, J. (1999). The effects of irrelevant stimuli: 1. The time-course of stimulus-stimulus and stimulus-response consistency effects with Stroop-like stimuli, Simon-like tasks, and their factorial combinations. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 688–714.
- Logan, G. D. (1980). Attention and automaticity in Stroop and priming tasks: Theory and data. *Cognitive Psychology*, 12, 523–553.
- Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, 95, 492–527.
- Logan, G. D., and Zbrodoff, N. J. (1979). When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory and Cognition*, 7, 166–174.
- Lu, C.-H. (1997). Correspondence effects for irrelevant information in choice-reaction tasks: Characterizing the stimulus-response relations and the processing dynamics. In B. Hommel and W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility*, pp. 85–117. Amsterdam: Elsevier.
- Lu, C.-H., and Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin and Review*, 2, 174–207.
- MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, 109, 163–203.
- MacLeod, C. M., and Dunbar, K. (1988). Training and Stroop-like interference: Evidence for a continuum of automaticity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 14, 126–135.
- Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22, 1423–1442.
- Meiran, N., and Daichman, A. (Forthcoming). Parallel processing in rapid switching between tasks.
- Meyer, D. E., and Kieras, E. D. (1997). A computational theory of executive cognitive processes and multiple task performance: 1. Basic mechanisms. *Psychological Review*, 104, 3–75.
- Miller, J. (1988). Discrete and continuous models of human information processing: Theoretical distinctions and empirical results. *Acta Psychologica*, 67, 191–257.
- Miller, J. (1991). The flanker compatibility effect as a function of visual angle, attentional focus, visual transients, and perceptual load: A search for boundary conditions. *Perception and Psychophysics*, 49, 270–288.
- Monsell, S. (1996). Control of mental processes. In V. Bruce (Ed.), *Unsolved mysteries of the mind*, pp. 93–148. Hove, U.K.: Erlbaum.
- Morin, R. E., and Grant, D. A. (1955). Learning and performance on a key-pressing task as function of the degree of spatial stimulus-response correspondence. *Journal of Experimental Psychology*, 49, 39–47.
- Neumann, O. (1984). Automatic processing: A review of recent findings and a plea for an old theory. In W. Prinz, and A. F. Sanders (Eds.), *Cognition and motor processes*, pp. 255–293. Berlin: Springer.

- Nicoletti, R., and Umiltà, C. (1989). Splitting visual space with attention. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 164–169.
- O’Leary, M. J., and Barber, P. J. (1993). Interference effects in the Stroop and Simon paradigms. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 830–844.
- Otten, L. J., Sudevan, P., Logan, G. D., and Coles, M. G. H. (1996). Magnitude versus parity in numerical judgements: Event-related brain potentials implicate response conflict as the source of interference. *Acta Psychologica*, 94, 21–40.
- Ouellette, J. A., and Wood, W. (1998). Habit and intention in everyday life: The multiple processes by which past behavior predicts future behavior. *Psychological Bulletin*, 124, 54–74.
- Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, 116, 220–244.
- Proctor, R. W., and Lu, C.-H. (1994). Referential coding and attention shifting accounts of the Simon effect. *Psychological Research*, 56, 185–195.
- Proctor, R. W., and Lu, C.-H. (1999). Processing irrelevant location information: Practice and transfer effects in choice-reaction tasks. *Memory and Cognition*, 27, 63–77.
- Proctor, R. W., Lu, C.-H., and Van Zandt, T. (1992). Enhancement of the Simon effect by response precuing. *Acta Psychologica*, 81, 53–74.
- Redding, G. M., and Gerjets, D. A. (1977). Stroop effect: Interference and facilitation with verbal and manual responses. *Perceptual and Motor Skills*, 45, 11–17.
- Rogers, R. D., and Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, 124, 207–231.
- Sanders, A. F. (1980). Stage analysis of reaction processes. In G. E. Stelmach, and J. Requin (Eds.), *Tutorials in motor behavior*, pp. 331–354. Amsterdam: Elsevier.
- Schweickert, R., and Boggs, G. J. (1984). Models of central capacity and concurrency. *Journal of Mathematical Psychology*, 28, 223–281.
- Shaffer, L. H. (1965). Choice reaction with variable S-R mapping. *Journal of Experimental Psychology*, 70, 284–288.
- Simon, J. R., Craft, J. L., and Webster, J. B. (1973). Reactions toward the stimulus source: Analysis of correct responses and errors over a five-day period. *Journal of Experimental Psychology*, 101, 175–178.
- Simon, J. R., and Small, A. M. (1969). Processing auditory information: Interference from an irrelevant cue. *Journal of Applied Psychology*, 53, 433–435.
- Sommer, W., Leuthold, H., and Hermanutz, M. (1993). Covert effects of alcohol revealed by event-related potentials. *Perception and Psychophysics*, 54, 127–135.
- St. James, J. D. (1990). Observations on the microstructure of response conflict. *Perception and Psychophysics*, 48, 517–524.
- Stoffer, T. H., and Umiltà, C. (1997). Spatial stimulus coding and the focus of attention in S-R compatibility and the Simon effect. In B. Hommel and W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility*, pp. 181–208. Amsterdam: Elsevier.
- Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 28, 643–662.
- Sudevan, P., and Taylor, D. A. (1987). The cuing and priming of cognitive operations. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 89–103.
- Teichner, W. H., and Krebs, M. J. (1974). Laws of visual choice reaction time. *Psychological Review*, 81, 75–98.

- Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology*, 14, 1–36.
- Toth, J. P., Levine, B., Stuss, D. T., Oh, A., Winocur, G., and 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.
- Umiltà, C., and Liotti, M. (1987). Egocentric and relative spatial codes in S-R compatibility. *Psychological Research*, 49, 81–90.
- Umiltà, C., and Zorzi, M. (1997). Commentary on Barber and O'Leary: Learning and attention in S-R compatibility. In B. Hommel and W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility*, pp. 173–178. Amsterdam: Elsevier.
- Valle-Inclán, F., and Redondo, M. (1998). On the automaticity of ipsilateral response activation in the Simon effect. *Psychophysiology*, 35, 366–371.
- Virzi, R. A., and Egeth, H. E. (1985). Toward a translational model of Stroop interference. *Memory and Cognition*, 13, 304–319.
- Welford, A. T. (1952). The "psychological refractory period" and the timing of high-speed performance: A review and a theory. *British Journal of Psychology*, 43, 2–19.
- Welford, A. T. (1968). *Fundamentals of skill*. London: Methuen.
- Woodworth, R. S. (1938). *Experimental psychology*. New York: Holt, Rinehart and Winston.
- Zachay, A. (1991). Diskrete und kontinuierliche Informationsverarbeitungsmodelle zur Erklärung von Reiz-Reaktions-Inkompatibilitäten: Evidenz für einen Antwortkonflikt beim Simon-Effekt. Master's thesis, University of Tübingen.
- Zorzi, M., and Umiltà, C. (1995). A computational model of the Simon effect. *Psychological Research*, 58, 193–205.