Acta Psychologica 136 (2011) 189–202

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/ locate/actpsy

The Simon effect as tool and heuristic

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ARTICLE INFO

Article history:
Received 22 January 2010
Received in revised form 3 April 2010
Accepted 19 April 2010
Available online 26 May 2010

PsycINFO classification:
2140 History & Systems
2300 Human Experimental Psychology
2346 Attention

Keywords:
Simon effect
Attention and action
Perception and action

ABSTRACT

On its 43rd anniversary the Simon effect can look back at a long and varied history. First treated as a curious observation with implications for human factors research, it slowly evolved not only into a valuable target of psychological theorizing itself but also into a handy means to investigate attentional operations, the representation of space and of one's body, the cognitive representation of intentional action, and executive control. This article discusses the major characteristics of the Simon effect and the Simon task that laid the ground for this success and reviews the major lines of research, theoretical developments, and ongoing controversies on and around the Simon Effect and the cognitive processes it reflects.

1. Introduction

In the early 1990s, I visited a meeting of the British Experimental Psychology Society in Cambridge. On our way to the conference site, I introduced myself to a British colleague and she was kind enough to recall: “ah yes, you are investigating the Simon effect”. I think I did say that I was but at the same time that struck me as extremely odd and worrying: Investigating an effect, rather than cognitive mechanisms or phenomena, was the least useful thing I could imagine, especially an effect that is as artificial as the Simon effect or its relatives, such as the Stroop effect. And, even though I recognize the scientific need to fully understand the experimental paradigms one is working with, I still feel that it is mechanisms and phenomena scientists should be interested to explain, not the rather artificial effects that we use to create in our labs to test these explanations.

However, the fascinating thing about the Simon effect, and the experimental design used to create it, is that it provides a particularly useful window into a whole number of central aspects of human cognition and action. Accordingly, the effect has fortunately often been used not so much as a major target of investigation itself but, rather, as a tool to investigate perception, attention, action planning, and cognitive control in various populations and species. As I will try to explain below, this is presumably because of two main characteristics of the effect and the design producing it. First, the effect in several ways raises many theoretically interesting questions and, second, the particularly straightforward design already hints at useful experimental strategies to investigate these questions. This, I think, is the main reason for why the Simon effect is so popular and why it is likely to stay in our methodological toolbox for quite a while.

In the following, I will briefly sketch the basic aspects of the Simon effect and the main characteristics of the experimental design used to create it and then pinpoint two theoretical lines of thinking the effect has inspired and driven for quite a while: the relationship between attention and action and intentional action control. I will not try to provide an exhaustive overview of the considerable amount of work that has been done to address these issues but, rather, try to distill the main theoretical issues and controversies. Moreover, my major theoretical goal will not be the explanation of the Simon effect, which I still consider a scientific tool and heuristic rather than a phenomenon of impressive ecological validity. Instead, I will focus on the wider, more general implications of the available research that either employs the Simon effect or that is inspired by theoretical questions it raises.

2. The Simon task and the Simon effect

The first Simon-type effect was reported by Simon and Rudell (1967). As shown in Fig. 1, participants were presented with the auditory words “left” and “right” through the left or right speaker of a headphone. They were to press a left or right key in response to the meaning of the word but to ignore the location where it was presented. The main finding was that participants were unable to ignore the location of the word: Even though it varied randomly and

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doi:10.1016/j.actpsy.2010.04.011

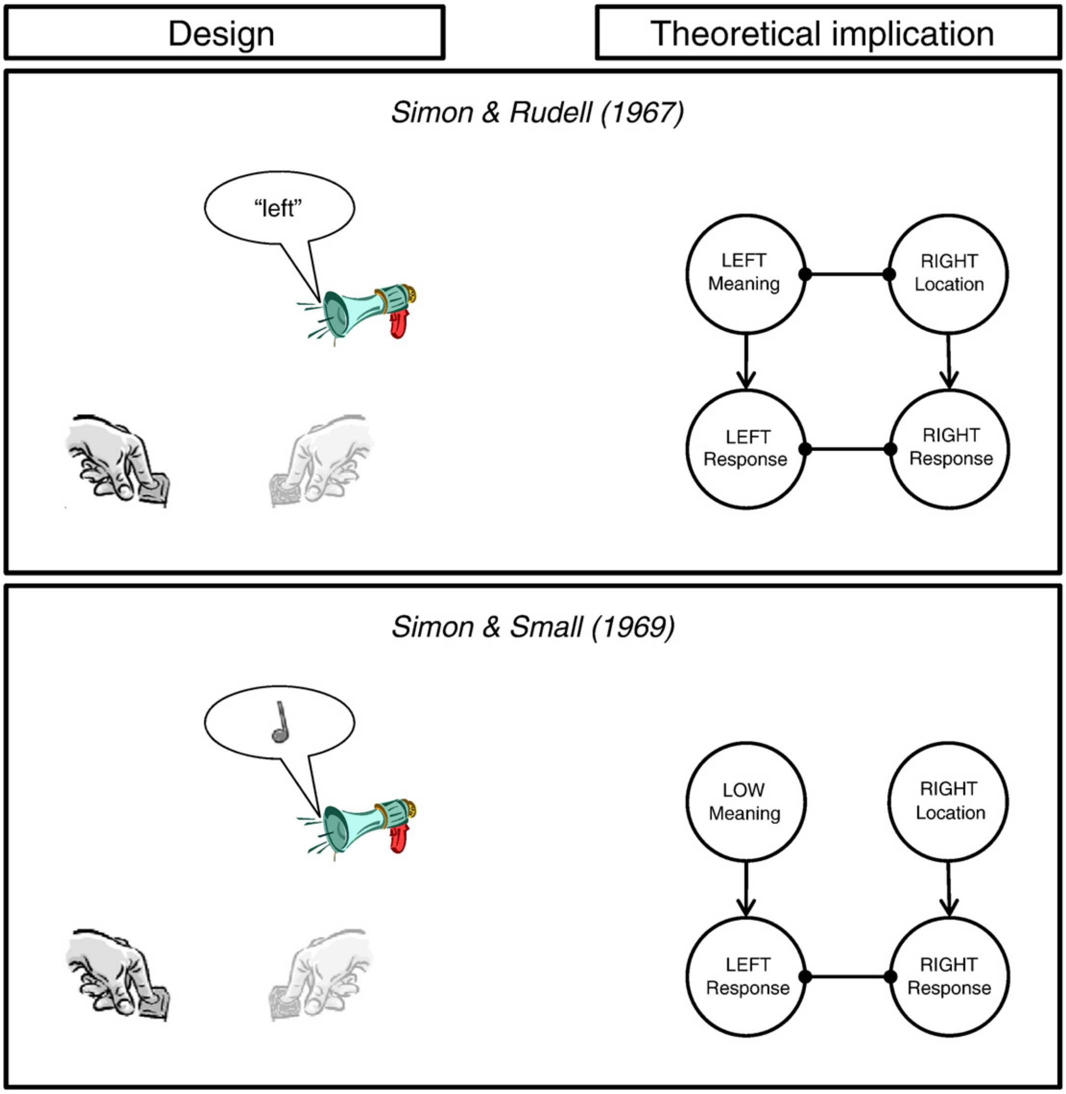

Fig. 1. The designs of Simon and Rudell (1967) and Simon and Small (1969) and their theoretical implications. Both examples refer to a left-hand keypress to either a word or a low tone presented on the right side. Note that the Simon and Rudell design allows for two types of conflicts (indicated by the horizontal dot connectors) while the Simon and Small design allows for only one type of conflict.

was thus not informative with respect to the relevant stimulus feature or the response, participants were faster if the location of the word was spatially corresponding to the response.

As unexpected and surprising this effect was, it does not really count as a true Simon effect. If we assume that the slower responses reflect some kind of conflict between cognitive representations, as basically all available theoretical accounts of the Simon effect or similar effects suppose, there are two types of conflict that might have played a role in the Simon and Rudell study. Consider a left-hand response to the word "left" presented on the right (see Fig. 1, upper row). For one, the representation of the right location could conflict with the left response. This could either be due to a direct interaction between the spatial stimulus code and the spatial response code or due to a response conflict—the right stimulus may prime the right response, which then competes with the left response. In any case, this would be a conflict that arises from the lack of spatial correspondence between stimulus and response. For another, however, the representation of the right location could conflict with the representation of the word "left". Hence, a conflict might arise from semantic incongruence between the two stimulus attributes meaning and location—a kind of Stroop effect (Stroop, 1935). Accordingly, the effect observed by Simon and Rudell is in some sense theoretically overdetermined and, thus, difficult to interpret.

Fortunately, however, a theoretically more transparent version of design and effect was presented not much later by Simon and Small (1969). As shown in the lower row of Fig. 1, left and right responses were now signaled by the pitch of tones appearing randomly on the left or right. Given the arbitrary mapping and relationship between high and low pitch on the one hand and left and right response location on the other, there was no longer any basis for a conflict between stimulus features. This left just one relationship that could account for the again observed better performance with spatial stimulus–response correspondence than with noncorrespondence: that between stimulus location and response location. The very existence of the Simon effect indicates that this correspondence matters, which suggests that the Simon effect is a particularly pure measure of the impact of a task-irrelevant stimulus feature on response conflict. This purity is a considerable methodological and theoretical advantage, especially if one compares the Simon effect with its closest relatives: the Stroop effect and the Eriksen flanker effect (see Fig. 2). As emphasized by Kornblum, Hasbroucq, and Osman (1990), these effects imply rather different processing problems and are likely to require different explanations.

The Stroop effect is obtained when people respond to stimuli with two related, congruent or incongruent stimulus features, such as the color of words that denote congruent or incongruent colors (Stroop,

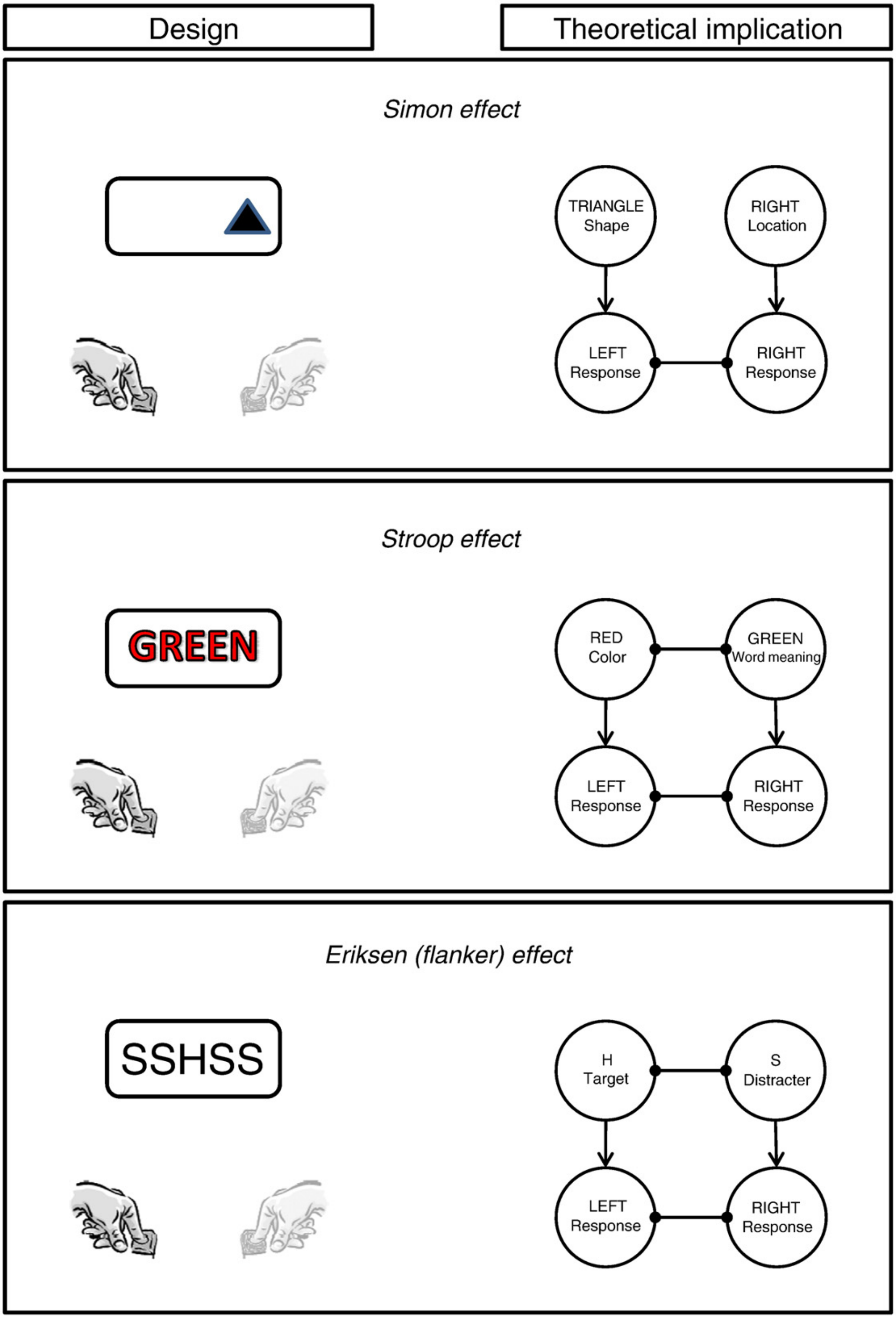

Fig. 2. The designs generating Simon, Stroop and Eriksen flanker effects and their theoretical implications. Note that the Simon effect can only result from one type of conflict (as indicated by the horizontal dot connectors) while Stroop and Eriksen flanker effects could result from two types of conflicts.

1935). In a simple (and less effective) version of the task, participants respond by pressing keys, so that no congruent or incongruent relationships exist between the response and either the relevant or the irrelevant stimulus feature (see Fig. 2). But even in this case, congruency manipulations might affect either of two relationships: that between the codes of any two stimulus features and that between the response codes mapped onto the relevant and irrelevant stimulus features. If, for instance, participants press a left-hand key in response to the color red, and the red color appears as part of the incongruent word GREEN, as in my example, a possible impairment of performance might be due to either a conflict between the two stimulus-related feature codes or a conflict between the two responses that are mapped onto green and red, or both. Even more complicated is the standard Stroop design in which participants are to name the color of the stimulus. In this design, conflict might not only arise between the codes of the two stimulus features and the two responses, but the code of the irrelevant color word might also interact and interfere with the activation of the code of the correct response. Indeed, systematic manipulations have revealed separable contributions of stimulus and response conflict (De Houwer, 2003). Compared with the straightforward interpretation that the Simon effect offers, the multitude of relationships in the Stroop design make the situation very complicated and possible effects difficult to interpret.

The Eriksen flanker effect is obtained if people respond to target stimuli that appear among distracters, such as a central target letter (S or H in the example of Fig. 2) flanked by irrelevant, congruent or incongruent letter distracters (Eriksen & Eriksen, 1974). Responses are typically manual, so that the relationship between either targets or distracters and the response do not vary in terms of congruency. And yet, even though numerous studies have demonstrated that incongruent flankers impair performance, this may be due to either one of two relationships: that between the code of the target and the codes of the distracters and that between the responses that are mapped onto targets and distracters. In the example, if participants press a left-hand key in response to the central letter H (and a right-hand key in response an S), S flankers may impair performance because of a direct conflict between H codes and S codes and/or because of a conflict between the response codes the stimuli are activating or priming (Fig. 2). Again, systematic manipulations have revealed separable contributions of stimulus and response conflict (Fournier, Scheffers, Coles, Adamson, & Villa Abad, 1997). As with the Stroop effect, this makes the interpretation of possible effects considerably less straightforward than in the case of the Simon effect. This is even more true for task versions that are using arrows instead of other shapes or alphanumerical stimuli, which introduces a third relationship: that between flankers and the (spatial) response.

To summarize, even though many researchers tend to treat Simon, Stroop, and Eriksen flanker effects alike—commonly referring to the intuition that all three tasks involve irrelevant stimulus information that in one way or another induce response conflict—a theoretical analysis reveals important differences with respect to the processes that might be responsible for these effects (Kornblum et al., 1990). Moreover, the effects produce markedly different reaction-time distributions (e.g., Hommel, 1997a) and involve partly different brain areas (Liu, Banich, Jacobson, & Tanabe, 2004). Of the three effects, the Simon task is the only one that provides full control over the manipulated relationships and possible conflicts between cognitive representations. Accordingly, outcomes obtained with the Simon task, such as the Simon effect, are much more straightforward to interpret and to relate to theoretical predictions. For that reason the Simon task is, or at least should be the preferred tool for investigating interactions between perception and action, and for investigations related to such interactions.

Apart from this methodological advantage, the Simon effect has raised particularly interesting theoretical questions and motivated numerous, often very creative experiments to answer them. The two issues that I will consider in this article have been with us from very early on. The first can be dated back to the seminal paper of Simon (1969), which investigated unimanual responses in the Simon task (i.e., pressing one of two keys with the same finger). A rather straightforward account of the standard Simon effect could be based on the neuroanatomical characteristics of processing left and right stimuli and carrying out left and right responses (Verfaellie, Bowers, & Heilman, 1988, 1990): Lateralized visual and (to some degree) auditory stimuli are processed in the contralateral cortical hemisphere and hand movements are controlled by the contralateral cortical hemisphere, so that spatially non-corresponding stimulus–response pairs might be processed more slowly simply because the neural signals involved need to travel a longer distance. If so, the Simon effect should disappear with unimanual responses. However, Simon (1969) could demonstrate a full-blown Simon effect under these conditions, thus ruling out an anatomical account. As an alternative, he suggested what has been taken to be the first attentional account of the Simon effect (Stoffer, 1991): People might have a primitive tendency to react toward the source of stimulation, a kind of orienting reflex (Sokolov, 1963) that facilitates actions towards, and interferes with actions away from the stimulus. This consideration actually consists of two components. For one, it presupposes some sort of attentional response to the stimulus, which is presumably automatic, and, for another, it assumes that this response somehow facilitates spatially corresponding reactions. Simon and his colleagues, and attentional accounts since then, have focused on the first of these two components and not really addressed the second. I will discuss the versions and major ideas of attentional approaches in the following section.

The second issue has been raised by Wallace in 1971 already (and, to some degree, by Simon, Hinrichs, & Craft, 1970). Like Simon (1969), Wallace was interested to see how “cognitive” the effect really is and whether anatomical factors could really be ruled out. Descriptions of the Simon effect often refer to “left” and “right” responses, without really saying what these spatial labels actually refer to. In fact, when pressing a left or right key with the left and right index finger, as in the most common setup, almost everything about the two responses is lateralized in corresponding ways and, thus, spatially confounded. When pressing a key, say, I am moving the left index finger of my left hand, which is located on the left side and pressing a left key—so exactly what is it that makes my response sufficiently “left” that it can be facilitated by a “left” stimulus? To address this question, Wallace (1971) had participants cross their hands, so that the left hand would operate the right key, and vice versa. As it turned out, the Simon effect went with the key but not the hand—as in the very similar study of Simon et al. (1970), which not only supports Simon (1969) claim that the effect does not have an anatomical basis but also suggests that it is the action, rather than the effector that counts. Wallace's study raises a general issue that is often neglected in cognitive psychology, namely, how actions are actually cognitively represented. I will get back to this issue.

3. Attention and spatial coding

Simon's (1969) line of thought provides a preliminary answer to the question of why the Simon effect occurs at all, but at the same time it raises at least two further questions: why is that and how does it work? Given that stimulus location is not important in the Simon task at all, it is not obvious why people would process location information. Hence, if the Simon effect reflects some sort of interaction between spatial stimulus and response codes, why do people form spatial stimulus codes if they don't need them? Moreover, if they do code stimulus location, exactly how might that work? Even though attentional approaches have emphasized this particular question (e.g., Umiltà, 2004), no available attentional approach has ever suggested a concrete mechanism of spatial stimulus coding. What attentional approaches did suggest, however, are conditions that are necessary or sufficient for coding to take place. A third, related question is what these codes are actually representing, that is, to which particular spatial relationship they are referring. I will address these three issues in the reverse order.

3.1. What do spatial codes represent?

A visual stimulus on the left side of a screen or a sound presented through the left speaker of a headphone obviously deserves the label “left stimulus”. But how about more complex displays? This was exactly the question of a seminal study by Nicoletti and Umiltà (1989). They presented their participants with six boxes on a screen (see Fig. 3, where boxes are numbered for clarity), and the visual target stimulus (a simple shape) could appear with equal probability

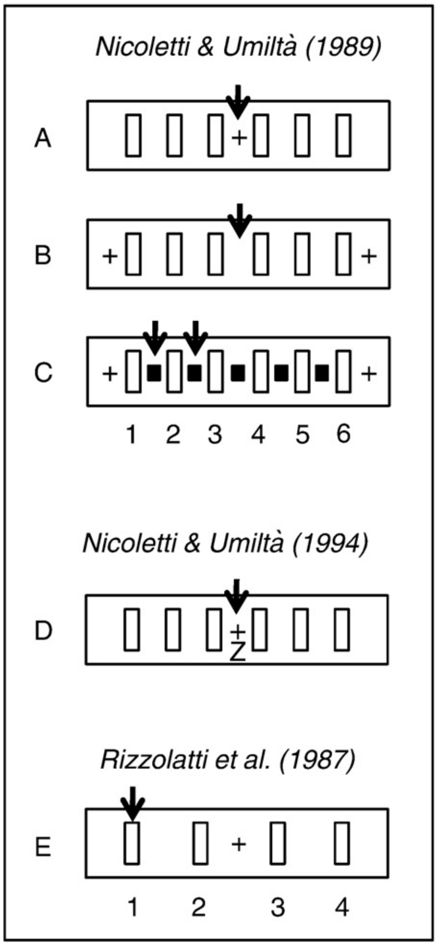

Fig. 3. Examples of the visual displays used in the studies of Nicoletti and Umiltà (1989), Nicoletti and Umiltà (1994), and Rizzolatti, Riggio, Dascola and Umiltà (1987). The boxes (which were continuously visible) indicate the possible target locations, the plus sign indicates the possible fixation locations, and the arrows indicate to-be-attended locations. For further explanation see text.

in each of the boxes. In one experiment, participants were to fixate a cross at the center of the screen (Fig. 3A). Left responses turned out to be faster if the stimulus appeared in one of the three boxes left from fixation (1–3), while right responses were faster if the stimulus appeared in the three rightmost boxes (4–6). In another experiment, participants were to fixate a cross left or right of the whole display (Fig. 3B) but attend to the screen center. Left responses were again faster with the three leftmost boxes and right responses were faster with the three rightmost boxes, suggesting that it is the focus of attention that counts for spatial coding but not the retina. In yet another experiment, participants were to attend to tiny squares in between two boxes (Fig. 3C). Irrespective of the absolute location of the attended square and the box containing the target stimulus, left responses were faster if the target appeared on the left of the attended square and right responses were faster if the target appeared on the right of it. These findings suggest that attention, and the attentional focus in particular, can play an important role in coding stimuli as left or right. Accordingly, the authors suggested that "…directing attention to a position in space brings about a right–left perceptual organization…" (Nicoletti & Umiltà, 1989: p. 164) of the stimulus display and its elements.

A few years later, Nicoletti and Umiltà (1994) and Stoffer and Yakin (1994) considered another possibility: Instead of the *current* focus of attention emphasized by Nicoletti and Umiltà (1989) it might be the *previously* focused location that matters for spatial coding. That is, a stimulus that appears on the left of a currently attended location might be coded as left not because it *is* on the left of this location but because attention needs to be *shifted to the left* in order to focus on that stimulus. If so, Nicoletti and Umiltà (1994) reasoned, stimuli should not be spatially coded if attention is prevented from moving towards the stimulus. And if a stimulus is not spatially coded there should be no Simon effect. To test that, participants were presented with a display as shown in Fig. 3D, where a small letter was presented right below the central fixation mark while the target stimulus appeared. This letter was to be reported and the assumption was that this required focused attention on that letter, thus preventing a shift towards the target stimulus. As expected, no Simon effect was obtained in this condition and in several other experiments conducted since then.

Even though the latter finding might suggest that only the (focus-) relative location of stimuli matters, other spatial stimulus codes have been demonstrated to contribute to stimulus–response compatibility as well. Lamberts, Tavernier, and d'Ydewalle (1992) had participants respond to visual stimuli that varied randomly in terms of hemispace (i.e., the absolute location in the given display), hemifield (the location relative to the fovea), and relative position (the location relative to the alternative stimulus location). All three reference frames varied orthogonally, so that that their contribution could be assessed independently. It turned out that all three frames play a role in stimulus–response compatibility: left and right responses were facilitated if they corresponded to the stimulus location with respect to either frame. This suggests that the cognitive system does not compute just one stimulus location but many, so that each stimulus is simultaneously coded in various spatial maps that presumably serve different computational purposes (Rizzolatti, Riggio, & Sheliga, 1994). Apparently, codes computed in each of these maps can interact with representations of the response, at least with the representations coding for its location.

Further evidence for the involvement of several codes was provided by Hommel and Lippa (1995). They presented a photo of Marilyn Monroe rotated by 90° to the left or right, with the target stimulus appearing in Monroe's left or right eye. This meant that all stimuli were presented at the same horizontal location and varied only in their vertical location. Irrespective of their vertical location, stimuli appearing in Monroe's left eye facilitated left responses and stimuli appearing in the right eye facilitated right responses, suggesting that object- or context-related spatial codes can also interact with spatial response codes. The same conclusion holds for the observation of Kerzel, Hommel, and Bekkering (2001) that centrally presented static stimuli can facilitate left and right responses if the visual context induces an apparent left- or rightward motion of that stimulus, respectively.

Yet another spatial code that apparently can interact with spatial response codes refers to the eye being stimulated by a particular stimulus. Valle-Inclán, Hackley, and De Labra (2003) had participants respond to monocular color patches presented to either the left or the right eye. The stimuli would always appear to be presented at the same central location and only half of the participants were able to report which eye was being stimulated. However, irrespective of the validity of this report, participants were faster if there was spatial correspondence between the response and the stimulated eye.

To summarize, the human brain seems to code for all sorts of spatial aspects of a stimulus event and there is evidence that all these codes can interact with the spatial representation of an action directed to, or at least triggered by a given stimulus. Moreover, the spatial representation of the action seems to comprise of several spatial codes as well, as indicated by the observation of separate contributions of the spatial characteristics of the effector being used, the movement carried out, and the goal being achieved to the overall Simon effect (Hommel, 1993a; Simon et al., 1970). These findings are certainly of interest for making sense of the Simon effect but they go way beyond this particular effect, thus demonstrating how the Simon effect can be employed as an experimental tool to investigate spatial representation in the broader sense.

3.2. How are spatial codes formed?

As mentioned already, attentional accounts of the Simon effect consider this question central to their approach (Umiltà, 2004) and they are commonly dealing with it by referring to the premotor theory of attention (Rizzolatti, Riggio, Dascola, & Umiltà, 1987). This theory was originally developed to account for the so-called meridian effect in spatial cueing. In the study of Rizzolatti et al., participants were to respond to visual target stimuli that could appear in any of four boxes on a screen (see Fig. 3E for a simplified example). The target was precued with 70% validity and, unsurprisingly, participants were faster if the target appeared in the cued location. More interesting were the invalid conditions, however. Reaction times increased with increasing distance between the cued location and the eventual target location and, importantly, if the cued location and target location fell into different hemifields (participants constantly fixated the center of the screen, so that boxes 1 and 2 fell into the left hemifield and boxes 3 and 4 into the right). Assume, for instance, the precue would indicate the leftmost box, as in Fig. 3E. If then the target would appear in box 2 performance would be better than if the target appeared in box 3. Likewise, if box 2 would be precued, a target appearing in box 1 would allow for faster responses than a target appearing in box 3.

To account for this meridian effect, Rizzolatti et al. suggested that moving visual attention in space is accomplished by programming (but not necessarily executing) eye movements. Rizzolatti et al. further assumed that an oculomotor program would require both a directional and a distance parameter, so to indicate whether the eyes should go to a location, say, to the left or right, and far or near. Moreover, specifying or modifying the directional parameter was assumed to be more time-consuming than specifying or modifying the distance parameter. Taken together, these assumptions could account for the meridian effect. If, say, box 1 would be cued, participants would program an eye movement to the far left, but not yet carry out the movement. If, then, the actual target would appear in box 2, they would need to change the distance parameter from “far” to “near” to move attention to this box, but they could keep the directional parameter. In contrast, if the target would appear in box 3, they would need to change both the directional and the distance parameter, which would be particularly time-consuming. The same logic would hold if the cue appeared in box 2, which would make it easier to move attention from there to box 1 (change of distance parameter) than to move it to box 3 (more time-consuming change of directional parameter).

Nicoletti and Umiltà (1994) argued that the premotor theory would explain why the spatial stimulus code would be formed in the Simon task even though it is nominally task-irrelevant. To attend the target, Nicoletti and Umiltà assume, people would need to move their attention to the target's location, which again would require the programming of a corresponding eye movement. To program the eye movement, however, requires the extraction of parameters from the stimulus location, so that participants simply cannot help but process the location information. If they are prevented to move attention, as in the Nicoletti and Umiltà (1994) study, no program is constructed and no location information processed. Hence, no Simon effect.

The linkage between the Simon effect and premotor theory is theoretically very interesting and it has sparked numerous experiments. And yet, there are reasons to doubt that this linkage really works—not only because the premotor theory cannot be considered to be widely accepted, but also because its link to the Simon effect is questionable. Consider the rationale underlying the Nicoletti and Umiltà (1994) study and almost any attention-shifting study of the Simon effect that followed. The spatial point of reference for coding an upcoming stimulus as left or right is claimed to be the current focus of attention. Once the focus is shifted, this point of reference changes and is now located wherever the focus has been shifted to. Let us play this through for the study of Rizzolatti et al. (1987). Cuing box 1, say, would move attention to the location of this box. If then the target would appear in box 2, this would require a shift of attention *to the right*! According to premotor theory, first moving attention to the left and then moving it to the right requires a change of the directional parameter, which premotor theory assumes to be rather time-consuming to change. In other words, the premotor theory does not work any longer if one assumes a spatial reference point that has its origin at the currently attended location. What premotor theory needs, instead, is a reference point that stays with the currently *fixated* location, that is, with the unmoved eye but not the shifted attention! Which of course makes sense for programming the movement of any body part: programming should always consider the *actual* location of this part rather than the location the part *would* occupy *had* a previous program been executed. This comes down to a structural incompatibility between premotor theory and the attention-shifting approach to spatial stimulus coding in the Simon task. Without premotor theory to back it up, however, the attention-shifting approach is void of any mechanism that could explain why stimulus location is coded and how stimulus codes are formed.

What adds to the problem is that almost none of the available attention-shifting studies provided any evidence that the assumed attentional shifts are actually taking place (and some studies assume even sequences of shifts, e.g., Treccani, Umiltà, & Tagliabue, 2006). Explaining the formation of a particular spatial code by assuming that the attentional focus moved from location L_1 that it occupied at time T_1 to location L_2 occupied at time T_2 would seem to presuppose an independent demonstration that attention really occupied L_1 at T_1 and L_2 at T_2. Such a demonstration would be easy to accomplish, for instance by occasionally presenting probes at the respective locations at the respective times. And yet, not one of these demonstrations is available, which basically renders attention-shifting theorizing circular: the presence of the shift is taken to be demonstrated by the very effect is assumed to explain.

Another major problem for the attention-shifting approach is that it is unable to explain the impact of multiple spatial codes. As reviewed above, there is now evidence for contributions from absolute and relative spatial stimulus location, object- and context-induced spatial codes, and even receptor-specific spatial codes, and they all seem to interact with the spatial response code (or several of them: Hommel, 1993a), apparently even in parallel (Lamberts et al., 1992). It is hard to see how an account that relates the formation of spatial codes in the Simon task to the programming of eye movements can account for the presence of all these codes—which for the most part are entirely useless for specifying parameters of eye movement programs, if not misleading.

A more conceptual problem for the attention-shifting approach is that it fails to differentiate between exogenous and endogenous control of attention. The task employed by Rizzolatti et al. (1987) required the willful, endogenous direction of visual attention to cue and target locations, and in this context it makes sense to assume that participants are actively engaging in programming activities to move their attention to the targeted locations. The same is true for the standard Simon task, where participants are to process a non-spatial feature of the target stimulus and, thus, understandably attend to the location of this target. However, Simon-like effects can also be obtained with so-called accessory stimuli, that is, stimuli that possess not a single feature that would be relevant for the task. For instance, Mewaldt, Connelly, and Simon (1980) had participants respond to visual stimuli presented at the center of a display, while presenting task-irrelevant and randomly chosen tones on the left or right. Even though the target location did not change during the whole experiment, participants were faster if the location of the tone corresponded to the correct response. This suggests that they had processed the tones and their location automatically and that the codes of these locations interacted with spatial response codes.

According to attention-shifting approaches, this effect would indicate that participants had programmed eye movements towards the tones, but why would they do this, especially given that moving attention away from the actual target stimulus is counterproductive? A recent study of Treccani et al. (2006) provides evidence that accessory stimuli affect response selection even if they are not consciously perceived. As Treccani et al. argue, this suggests that accessory stimuli attract attention automatically, irrespective of the stimulus that participants actually want to analyze. However, what does it mean to say that entirely exogenous, automatically triggered attention shifts require the "programming of an eye movement"? This way of theorizing does not seem to go anywhere beyond assuming the fact that stimulus location is automatically coded and that this spatial code interacts with the response representation, an assumption that was at the core of Simon (1969) original suggestion already and that is shared by all available non-attentional theories of the Simon effect (e.g., Hommel, 1993b; Kornblum et al., 1990). This by no means denies or excludes the apparently intimate relationship between visual attention and eye movements (Deubel & Schneider, 1996): (exogenously) attracting or (endogenously) directing attention to a particular location is indeed very likely to induce the tendency to move one's eyes to this location as well, and there is nothing wrong with calling this tendency "programming". However, using this label for a tendency does not seem to add anything and makes no contribution to explaining why the tendency exists and how it actually works.

So, even though one can doubt whether the attention-shifting approach to the Simon effect provides any further insight into why spatial stimulus codes are formed, Simon studies have provided broad evidence for the concurrent coding of numerous kinds of spatial stimulus codes that are coding for various spatial aspects and characteristics of a stimulus and its relationship with other stimuli and the general context. This supports the idea that the primate brain comprises of various spatial maps that serve different computational purposes (Rizzolatti et al., 1994). Moreover, attention-shifting studies on the Simon effect were successful in revealing various factors that apparently affect which kind of spatial relationship is interacting with response representations more strongly. This suggests that task and contextual factors are able to change the relative weight to which the contents of the various spatial maps are considered in information processing and response selection. Let us now turn to the question of how that might work.

3.3. Why are spatial codes formed?

Valle-Inclán and Redondo (1998) carried out a Simon task in which the mapping of responses to the relevant stimulus features was not constant but varied randomly from trial to trial, as did the temporal order in which the mapping and the target stimulus were presented. If the mapping preceded the stimulus, which mimics the standard condition in the Simon task, a normal Simon effect was obtained with faster responses for spatially corresponding stimuli and responses. However, if the stimulus preceded the stimulus–response mapping, the Simon effect disappeared. One might speculate that this was because the spatial code of the stimulus had decayed before participants were able to select a response, as decay is known to prevent Simon effects with longer reaction times and higher reaction-time levels (De Jong, Liang, & Lauber, 1994; Hommel, 1993b). However, Valle-Inclán and Redondo also measured the lateralized readiness potential (LRP), an electrophysiological indicator of stimulus-induced response activation, and there was no LRP in the stimulus-first condition either. This means that Simon effects require responses to be known and prepared,[1] which again raises the question which exact role response processes play in the Simon task.

Apart from the presumably more obvious relevance of response processes for response coding that I will discuss in the next section, there are also reasons to assume that response processes affect attentional mechanisms and, thus, stimulus coding. This idea becomes a bit more plausible if we consider how responses are cognitively represented and controlled. As I will elaborate later, human actions are cognitively represented in terms of their features and controlled by activating representations of their sensory consequences. One of the sensory consequences of a left-hand keypress, say, is that it produces various effects on the left: the feeling of a finger moving, of a key going down, and so forth. The major distinction between a left- and a right-hand keypress action thus relates to space, suggesting that people discriminate between the representations of these actions by considering location. From this perspective, location is thus not irrelevant but task-relevant. If we further assume that task-relevant feature dimensions are weighted more strongly (Hommel, 2010; Hommel, Müsseler, Aschersleben, & Prinz, 2001), so that the features they are coding receive "more attention" (i.e., more impact on information processing), it seems possible that the dominant role spatial stimulus codes play in the Simon task is a direct consequence from adopting a spatially defined response set.

The most obvious prediction from these considerations is that there would be no Simon effect if the responses in the Simon task would not refer to, and invite attending to space. Not only does this sound self-contradictory but it also seems impossible to test. And yet, there are more somewhat indirect indications that the prediction actually holds. One is the observations of Valle-Inclán and Redondo (1998), which seems to fit perfectly into this picture: no Simon effect if the spatial responses are not yet prepared. Another is the study of Fagioli, Hommel, and Schubotz (2007), which compared the attentional consequences of pointing and grasping movements. If preparing for an action does indeed lead to the stronger weighting of the feature dimensions that are particularly important for defining the action, and for discriminating between action alternatives in particular, one would expect that preparing for pointing versus grasping movements would affect attentional weightings differently. Most important for pointing (not unlike keypressing) should be location information, so that preparing for a pointing movement would sensitize the perceptual system for processing location. In contrast, grasping movements should rely more on information about the size of the object, which signals the hand's aperture. To test these hypotheses, Fagioli et al. had participants either point to or grasp an object in front of them. Before the action was executed, however, participants were presented with a sequence of visual stimuli following a particular rule (Schubotz & von Cramon, 2001) and they were to detect possible rule violations. As soon as a violation was observed, the prepared movement was to be carried out. As predicted, the movements were initiated faster if the violation occurred on the perceptual dimension that was assumed to be more important for the particular movement: pointing movements were initiated faster with spatial violations while grasping movements were faster with size violations. To rule out that this effect was due to the priming of the movement through the violating event, the experiment was (successfully) replicated with foot responses to signal rule violations. Recently, these findings were extended to a visual search task (Wykowska, Schubö, & Hommel, 2009), where preparing for a pointing movement facilitated the detection of luminance-defined targets while preparing for a grasping movement facilitated the detection of size-defined targets.

Further evidence for the idea that action preparation is priming the perceptual dimension of the features that are defining the action comes from a recent fMRI study of Kühn, Keizer, Rombouts, and Hommel (in press). Participants responded to the color of a visual stimulus by either pressing a left versus right key with their index fingers (the manual response set) or by carrying out a smiling versus kissing movement with their face (the facial response set). The response set varied randomly from trial to trial and participants received a precue that indicated the

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[1] This is not to say that preparation needs to take place before every trial. Stimulus–response correspondence can affect performance even if the correct response is precued in advance or fixed within a short sequence of trials (Hommel, 1996a), suggesting that making two or more responses task-relevant induces a sufficient degree of preparation to create a Simon-type effect.

response set for the upcoming trial. Brain activation in the interval between cue presentation and stimulus presentation differed between response sets: while preparing for manual action activated the extrastriate body area, which is assumed to be coding for perceived non-facial body parts (Taylor, Wiggett, & Downing, 2007), preparing for facial action activated the fusiform face area, which is assumed to code for perceived faces (Kanwisher, McDermott, & Chun, 1997). Even though these observations do not provide direct evidence that preparing for spatially defined actions primes neural maps coding for location information, they do suggest that this is a very reasonable assumption.

To summarize, there is converging evidence that preparing for particular types of actions increases the weightings of features on perceptual dimensions that are relevant for controlling (selecting and fine-tuning) this type of action. In the Simon task, responses are spatially defined, which suggests that preparing for those responses induces a higher weighting for location information, irrespective of whether this information is related to stimuli or responses (Fagioli et al., 2007; Hommel, 2010). This explains why no Simon effect is observed if the spatial responses are not prepared (Valle-Inclán & Redondo, 1998) and why in the standard Simon task the nominally irrelevant stimulus location is not entirely neglected. Even though these considerations suggest that action preparation has a strong impact on the weighting of feature dimensions, it is important to point out that action processes are not the only factors affecting these weightings. Other likely candidates comprise of general task intentions and context factors, which presumably account for the considerable effects of stimulus configurations and task specifics discussed in the previous section.

4. Intentional action and response coding

The demonstration of Wallace (1971) that it is not the hand but the hand's location that matters (more) for the Simon effect has raised a particularly interesting theoretical question that is commonly ignored in cognitive psychology, however: what is a response and how is it represented? Logically speaking, each movement can be described in numerous ways and at numerous levels of analysis, ranging from neural firing rates and muscle potentials over cognitive codes for numerous features of the movement and its consequences, to the specific action intention driving it and the general goal the movement is thought to subserve. And from a logical standpoint, there is no reason to prefer one description and one level of analysis over another—which among other things provides little help in understanding the roles of the hand and the hand location in the Simon effect. And yet, people do carry out intentional actions, where sometimes the very same physical movement can serve different purposes, so that we need some theoretical language and model to capture both the similarities and the differences.

Wallace (1971) made an important move in theorizing on the relationship between stimuli and responses. He argued that his observation that the relationship between stimulus location and response location matters more than the relationship between stimulus location and the anatomical hand is difficult to tackle for the back then popular strategy to explain reaction-time effects in terms of the number of recodings necessary, or the number of processing stages passed from input to output. Instead of considering the response as mere outflow—as the terminal stage of information processing—Wallace reconstructed the response as a stimulus. People do cognitively represent their hands, he argued, but they bind these representations to continuously updated location codes. Hence, they represent their hands as perceived entities that have perceptual features that can match or mismatch with perceptual features of the target stimulus. Accordingly, even one's right hand would be represented as "left" if it is located—and thus perceived to be—on the left, and therefore be facilitated if a movement of this hand is signaled by a "left" target stimulus. In other words, stimulus–response compatibility comes down to feature matching.

The general idea that stimulus–response effects are due to feature overlap has gained considerable acceptance in various models of the Simon effect and stimulus–response compatibility in general (e.g., Kornblum et al., 1990; Kornblum, Stevens, Whipple, & Requin, 1999; O'Leary & Barber, 1993; Zorzi & Umiltà, 1995). However, a major conceptual weakness of these models is that their treatment of feature overlap is descriptive rather than explanatory. For instance, the observation that a left stimulus can prime a left response is modeled by creating an association between the representations of the two. Note that this is a mere acknowledgment of the empirical finding and, thus, void of any explanatory content. Why do such associations (which, as Wallace has shown, cannot be permanent) exist, which purpose do they serve, and according to which criteria are they created? In the following, I will review some of the evidence addressing this issue. First I will discuss where response codes are coming from and how they are acquired, and then I will consider which exact role response codes are playing in the control of voluntary actions.

4.1. Where do response codes come from?

Addressing this question leads us back to the original idea of Wallace. Even though this idea is fruitful in helping to understand how stimulus events and actions can be compared and be related to each other, Wallace failed to explain how the perceptual codes of actions are eventually used to carry out the required response. Fortunately, such an explanation is available. In their considerations of how people can perform intentional actions while at the same time knowing so little about their own motor system, Lotze (1852), Harless (1861), and James (1890) came very close to the perceptual response-code idea of Wallace (1971). Even though we do not have any direct, at least no conscious access to our motor representations, so the line of thought, we can access the perceptual consequences of our actions. If thus there were a learning mechanism that would integrate the inaccessible motor patterns with (cognitive representations of) the accessible perceptual consequences, we could then reactivate the motor patterns by intentionally "thinking of" and, thus, reactivating these perceptual representations.

This so-called ideomotor theory has been neglected for most of the 20th century but regained considerable interest more recently (Stock & Stock, 2004). Hommel et al. (2001; Hommel, 2009) have extended this theoretical approach and integrated it with previous ideas that perception and action are processed in the same representational medium (Prinz, 1990) and that actions are represented in terms of sensorimotor bindings (Hommel, 1997b, 1998). Their Theory of Event Coding (TEC) claims that perceived events (i.e., stimuli) and produced events (actions) are represented in the same way and by using the same kinds of codes. With respect to stimulus representations, TECs basic assumptions are relatively uncontroversial: Stimuli are cognitively represented as composites of distributed feature codes, which refer to the stimulus' distal attributes. Less uncontroversial is the assumption that actions are represented exactly the same way, so that the cognitive system does not really distinguish between stimuli and responses. Moreover, both stimuli and responses are assumed to be represented by sensorimotor units, which contain information about the motoric means to (re-)create a perceptual event. With respect to what compatibility researchers call a response, this means that the representing code integrates the motor pattern producing the response and the sensory consequences that the execution of the motor pattern generates. With regard to what is called a stimulus, it means that the representing code integrates the perceivable features a stimulus possesses and the motor pattern needed to perceive those features (e.g., particular eye, head, or body movements to position receptors in such a way to pick up the feature information).

Regarding the Simon effect, TEC implies that stimulus representations in the Simon task are compounds of feature codes that, among others, are coding for the task-relevant stimulus feature (e.g., color) and stimulus location. Likewise, the responses would be represented by compounds of feature codes coding for the motoric patterns generating the responses as well as the resulting perceptual consequences. These consequences are commonly including several “left” features for the left response (e.g., tactile feeling of the left finger moving, seeing the left key moving, etc.) and several “right” features for the right response. Accordingly, left (right) stimuli would not just be associated with left (right) responses but be partially represented by the same feature codes. In other words, representations of left stimuli and of left responses are not just related or associated but overlap physically (i.e., neurally). Accordingly, it is unavoidable that activating a stimulus representation activates overlapping response representations, and vice versa.

Numerous studies have provided independent evidence that actions are represented by sensorimotor compounds that include information about action effects. For instance, Elsner and Hommel (2001) had participants carry out self-chosen left and right keypresses that produced task-irrelevant, novel auditory effects (e.g., left keypresses generated low-pitched tones and right keypresses high-pitched tones). Thereafter, participants carried out a free-choice task in which the previously produced sounds were used as trigger signals. It turned out that participants were more likely to choose the response that had previously produced the sound that now appeared as a trigger (e.g., left keypresses were chosen more often in the presence of a low-pitched tone). Comparable findings have been obtained in numerous labs and with various tasks, stimuli, actions, and effects, and with participants of any age from 9 months on (for an overview, see Hommel & Elsner, 2009). Neuroimaging studies have confirmed that action-effect acquisition results in sensorimotor compounds. For instance, presenting a tone that previously had been actively produced—a previous action effect that is—activates not only sensory areas and the hippocampus but also the supplementary motor area (Elsner et al., 2002; Melcher, Weidema, Eenshuistra, Hommel, & Gruber, 2008). Moreover, the already mentioned fMRI study of Kühn, Keizer, Rombouts, and Hommel (in press) has shown that preparing for a particular type of action increases the activation of brain areas that are coding for the perceptual consequences of these actions.

These observations are consistent with the idea that is actually the correspondence between the stimulus features and the features of the perceived action effects (i.e., the response as perceived entity) that is producing the Simon effect, exactly as reasoned by Wallace (1971). If so, it should be possible to change the size, the direction, and possibly even the presence of the Simon effect by manipulating perceivable action effects. The first expectation was confirmed in two studies (Hommel, 1993a, 1996b). In one of them, participants carried out an auditory Simon task that required left and right keypresses in response to the pitch of a tone presented on the left or right (see Fig. 4). Response keys were connected to light emitting diodes in such a way that every keypress would flash a light on the opposite side. This meant that each response in this condition would have both left and right action effects, so that each response should be primed by both left and right stimuli. Even though one would expect that the relevant key and hand locations are weighted more heavily, the contralateral tone should also contribute and, thus, reduce the size of the Simon effect. This is exactly what was observed.

The second prediction, that it should be possible to reverse the Simon effect, was born out in the Hommel (1993a) study. Keypresses were again flashing lights on the opposite side but, in addition to that, the instruction for the task was slightly modified in one of the two groups of participants. Instead of the standard instruction to “press the left/right” key in response to the auditory stimuli that the other group received, this group was instructed to “flash the right/left” light in response to the auditory stimuli. Given the setup, this amounted to exactly the same task, as right lights were flashed by pressing the left key, and vice versa. However, given that each response had both left and right action effects, the emphasis on keypressing versus light flashing was expected to induce a stronger weighting of the features related to keys and lights, respectively. If so, pressing the left key should be coded (more) as “left” in the key-instruction group but (more) as “right” in the light-instruction group. Accordingly, it was expected that the Simon effect would reverse in the light group, that is, participants should now be faster if the stimulus would spatially correspond with the light being flashed by the response. This expectation was fully confirmed.

The third prediction assumes that it should be possible to create a Simon effect even with movements that do not have any particular spatial feature by introducing a novel action effect that can be coded as left or right. Hommel (1996b) tested this prediction by having

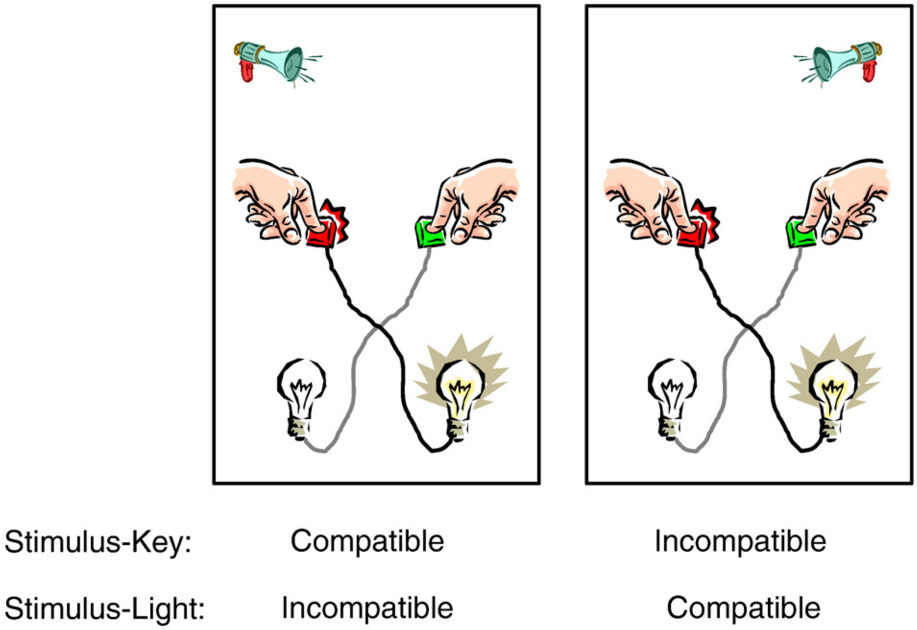

Fig. 4. The experimental setup in the Hommel (1993a) study. Both examples show a left-hand keypress in response to a particular tone, presented on the left side or on the right side. Pressing the left key flashed a light on the right side and pressing the right key a light on the left side. Left tones are thus spatially corresponding to the response key (and the responding hand), whereas right tones are spatially corresponding to the response-contingent light.

participants respond to lateralized color stimuli by pressing a single central key once or twice. One of the responses produced a tone on the left and the other a tone on the right. As predicted, the former was facilitated by left stimuli and the latter by right stimuli; there was thus a Simon effect for responses that differed in location only with respect to their action effects. Interestingly, the same logic can be applied to the Stroop effect: color-unrelated manual responses are faster if they produce visual effects the color of which matches the task-irrelevant color of the stimuli (Hommel, 2004a).

To summarize, response codes are acquired by integrating representations of the perceptual consequences of an action with the motor patterns producing it. This renders action effects, and stimuli that feature overlap with these action effects, effective primes of these integrated motor patterns. Lateralized stimuli feature overlap with the action effects of lateralized responses, which explains why they prime spatially corresponding actions or actions with spatially corresponding effects. Action effects are capable to activate the human supplementary motor area (Elsner et al., 2002; Melcher et al., 2008), which accounts for the observation that lateralized stimuli can activate the corresponding response up to a degree that produces electrophysiological responses over the motor area (e.g., Valle-Inclán & Redondo, 1998). Action effects can be integrated by associative learning (Elsner & Hommel, 2001) but there is also evidence for the spontaneous short-term binding of actions and effects on a trial-by-trial basis (Dutzi & Hommel, 2009). This provides strong support for the claim of Wallace (1971) that hand representations might be flexibly bound to location codes, and that these location codes (which in TECs terminology are perceptual effects of hand movements towards or at the current location) interact with codes representing the stimulus location.

4.2. What role do response codes play in action control?

As we have seen, people integrate action effects rather spontaneously even under circumstances where these effects do not seem to play any functional role. Why people are doing that is likely to relate to the more general theoretical issue addressed by ideomotor theorists. Without integrating actions and effects, so the idea, we simply do not know which goals we might want to have and how we could achieve them. In other words, we continuously pick up possible future goals and the motoric means to realize them. This approach takes one of the two old philosophical sides regarding the origin of the human will. One possibility is that we are born with intentions but need time, a better understanding of our developing body, and good motor skills to find out how they can be translated into effective action (e.g., Rochat, 2001). In contrast, the ideomotor approach would suggest a more empirical view according to which we are learning new, possible intentions by doing—a view that in some sense is closer to Piaget (1946). This view suggests that true actions, that is, movements performed to reach a particular goal, can only emerge from the integration of movements and effects: As it is the anticipation of an effect that transforms a mere movement into a true action, and as the anticipation requires knowledge about the to-be-expected action effects, action representations could not exist without the previous integration of movements and their effects (if we ignore the possibility of observational and imitation learning for a second).

More mechanistically speaking, integrating movements or actions and their effects provides the cognitive system with effective access cues to the motor system. This implies that action-effect representations provide the medium for action planning and response-selection processes to operate on. Even though this is difficult to demonstrate directly, there is converging evidence that action-effect codes play at least some role in response selection. For one, we have seen that reaction time is affected by all sorts of manipulations of action effects and that these effects modify effects that are attributed to response-selection problems, like the Simon effect (Elsner & Hommel, 2001; Hommel, 1993a, 1996b). Given that the physical effects themselves appear too late in an experimental trial to directly affect response selection, it must be their anticipation that does the trick. Anticipation necessarily relies on action-effect learning and what is being anticipated must be codes of the action's effects—hence, action-effect codes are involved in response selection. This conclusion is further supported by the observation of action-effect compatibility effects: manual responses are initiated faster if they trigger visual events in spatially corresponding locations (Kunde, 2001) and comparable effects of have been reported for temporal (Kunde, 2003) and semantic (Koch & Kunde, 2002) action-effect relations.

However, action-effect associations seem to be involved in at least one other action-control process. According to systems-theoretical models of action control, actions are not just launched and executed but more or less continuously monitored, in order to check whether the action goes as expected (e.g., Adams, 1971; Schmidt, 1975; Wolpert & Ghahramani, 2000). To do so, it is commonly assumed that expectations about action outcomes are generated and matched against the actual outcomes, so that substantial discrepancies could signal a failure of action control and trigger remedial activities. Even though such control models are often not very explicit with respect to the codes being used for the matching and the processes responsible for the acquisition of these codes, it seems obvious that these codes could be provided by action-effect integration. Hence, associations between actions and effects could be used not only for selecting actions but also for checking whether the wanted perceptual effects are actually produced.

First evidence for this possibility was reported by Waszak and Herwig (2007). They had participants acquire associations between left and right keypresses and tones of different pitch before presenting them with an auditory oddball task. In this task, participants encountered numerous standard tones and infrequent deviants (tones that differed from the standards in frequency), which they all had to trigger with a keypress. The deviants produced an electrophysiological P3 component (Pritchard, 1981) that was more pronounced when it was triggered by the response that had previously produced the standard. This suggests that selecting and/or performing an action leads to the active perceptual anticipation of the action's effects. Along similar lines, Band, van Steenbergen, Ridderinkhof, Falkenstein, and Hommel (2009) had participants perform a probabilistic learning task, in which some keypresses produced a tone of a particular pitch in 80% of the trials and another tone in the remaining trials. This should have generated action-effect representations that would lead to an expectation of the most frequent tone when selecting and/or carrying out the action. Indeed, the less expected action effect generated a so-called feedback-related negativity (Miltner, Braun, & Coles, 1997)—an electrophysiological component that is commonly seen with the presentation of negative performance feedback. This provides evidence that acquired action effects are used to predict upcoming perceptual events and to match these expectations against the actually achieved events.

A third possible role in action control that action-effect associations could be involved in relates to the consequences of action monitoring, that is, to the adjustment of action representations. This topic has received considerable attention recently (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Yeung, Botvinick, & Cohen, 2004) and the emerging theoretical discussion has strongly benefited from the straightforward design of the Simon task and the available research on the Simon effect. The empirical focus in this area is directed to manipulations of the frequency of compatible and incompatible trials and to sequential effects, that is, to aftereffects of one trial on the next trial. For instance, Hommel (1994) presented different groups of participants with Simon tasks in which 20%, 50%, 75%, or 80% of the trials were incompatible, that is, stimulus location did not correspond to response location. The size of the Simon effect was a direct reflection of this manipulation and decreased with increasing frequency of incompatible trials. Stürmer, Leuthold, Soetens, Schröter, and Sommer (2002) analyzed the Simon effect as a function of stimulus–response correspondence in both the current trial (as usual in the Simon task) and the previous trial. Similar to observations with the Eriksen flanker effect (Gratton, Coles, & Donchin, 1992), the Simon effect was less pronounced (or even absent) if the previous trial was incompatible, hence, if stimulus and response did not correspond. According to Stürmer et al. (2002), the impact of the frequency of compatible trials and the trial-to-trial effects may reflect the same mechanism: Encountering response conflict might trigger adaptation effects that reduce the impact of irrelevant information (as suggested by Botvinick et al., 2001) and, hence, of stimulus location in the Simon task. As the effect is a result of the impact of stimulus location on response selection, this reduction leads to a decrease of the effect size. Even though this is a tenable interpretation, it has been shown to run into a number of empirical and theoretical problems.

With regard to the frequency manipulation, there is an obvious alternative interpretation that relies on well understood learning mechanisms (Hommel, 1994). Consider a design in which incompatible trials are very frequent, so that the left response would often be signaled by stimuli appearing on the right and the right response by stimuli appearing on the left. This manipulation renders stimulus location informative, which is likely to induce associative learning. As indicated in Fig. 5A (which assumes that the letters O and X serve as relevant target stimuli), the “left” code representing stimulus location would become associated with the “right” code representing response location, and vice versa. This would mean that incompatible trials induce both conflict (due to a mismatch of stimulus and response location) and facilitation (due to associative learning), which depending on the relative contribution of these two processes might lead to a reduced, eliminated, or inverted Simon effect—patterns that all have been reported in the literature.

With regard to trial-by-trial effects, there is another alternative (that may also apply to frequency effects). Note that the analysis of these effects considers two factors with commonly two levels: stimulus–response congruence in the present trial (congruent versus incongruent) and stimulus–response congruence in the previous trial (congruent versus incongruent). As pointed out by Hommel, Proctor , and Vu (2004), these four cells of the design are entirely confounded with the ways stimulus location and response location are combined in the present and the previous trial. Consider the sequence of a corresponding trial followed by another corresponding trial. Sequences of this type include four different combinations of stimulus and response locations: left stimulus/left response → left stimulus/left response, right stimulus/right response → left stimulus/left response, left stimulus/left response → right stimulus/right response, and right stimulus/right response → right stimulus/right response. Two of these combinations are complete repetitions (where all features repeat) and the other two combinations are “complete” alternations (no feature repeats). Interestingly, the same holds for sequences of a non-corresponding trial by a non-corresponding trial. Now consider the sequence of a non-corresponding trial followed by a corresponding trial. Sequences of this type include the combinations: right stimulus/left response → left stimulus/left response, left stimulus/right response → left stimulus/left response, left stimulus/right response → right stimulus/right response, and right stimulus/left response → right stimulus/right response. All of these combinations are what one can call a partial repetition, that is, one feature repeats while the other alternates. Hence, there is a perfect confound between compatibility sequence and feature-combination sequence.

This confound opens the possibility that what looks like an effect of cognitive control processes might actually be an effect of stimulus–response binding. Numerous studies have shown that people perform better with both complete repetitions and alternations of combinations of stimulus and response features than with partial repetitions (for a review, see Hommel, 2004b). The likely reason is the spontaneous integration of stimulus and response codes into episodic, content-retrievable event files (as assumed by TEC) on a trial-by-trial basis. Any feature repetition would thus retrieve the previous event file, which would induce code conflict if the repetition is only partial. Indeed, an fMRI study has demonstrated that combining a manual response and the picture of a face or a house increases the activation in the fusiform face area or the parahippocampal place area, respectively, if the response is repeated, while repeating the face or the house increases activation in the motor cortex (Kühn, Keizer, Colzato, Rombouts, & Hommel, in 2011).

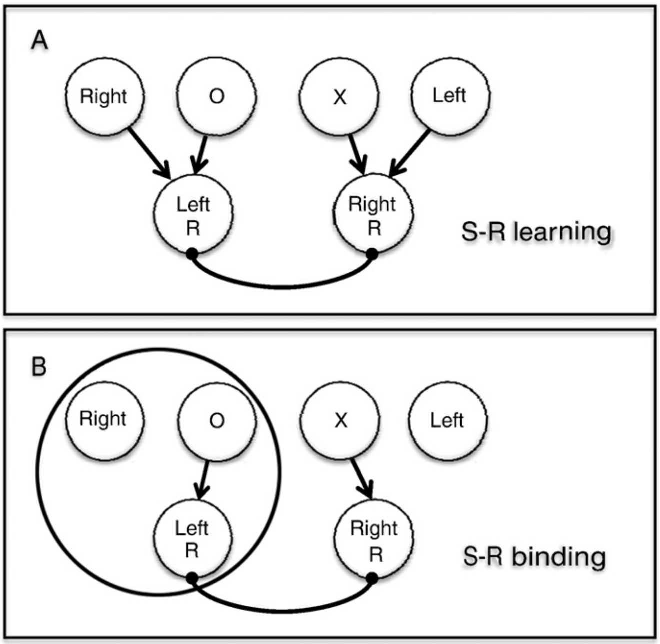

Fig. 5. Non-executive accounts of frequency effects (see panel A) and sequential effects (see panel B) in the Simon task. In the example, the target letters O and X are to be responded to by pressing a left versus right key, respectively. The letter codes are assumed to prime their corresponding responses, which compete for response selection. A. A high frequency of incompatible trials implies that a right stimulus location predicts, and will thus become associated with, the left response and the same is true for the left stimulus location and the right response. B. Selecting and executing an incompatible left response might lead to the binding of the right stimulus code, the letter code, and the left response code. This would impair performance in the next trial if the stimulus–response combination would partially overlap, as with a left response to a left stimulus or a right response to a right stimulus.

Let us apply this reasoning to the Simon effect. Assume, for instance, a participant is presented with an O appearing on the right side but signaling a left response, the example sketched in Fig. 5B. Integrating the respective features would lead to a binding of the codes representing the shape (O), stimulus location (right), and response location (left). Given that shape and response location are mapped onto each other anyway and thus always confounded, let us focus on the relationship between stimulus location and response location. If the next trial would repeat all features, the just created binding would be automatically retrieved (because of the matching features) but would not create any conflict. If none of the features repeats, the binding would not even be retrieved. However, if one feature repeats but the other alternates, the previous event file would be retrieved and create conflict with the present codes. For instance, if the combination of left stimulus location and right response location would be followed by the combination of right stimulus location and right response location, retrieving the previous file would reactivate the left stimulus code, which would interfere with the present right code. As demonstrated by Hommel et al. (2004), applying this logic to tasks that are very unlikely to involve stimulus or response conflict produces result patterns that nevertheless perfectly mimic those observed by Stürmer et al. (2002) and later Simon studies on trial-by-trial effects.

Recent studies have tried hard to avoid the confound of compatibility sequence and feature repetitions in several ways. For one, some researchers have excluded complete repetitions from analysis (e.g., Mayr, Awh, & Laurey, 2003), as complete repetitions might be special by allowing participants to shortcut response-selection processes (Bertelson, 1963). However, given that partial repetitions and alternations are still present, this strategy is insufficient to avoid the interpretational problems. Others have restricted their analysis to alternations, that is, to trial transitions that do not involve any feature repetition (e.g., Akçay & Hazeltine, 2007), the idea being that this should prevent event-file retrieval altogether. However, even though this logic might hold for the event file that was created in the immediately preceding trial, it does not hold for other event files created before. More importantly, even the binding of features that do not overlap with the present features can affect the coding of a subsequent feature combination by reducing the competition between alternative stimulus and response codes (Dutzi & Hommel, 2009). These considerations let one doubt whether feature-integration processes were successfully eliminated in the available studies on sequential effects and imply that adaptation processes have yet to be demonstrated convincingly.

Apart from these theoretical considerations, there are empirical observations suggesting that adaptive control processes, should they exist, are not separate from, or even opposite to feature-integration effects but, rather interwoven with episodic integration. As we have shown for the Simon effect (Spapé & Hommel, 2010) and the Stroop effect (Spapé & Hommel, 2008), the standard interaction between compatibility in the present and compatibility in the previous trial can be eliminated entirely by introducing task-irrelevant changes of the perceptual context (such as a rotation of the boxes in which stimuli appear or a voice change) from one trial to the next. This suggests that conflict-induced changes in control parameters, if they exist, are not administered and maintained by executive control processes but, rather, become part of the episodic event file (Waszak, Hommel, & Allport, 2003), which is retrieved only if the perceptual context is sufficiently similar across trials.

To summarize, action codes—and the codes of perceptual action effects in particular—seem to play multiple roles in the control of voluntary actions. For one, they seem to subserve response selection by representing the to-be-expected action outcomes, thus allowing the agent to compare these outcomes against the currently intended outcome. Once a given action-effect code is selected, it spreads activation to the associated motor pattern, which then carry out the action. A second role of representations of action effects is related to action monitoring. Representations of the expected perceptual outcomes are matched against the actually produced outcomes, so that possible mismatches in the case of an action failure can be signaled. A third possible role could be related to the adaptation of action representations. Registered conflict might lead to the fine-tuning of action parameters, which then are stored together with other stimulus and response codes and, presumably, information about the context.

5. Conclusion

Here ends our brief journey through a whole number of central areas of cognitive psychology. My first take-home message is that the Simon effect raises extremely interesting theoretical questions, and I have tried to show that for the domains of perception, attention, action planning, and executive control. The Simon effect has led us to ask why and how basic perceptual codes are generated, how they are modulated or even induced by higher-level processes including task intentions and action control. It has also made us ask how voluntary actions are actually cognitively represented, where these representations are coming from, and what cognitive functions they are playing. There are many more Simon-related topics I could have covered, such as memory encoding and retrieval (Hommel, 2002), the control of action sequences (Inhoff, Rosenbaum, Gordon, & Campbell, 1984), affective processes (Beckers, De Houwer, & Eelen, 2002), cognitive processes in rats (Courtière, Hardouin, Burle, Vidal, & Hasbroucq, 2007) and pigeons (Urcuioli, Vu, & Proctor, 2005), and so forth and so on. However, I hope that even my rather selective tour has demonstrated that the discovery of the Simon effect has stimulated extremely interesting and important theoretical discussions that go way beyond the mere observation of faster responses to spatially corresponding stimuli.

My second take-home message is that the Simon effect does not only raise these questions and issues but the Simon task also provides an extremely useful tool to investigate and clarify them. This holds for the standard Simon task already, which has the advantage of a much more straightforward and pure design as related tasks. But it also holds for the numerous extensions and variants, ranging from designs that have been tailored to demonstrate Simon effects for color (Kornblum, 1994) and emotions (Beckers et al., 2002) to design versions to investigate the imitation of hand movements (Stürmer, Aschersleben, & Prinz, 2000) and social cooperation (Sebanz, Knoblich, & Prinz, 2003).

Hence, the seminal studies of Richard Simon in the late 60s and the 70s have provided us with both an effect that turned out to serve as a very influential heuristic to generate exciting and fruitful research questions and a task that has proven to serve as an important empirical tool to study these and many other questions. This, I think, is what makes this work, the effect, and the task a success story that will stick with us for quite a while.

Acknowledgments

The author would like to thank J. Richard Simon for years of inspiration and Eliot Hazeltine and Toby Mordkoff for organizing the Simon Fest that motivated this article. He is also grateful to Robert Proctor and an anonymous reviewer for constructive comments.

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