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ORIGINAL ARTICLE

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# Coloring an action: Intending to produce color events eliminates the Stroop effect

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**Abstract** The implications of an ideomotor approach to action control were investigated. In Experiment 1, participants made manual responses to letter stimuli and they were presented with response-contingent color patches, i.e., colored action effects. This rendered stimuli of the same color as an action's effect effective primes of that action, suggesting that bilateral associations were created between actions and the effects they produced. Experiment 2 combined this set-up with a manual Stroop task, i.e., participants responded to congruent, neutral, or incongruent color-word compounds. Standard Stroop effects were observed in a control group without action effects and in a group with target-incompatible action effects, but the reaction time Stroop effect was eliminated if actions produced target-compatible color effects (e.g., blue word → left key → blue patch). Experiment 3 did not replicate this interaction between target-effect compatibility and color-word congruency with color words as action effects, which rules out semantically based accounts. Theoretical implications for both action-effect acquisition and the Stroop effect are discussed. It is suggested that learning action effects, the features of which overlap with the target, allows and motivates people to recode their actions in ways that make them more stimulus-compatible. This provides a processing shortcut for translating the relevant stimulus into the correct response and, thus, shields processing from the impact of competing word distractors.

## Introduction

We carry out actions to produce particular intended effects on ourselves, on our physical and social environment, or on the relationship between the two, such as when eating a meal, communicating with others, or fleeing a threat. In order to select the action that is appropriate to produce an intended effect we need to have available and to consult knowledge about which action is likely to generate those effects. As most everyday actions are chosen very quickly and without much, some would even say without any, deliberation (e.g., Bargh, 1997; Wegner, 2002), this knowledge base needs to allow for the selection of goal-directed action in a reliable and automatic fashion. Ideally, this knowledge base would generate appropriate actions as envisioned by William James (1890): Merely thinking of the goal should prime the motoric means to achieve it.

How this sort of goal-controlled action selection may work and how the underlying database may look have been central topics in ideomotor approaches to action control in the tradition of Lotze (1852), Harless (1861), and James (1890). Recently, attempts have been made to translate the introspection-based considerations of ideomotor theorists into a more functional, empirically accessible terminology (Greenwald, 1970; Prinz, 1987) and to enrich them with our current knowledge about distributed representations of action plans (Hommel, 1996, 1997a, 1998a). The emerging picture suggests what Elsner and Hommel (2001) have called a two-stage model of the acquisition of action control. At the first stage, the becoming actor is actually more a perceiver: He or she carries out random, reflex-like, or over-learnt movements and observes which perceivable effects these movements produce. Due to the mere temporal overlap of the motor patterns producing the movement and the perceptual traces coding the perceived effects these two become associated by means of a sort of trace conditioning. The result is a sensorimotor structure subserving a dual function. On the one hand, activating the perceptual part of the structure—be it by sensing or by imagining the corresponding stimulus or stimulus feature—primes the associated motor pattern. Hence, as suggested by James (1890) and others, "thinking of" the

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intended goal (the perceivable effect one wishes to create) primes the motoric means to bring it into being. On the other hand, planning a particular action also affects perception by priming the input of action-related perceptual events and inhibiting the processing of action-unrelated events. Along these lines, perceiving the effects of an action leads to the creation of cognitive structures that mediate both perception and action, which is why Hommel (1997a) has suggested the term *action concepts* to describe them.

Recent research provides ample support for the assumption of action concepts. With regard to the latter function, the action-induced biasing of perception, planning an action has indeed been found to facilitate the processing of action-related perceptual events (Craighero, Fadiga, Rizzolatti, & Umiltá, 1999; Hommel & Schneider, 2002) and to interfere with the processing of feature-overlapping but action-unrelated perceptual events (Müsseler & Hommel, 1997; Wühr & Müsseler, 2002). With regard to the former function, the perception-induced biasing of action planning, three complementary research strategies have been followed.

## Acquisition of action effects

The first strategy looks mainly into the acquisition of action effects. People are presented with novel, action-contingent events (action effects) with the expectation that this leads to an integration of effect and action. To diagnose the hypothesized action-effect association the effect is also used as a prime stimulus. To the degree that the prime activates the code of the presumably acquired action effect and if that code is really associated with the action it was perceived to follow, the activation should spread to the action and, hence, facilitate its selection.

Indeed, a number of studies have demonstrated that if a particular, nominally task-irrelevant event is perceived to consistently follow a particular action carried out, this event becomes an efficient prime of that action. For instance, Hommel (1996) instructed participants to perform left- and right-hand key presses in response to visual stimuli. One response was always followed by a low tone, the other response by a high tone. After a first acquisition phase randomly chosen, uninformative tones were also presented briefly before or simultaneously with the visual stimulus. As the action-concept idea would suggest, tones turned out to prime the responses they were previously perceived to follow; hence, the low tone decreased the reaction time (RT) for the response that also produced the low tone and the high tone did the same for the other response.

Along the same lines, Elsner and Hommel (2001) first presented participants with irrelevant but action-produced tones before instructing them perform a task, in which one of two responses was to be chosen freely in each trial. Tones again turned out to be effective action primes: When tones were presented before the response was selected participants tended to select the response that they had experienced to produce that tone. Thus, even irrelevant events that are perceived to consistently follow an action are apparently integrated with that action in a bilateral manner (action↔effect). Accordingly, the causal and temporal arrow can be reversed from acquisition (action → effect) to use (effect → action), so that perceiving the event can prime the associated action.

Indeed, a recent brain-imaging study has shown that, once an action effect has been acquired, its presentation activates motor structures (in the caudal supplementary motor area) even in a passive tone-monitoring task (Elsner et al., 2002). And the automatic acquisition of action effects is by no means restricted to auditory events: Apart from tones of varying location (Hommel, 1996) and pitch (Elsner & Hommel, 2001; Elsner et al., 2002; Hazeltine, 2002; Hoffmann, Sebald, & Stoecker, 2001; Hommel, 1996; Hommel & Elsner, 2000; Kunde, Hoffmann, & Zellmann, 2002), action-effect learning has been established for visual stimuli of varying location (Ansorge, 2002; Hommel, 1993), visual letters (Ziessler, 1998; Ziessler & Nattkemper, 2001, 2002) and words (Hommel, Alonso, & Fuentes, in press), or the affective valence of visual (Van der Goten, Caessens, Lammertyn, De Vooght, & Hommel, 2003) and electrocutaneous (Beckers, De Houwer, & Eelen, 2002) feedback. Thus, the integration of actions and their effects seems to be a general phenomenon.

## Action-effect compatibility

A second line of research has focused on the compatibility between "natural" (or already acquired) action effects and novel, experimentally induced effects of the same action. The underlying reasoning shares a basic assumption with the first research strategy, that novel, action-contingent events become integrated with the action they follow. If so, their impact on action control might be expected to depend on their fit with the action effects the actor actually uses to select his or her actions. For instance, if people can be assumed to code and select their responses with respect to the relative location of the response (e.g., a left vs. right key press response) acquiring novel effects that are compatible with these codes (a novel left effect produced by the left key press, and a novel right effect produced by a right key press) should allow for better performance than acquiring effects that are incompatible (a novel right effect produced by the left key press, and a novel left effect produced by a right key press).

Along these lines, Hommel (1993) and Kunde (2001) instructed participants to perform spatial responses that produced visual effects. In some conditions, the spatial relationship between response (i.e., finger and key location) and visual effect was compatible (i.e., the relative spatial locations of visual effects and responses matched), whereas in other conditions the relationship was incompatible (i.e., the relative spatial location of visual effects and responses did not match). Both studies found a drop in performance with incompatible response-effect mapping, even when the effects were of no relevance to the task and could safely be ignored. In agreement with the learning studies already discussed, this suggests that the irrelevant action effect was acquired and associated with the action producing it. What is more, these findings indicate that selecting the action must have involved action-effect codes. Thus, selecting a right-hand action, say, must have involved activating the RIGHT code of the "natural" action effect (i.e., the right-side events performing that action is anticipated to produce) as well as activating the codes of the novel, just acquired action effects. If these two codes did not match (or, more precisely, if they were not identical to each other), a conflict arose the resolution of which can be assumed to cost time.

Of particular interest for the present study, analyses of response-effect compatibility were recently extended into the color domain. Koch and Kunde (2002) instructed participants to perform vocal color-word responses to digits. Each color-word response evoked the visual presentation of a color patch, a color word, or a congruently-colored color word that was either compatible with the vocal response (e.g., "blue" → BLUE) or incompatible (e.g., "blue" → GREEN). Both color effects and color-word effects produced a compatibility effect. This shows that action-contingent colors, which will be used in the present Experiments 1 and 2, and color words, to be used in Experiment 3, can be acquired and associated with the respective action.

## Impact of action effects on response selection

A third research strategy has attempted to tie the impact of action effects in an even more direct fashion to response selection. This can be done by showing that phenomena that are commonly attributed to response conflict or other problems in response selection interact with action effects or, more precisely, that these phenomena can be systematically modified by manipulating acquired action effects. Until now, two studies applied this logic to the Simon effect, which is observed when people perform spatial responses to a nonspatial feature of a spatially varying stimulus. If, for instance, a left-hand response is signaled by green stimulus and a right-hand response by a red stimulus, the left-hand response will be faster if the green stimulus appears on the left side while the right-hand response is faster if the red stimulus appears on the right side (Craft & Simon, 1970; Simon & Rudell, 1967). Most accounts attribute the Simon effect to some sort of match between the stimulus code and the response code that in some fashion (commonly not further explicated) leads to the priming of the response that corresponds to the stimulus—which is beneficial if this happens to be the correct response but produces response competition or other sorts of response-selection problems if not (e.g., De Jong, Liang, & Lauber, 1994; Hommel, 1995; Kornblum, Hasbroucq, & Osman, 1990; Umiltà & Nicoletti, 1990; Wallace, 1971; for overviews, see Hommel & Prinz, 1997 and Lu & Proctor, 1995).

Hommel (1996, Experiment 1) investigated whether the Simon effect can be modified by introducing and manipulating novel action effects. In one part of this experiment, participants carried out a standard Simon task. They responded to the color of a visual stimulus by pressing a left or right key. In another part they performed the same task but now each key press produced a brief tone on the opposite side. The idea was that pairing each response with an irrelevant, but hardly to be missed action effect on the opposite side should make spatial action coding more equivocal: both left- and right-hand actions had both left- and right-side action effects, so that they would be partly compatible and partly incompatible with either stimulus location. For one thing, that might be suspected to produce effects of action-effect compatibility, as discussed in the previous section. More important for that study, however, was the prediction that the Simon effect should be smaller in the incompatible-tone condition. Indeed, a Simon effect was obtained in both conditions, i.e., participants performed better if visual stimulus and key press corresponded spatially. However, as predicted, the effect was significantly smaller in the condition with tone presentation.

Hommel (1993) went one step further in investigating whether people can be made to selectively attend either the more "natural" action effects or their experimentally induced counterparts. He instructed participants to react to the pitch of tones by pressing a left- or right-hand key. Pressing a key flashed a light on the opposite side; hence, pressing the left key flashed a right light, and vice versa, i.e., the action-effect mapping was incompatible. One group of participants was instructed in terms of keys to be pressed, i.e., they were to "press the left-hand key" in response to a low tone and to "press the right-hand key" in response to a high tone. As expected, these participants produced a Simon effect; hence, they responded faster if the tone sounded on the same side as the key they needed to press. Another group was instructed in terms of light flashing, i.e., they were to "flash the right-hand light" in response to a low tone and to "flash the left-hand light" in response to a high tone. As the right-hand light was flashed by pressing the left-hand key, and vice versa, the task this group carried out was nominally identical. However, if people code their actions in terms of intended action effects, or goals, as the action-concept approach implies, participants in this light-instruction group would be expected to code their actions in terms of the light location. If so, the Simon effect should reverse because now a stimulus on the left side would correspond to the (left) goal of the right-hand action and vice versa. Indeed, this is what the findings show, suggesting that acquiring novel action effects provides a viable alternative to cognitively coding one's own actions.

## Aim of the study

Thus far, we have discussed evidence suggesting that novel action effects are not only picked up and integrated with the responses producing them, they also seem to play a central role in everyday action control. In particular, phenomena known to be related to response selection can be systematically influenced by manipulating action effects, or the attention given to them. The aim of the present study was to extend this logic to another well-known phenomenon, the Stroop effect (Stroop, 1935). This effect is observed if people are to name or to react to the color of words, the meaning of which also implies a color. If ink and meaning of a stimulus are congruent (e.g., the word RED written in red ink), performance is better than if they are incongruent (e.g., the word GREEN written in red ink). With only few exceptions (e.g., Kornblum, 1994) the Stroop effect is attributed to a scenario very similar to that assumed for spatial compatibility: The inability to prevent oneself from reading the word leads to the priming of the congruent response, which speeds up response selection if this is the correct response but induces response conflict if not (e.g., Cohen, Dunbar, & McClelland, 1990; Dunbar & MacLeod, 1984; Logan & Zbrodoff, 1979; Lu & Proctor, 1995; Phaf, Van der Heijden, & Hudson, 1990; for an overview, see MacLeod, 1991).

On the one hand, it seems worthwhile to bring research on action effects into contact with the rich literature on the Stroop effect; this provides an opportunity to broaden the scope of the former and is not unlikely to make an original contribution to the latter. On the other hand, however, the standard Stroop effect with vocal responses is not easy to deal with experimentally. In order to synchronize novel, response-contingent events with particular responses the vocal utterances would need to be speech-recognized and categorized on-line and rather quickly, because even brief delays between responses and effects can reduce the likelihood of their integration (Elsner & Hommel, in press; Hommel & Elsner, 2000). Fortunately, however, Stroop effects are not restricted to vocal responses but occur with manual responses as well (e.g., Hommel, 1997b; Simon & Berbaum, 1990; Simon, Paullin, Overmyer, & Berbaum, 1985), even though it has been argued that the manual version lacks some aspects of the vocal counterpart (Kornblum et al., 1990). As the manual version allows for an easy way to register responses and to select action-contingent effect accordingly, it was in this study preferred over the vocal version.

The following experiments were guided by three questions. The first, more technical question was whether color-related effects are acquired and integrated even with actions that themselves are not defined with respect to color, such as the left-right key presses employed in this study. Obviously, this represents a central precondition for any attempt to influence the Stroop effect in a manual task by introducing colored action effects. Experiment 1 was designed to answer this question and, as we will see, the answer was affirmative. The second question was whether (re) coding one's responses in terms of the color effects they produce is a purely spontaneous, automatic process or whether recoding reflects the utility action effects have in a particular task setting. To tap into this issue, color and color-word action effects were manipulated in Experiments 2 and 3 respectively, by assigning them to color-related responses in a compatible or incompatible way, or by presenting no visual effects at all. The third and most central question was whether the Stroop effect can be influenced by manipulating the effects the actions produce in a manual Stroop task. Exactly how this influence may look depends on which particular processes the action-effect manipulation will affect, and how it will do so—an issue I will get back to in Experiment 2. In any case, if acquiring novel action effects can be shown to affect a phenomenon that is commonly associated with response selection that would provide additional support for an ideomotor approach to action control.

## Experiment 1

As pointed out, an increasing number of studies provides evidence that novel action-contingent events are spontaneously associated with the action they accompany. With respect to the color effects that are of relevance for the present study, Koch and Kunde (2002) were able to show that both color patches and color words fulfill this criterion as well. However, as these authors were focusing on response-effect compatibility, they employed responses that were themselves related to color, namely, vocal utterances of color names. Accordingly, color was a relevant dimension for action control, which means that both color and color-word effects must have been primed by the task set. Whether color-related effects are also integrated with manual, i.e., nominally color-unrelated responses—the responses to be used in the manual Stroop task—remains to be demonstrated. This demonstration is of particular importance for the interpretation of possible null effects of the response-effect compatibility manipulations introduced in Experiments 2 and 3.

Experiment 1 was therefore conducted to find out whether manual actions can also be "colored" by having them produce visual effects of a particular color. It was modeled after Hommel (1996) and, thus, comprised two phases. In the acquisition phase, participants responded to white letter stimuli by pressing a left or right key. Pressing a key had the effect of coloring the target letter green or red, depending on the key. The rationale was that producing color effects would lead to an integration of the color code and the motor pattern responsible for the key press into a common action concept. The test phase was carried out to diagnose the emergence of the hypothesized action-color associations. In this phase, the letter stimuli were surrounded by green or red frames. The color of these frames was irrelevant to the actual task and varied randomly. Nevertheless, frames were expected to prime the action that produced the same color. In half of the trials the color of the frame matched the color of the effect of the correct action (prime-effect compatible); in the other half frame and effect colors did not match (prime-effect incompatible). As frame-induced action priming should be more beneficial (or less interfering) if the correct response is primed, prime-effect compatibility was expected to yield better performance than incompatibility.

A further factor that was considered was the interval between the onsets of prime and target stimulus. Standard priming studies commonly use substantial intervals so to allow possible prime-induced effects to unfold. However, studies on the impact of task-irrelevant spatial primes have indicated that stimulus-induced action priming is only transient (e.g., Hommel, 1994), which would call for a rather short prime-target interval. To compare these possibilities two different stimulus-onset asynchronies (SOAs) were used, a long one of 1 s and the shortest possible of 0 ms.

## Method

### *Participants*

Forty adults were paid to participate in single sessions of about 30 min. They were randomly assigned to the two experimental groups, so that 20 participants were tested in each group.

### *Stimuli and apparatus*

The display and timing was controlled by a standard PC and participants responded by pressing the left or right shift key of a standard computer keyboard with the corresponding index finger. All stimuli were presented in EGA text mode on a black screen. The uppercase letters X and Y served as target stimuli, to signal a left- and right-hand response respectively. They were presented in white but changed to red or green, depending on the response given, upon response onset. Targets appeared inside a one-pixel wide frame that could be either gray, red, or green. From a viewing distance of about 60 cm, targets measured .3×.4° and frames 1.2×.8° of visual angle.

### *Procedure*

The experiment was divided into an acquisition phase and a test phase.

*Acquisition phase* Each trial began with a blank interval of 1,500 ms, followed by the presentation of a gray frame. In the long SOA group the frame stayed for 1,000 ms before it was replaced by the target. In the short SOA group the frame accompanied the target and disappeared 150 ms after the onset of frame and target. Participants were verbally instructed to respond to the letter target by pressing the left or right key as quickly as possible within 1,000 ms while ignoring the frame. Each key press triggered a color change of the target (the action effect): Pressing the left key changed it to green and pressing the right key changed it to red. The color change took place on response onset and the colored target stayed for 500 ms. Participants worked through 80 valid acquisition trials comprising 40 miniblocks composed of a random sequence of the two targets or response-effect pairings.

*Test phase* After having completed the acquisition trials, participants received a message on the screen informing them that from now on the frame would be colored, but that they were to ignore this color. Participants were prepared that this would happen as it had already been announced in the initial instruction. The actual task was exactly as in the acquisition phase; the only exception was that in a given trial the frame was either green or red. Participants worked through 280 valid test trials, comprising 70 miniblocks composed of a random sequence of the four possible combinations of two targets (or response-effect pairings) and frame colors.

## Results

Trials with response omissions (< 1%) were excluded. Mean RTs and percentages of error (PEs) were calculated and analyzed as a function of prime-effect compatibility (i.e., same vs. different colors of frame and response effect) and SOA (0 vs. 1,000 ms). The RT analysis revealed a marginal effect of prime-effect compatibility, $F(1,38) = 3.94$, $p < .06$, which was modified by a highly significant interaction with SOA, $F(1,38) = 11.36$, $p < .005$. With zero SOA, RTs were faster if the colors of prime and action effect matched (454 ms) than if they did not (462 ms). This effect disappeared with long SOA (477 vs. 475 ms). The error analysis produced only a main effect of SOA, $F(1,38) = 4.87$, $p < .05$, indicating more errors with zero SOA (3.8% and 4.7% in the compatible and incompatible condition respectively) than with a long SOA (2.0% and 2.3%). However, the effect of compatibility approached the significance criterion, $p < .07$.

## Discussion

The results are clear-cut. Perceiving a color event to consistently follow a particular action makes a stimulus of that color an efficient prime of that action. This strongly suggests that the cognitive representations of the color effect and the action it followed became associated, even though the color effect was in no sense relevant to the task or the participant's action goals. Accordingly, encountering a prime of the same color as one of the action effects will induce some degree of activation of the respective action, activation that facilitates response selection in the compatible case but leads to response (selection) conflict in the incompatible case. This observation extends previous demonstrations that action-contingent events are spontaneously acquired and supports the idea that actions become coded in terms of the effects they produce, hence, by means of action concepts (Hommel, 1997a). Interestingly, the priming effect was rather small, an issue I will get back to in the general discussion section, and it disappeared with a longer SOA, suggesting that color-induced action priming is as transient as that induced by spatial stimulus features (Hommel, 1994).

## Experiment 2

Having demonstrated that visual color effects become integrated with the actions preceding them the next step was to combine the color-acquisition design of Experiment 1 with a manual Stroop task. Accordingly, participants were presented with congruently, neutrally, and incongruently colored words and they were to respond to word color by pressing a left or right key. Pressing a key produced or did not produce a color effect. Three groups were compared, one with a *compatible* mapping of color effect and target color, a second, *control* group without color effects, and a third group with an *incompatible* mapping.

### Expectations

If action effects are acquired under the conditions of Experiment 2 they may affect performance in two ways: Firstly, they may affect the color-effect compatibility groups differently, i.e., produce a compatibility main effect and, secondly, they may yield interactions between color-effect compatibility and color-word congruency. Even though an ideomotor approach suggests that such effects occur, some additional assumptions are necessary to predict and interpret particular effect patterns. Let us consider the two types of effects in turn.

#### *Impact of target-effect compatibility*

With regard to the match between color targets and action-produced color patches one might expect two different outcomes, depending on how "automatic" the impact of action effects is, i.e., depending on whether or not intentional processes are required to code one's actions in terms of their color effects.

Firstly, let us consider that action effects are not only learned automatically, as Experiment 1 suggests, but that they also automatically redefine one's actions in terms of the colors they produce. In the compatible group, this would "color" the actions in a target-consistent fashion: Responses to the colors blue and green—the two colors used in Experiments 2 and 3—would "become" blue and green themselves. This would render targets and responses more compatible and thus facilitate the translation of the relevant stimulus codes into responses. In the incompatible group, the opposite would be true: responses to the color blue would become green and responses to the color green would become blue, which would render targets and responses incompatible and thus hamper the translation of the relevant stimulus codes into responses. As neither facilitation nor interference would be expected in the control group, this scenario would produce a symmetric effect pattern: Performance in the target-effect compatible group should be better, and performance in the incompatible group should be worse than in the control group.

Secondly, let us assume that action effects are acquired automatically but that they affect performance only if they are strategically employed. Indeed, Hommel's (1993) observation that the Simon effect can be reversed by only slightly changing the task instructions suggests that people have control over the effect codes used to define their actions in a given situation. In the compatible group, participants have any reason to switch to color coding their responses, as this increases the fit between stimulus and response and, thus, makes the task easier. In contrast, participants in the incompatible group would have no reason to prefer color coding to location coding of their responses as the former would be likely to make their task more difficult. This suggests an asymmetric effect pattern: performance in the target-effect compatible group should be better than in both the incompatible and the control groups, while the latter two groups should not differ.

#### *Interaction of color-effect compatibility and target-distractor congruency*

Apart from possible main effects of color-effect compatibility, action effects may also influence the Stroop effect, i.e., produce interactions between target-effect compatibility and target-distractor congruency. It is reasonable to assume that the patterns of these effects are sensitive to the same factors that play a role in target-effect compatibility, i.e., if action effects automatically redefine the action they are produced by, it would be expected that congruency effects in both the compatible and the incompatible group differ from those observed in the control group. In contrast, the second, more strategic hypothesis considered above would lead to the expectation that the compatible group produces congruency effects that differ from both the incompatible and the control group. How a hypothetical interaction of target-effect compatibility and target-distractor congruency might look depends on the assumed origin of the Stroop effect. Figure 1 sketches predictions from three major accounts of the Stroop effect in manual tasks, a later version of the dimensional-overlap model of Kornblum and colleagues (Kornblum, 1994; Kornblum, Stevens, Whipple, & Requin, 1999), the interactive activation models suggested by Cohen et al. (1990) and Phaf et al. (1990), which share many characteristics with

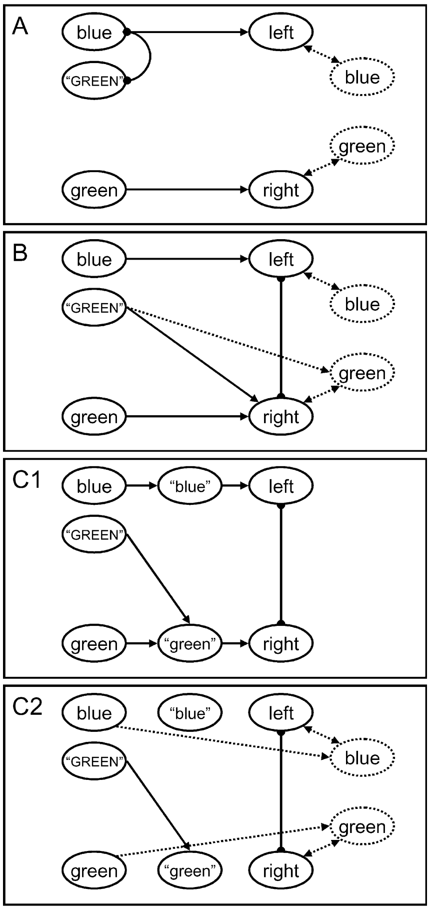


**Fig. 1A–C** Overview of predictions for Experiment 2 from three different theoretical accounts of the Stroop effect. The example assumes that left- and right-hand key presses are carried out in response to blue and green colors respectively, and it shows how the response to a blue stimulus is affected by the incongruent word "GREEN". *Dotted lines and shapes* show how the situation changes after target-compatible action effects are acquired. **A** The *dimensional overlap model* attributes Stroop effects in manual tasks to interactions between stimulus codes; it therefore predicts no impact of action effects. **B** *Interactive activation models* attribute Stroop effects to distractor-induced response conflict; they therefore (might) predict an increase in the Stroop effect. **C** *Translation models* attribute Stroop effects to the verbal (re)coding of stimuli and/or responses; as visual action effects offer an alternative, nonverbal coding these models predict a decrease in the Stroop effect

the original dimensional overlap model (Kornblum et al., 1990), and the translation models put forward by Virzi and Egeth (1985), Glaser and Glaser (1989), and Lu (1997).

Recent versions of the dimensional-overlap model locate the manual Stroop effect at the perceptual stage (stimulus identification) and attribute it to direct interactions between the codes of the target color and of the word distractor (Kornblum, 1994; Kornblum et al., 1999). Thus, pressing a left key in response to the blue color, say, is delayed in the presence of the distractor word "GREEN" because the color-incongruent word makes it more difficult to identify the color as "blue" (see Fig. 1A). It is hard to see how this process would be influenced by associating the left key press with a particular color effect, so that the newer versions of the dimensional-overlap model would actually not predict any impact of target-effect compatibility on target-distractor congruency.

According to the original version of the dimensional-overlap model (Kornblum et al., 1990) and the similar interactive activation models of Cohen et al. (1990) and Phaf et al. (1990), both color stimuli and color-related distractors have access to the response domain and, thus, compete for action selection. Accordingly, any kind of Stroop effect results from response competition (see Fig. 1B). Thus, in our example, the word "GREEN" delays the correct, left-hand response to a blue target because any visual or verbal code having to do with green feeds into the alternative, right-hand response, which therefore competes more strongly with the correct response than if the word was "BLUE" or neutral. Even though none of these models addresses acquired action effects, it may be speculated that learning target-compatible color effects increase the impact of target colors and/or distractor words. In our example, learning that pressing a left key produces a blue effect and integrating the corresponding codes (left and blue) might increase the effective feature overlap (Kornblum et al., 1990) or the association (Cohen et al., 1990; Phaf et al., 1990) between the target stimulus and the correct response. Likewise, learning that pressing a right key produces a green effect and integrating the corresponding codes (right and green) might increase the effective feature overlap or the association between the distractor word "GREEN" and the incorrect response. Depending on which of these changes has a stronger impact on performance, one would expect the Stroop effect to increase or decrease compared with the control group. If we assume that the task-defining association between the blue stimulus and the left response is very strong anyway, action effects should have a stronger impact on the association between distractor and response,[1] as indicated in Fig. 1B. This would mean that the compatible-mapping group should produce the biggest Stroop effect.

Finally, translation models attribute the manual Stroop effect to the tendency of participants to verbally

[1]Alternatively, one might argue that action effects have a stronger impact on the association between target and response because they are both colors and, thus, share format and modality. This reasoning—which we will find again in the discussion of translation models—would imply the exactly opposite outcome, i.e., the compatible-mapping group should produce the smallest Stroop effect. However, neither version of the dimensional overlap model or any of the interactive action models discussed address the issue of format- or modality-specific stimulus-response overlap (see Lu, 1997, for a broader discussion), which renders this kind of reasoning overly speculative. However, Sugg and McDonald (1994) have presented a hybrid model combining aspects of the Cohen et al. (1990) model with aspects of translation models à la Glaser and Glaser (1989), and this model would be well equipped to deal with format-specific effects.

recode color stimuli and/or responses to them (Sugg & McDonald, 1994). The general idea underlying most translation models is privileged access. For instance, Glaser and Glaser (1989) assume that color information can be translated into manual actions within what they call the "semantic executive system." Importantly, this system works without any need to consult linguistic knowledge bases (the lexicon), so that words do not have any impact on performance. This would imply that manual tasks should not actually produce a Stroop effect. To account for the fact that they commonly do (e.g., Keele, 1972; Pritchatt, 1968; Simon & Sudalaimuthu, 1979; White, 1969), researchers have speculated that participants may often attach covert verbal labels to the color targets and/or the response keys (for an overview, see Sugg & McDonald, 1994). According to translation models, this means that linguistic systems get involved, so that linguistic distractors, such as incongruent color words, gain access and affect performance. A simplified version of this scenario is sketched in Fig. 1C1. Color targets (and/or response keys) are recoded verbally, so that an incongruent word can intrude and activate the incorrect response alternative. If we assume that action effects are integrated with the responses they accompany, this means that color effects provide participants with a nonverbal response-coding alternative, i.e., instead of recoding responses verbally participants may recode them in terms of their visual consequences. If so, color-key translation would be confined to Glaser and Glaser's (1989) semantic executive system and the linguistic word distractors could be successfully excluded. As color-based response recoding makes sense in the compatible-mapping group only, a translation account would predict that the Stroop effect will be eliminated in the compatible group.

## Method

### Participants

Thirty-six native German speakers were paid to participate in single sessions of about 30 min. They were randomly assigned to the three experimental groups, so that 12 participants were tested in each group.

### Stimuli and apparatus

These were as in Experiment 1, with the following exceptions. Target stimuli were preceded by a fixation mark, a right-pointing and a left-pointing gray arrowhead separated by an area of 1.8° (> <). The target set comprised the words "Blau", "Grün", and "Doch" (German for blue, green, and yet), and a row of four uppercase Xs, presented in blue or green. Action effects consisted of blue and green squares of 1.8×1.2°. All stimuli were presented in the center of the screen.

### Procedure

The procedure was similar to that in Experiment 1 and again comprised an acquisition phase and a test phase.

*Acquisition phase* After a blank interval of 1,500 ms the fixation mark appeared for 100 ms. Another 500-ms blank interval followed before the target stimulus was presented for 150 ms. Only the Xs were used during acquisition. They appeared in blue or green and participants were instructed to respond to the color by pressing the left or right response key respectively within 1,000 ms. Note that the relationship between targets (stimulus colors) and distractors (the Xs) was always neutral, i.e., there were no Stroop stimuli. Each key press triggered the 300-ms presentation of the corresponding action effect. In the *compatible* group, the action effects were of the same color as the responses' instructed stimuli, i.e., the left response to the blue stimulus produced a blue action effect while the right response to the green stimulus produced a green effect. In the *incompatible* group, the relationship between stimulus color and effect color was reversed, i.e., the left response to the blue stimulus produced a green action effect while the right response to the green stimulus produced a blue effect. In the *control* group, no action effects were presented. Participants worked through 80 valid acquisition trials, comprising 40 miniblocks composed of a random sequence of the two targets or response-effect pairings.

*Test phase* The Xs were replaced by the three word stimuli. Combining the three words and the two target colors resulted in six possible stimuli; two of them were target-distractor *congruent* (BLUE presented in blue and GREEN in green), two were *neutral* (YET presented in green or blue), and two were *incongruent* (BLUE presented in green and GREEN in blue). After having completed the acquisition trials, participants were reminded that words would appear instead of Xs and that those words were distractors and to be ignored. The task and the mappings of responses to stimulus colors, and of action-effect colors to responses and target colors, all stayed the same. Miniblocks were composed of random sequences of the six possible combinations of target color and target word. Forty-one miniblocks were presented; the first was considered a practice block.

## Results

Trials with response omissions (1.2%) were excluded. Mean RTs and PEs were calculated and analyzed as a function of target-distractor congruency, which varied within participants, and target-effect compatibility, which varied between participants. Trials with a match of meaning and color of the target word were considered as target-distractor *congruent*, trials with a mismatch as target-distractor *incongruent*, and trials with the neutral word as *neutral*. Target-effect compatibility was coded according to the three experimental groups as compatible, incompatible, or as neutral control.

The RT analysis revealed two significant effects: A main effect of target-distractor congruency, $F(2,66) = 11.85$, $p < .001$, that was modified by an interaction with target-effect compatibility, $F(4,66) = 3.29$, $p < .05$. Figure 2 provides an overview of the resulting pattern. Both the control and the incompatible groups showed an effect of target-distractor congruency with RTs increasing from the congruent and neutral to the incongruent condition—a standard Stroop effect. The effect was reliable in both groups, as confirmed by separate ANOVAs, and it did not differ in size between these two groups, as indicated by the absence of the interaction with target-effect compatibility in an ANOVA where the compatible group was excluded. In

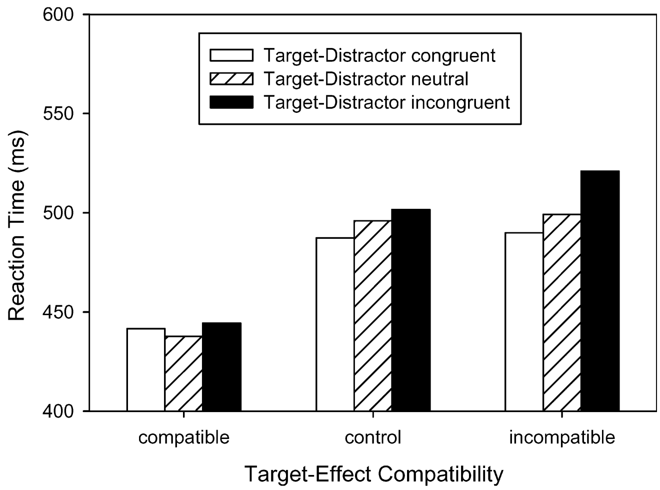


**Fig. 2** Mean reaction times (RTs) in Experiment 2 as a function of target-effect-compatibility group and target-distractor congruency

contrast, there was no evidence of an effect of target-distractor congruency in the compatible group, as confirmed by a separate test, $F < 1$. The main effect of target-effect compatibility only approached the significance criterion, $p < .08$. However, given the theoretical relevance of the mapping effect and its substantial numerical size planned *t*-tests for independent measures were carried out to compare the neutral congruency conditions of the three compatibility groups. Whereas the compatible group differed significantly from the control group, $p < .05$ (two-tailed), the incompatible group did not, $p > .9$.

The PE analysis revealed two significant effects (see Table 1): A main effect of target-distractor congruency, $F(2,66) = 10.41$, $p < .001$, and a main effect of target-effect compatibility, $F(2,33) = 4.05$, $p < .05$. The resulting pattern partially mirrored the RTs findings, i.e., error rates increased from the target-distractor congruent condition to the neutral and the incongruent condition (4.3%, 6.0%, and 6.6%, respectively) and they increased from the compatible and control to the incompatible target-effect group (3.7%, 4.1%, and 9.0%). However, in contrast to RTs the interaction in PEs was far from significance, $F < 1$.

Given the different effect patterns in RTs and errors some additional analyses were carried out to see whether and how RTs and PEs are related to each other, and whether there are indications of a speed-accuracy trade-off. Firstly, individual sizes of the target-distractor congruency effect in RTs and PEs were computed for participants from all three groups and entered into a correlation analysis. The correlation was small, $r^2 = .14$, and far from significance, $p > .4$, which speaks against a trade-off between RT and PE effects. Next, it was checked whether the type of errors differed between the groups. For instance, it might have been that members of the compatible-effect group had a stronger tendency to respond prematurely and, hence, to the word aspect of the Stroop compounds (MacLeod & MacDonald, 2000). This would artificially speed up valid responses to congruent stimuli (as word-related responses were as correct as color-related responses) but produce relatively fast errors with incongruent stimuli. Although this would not really work to move a RT effect to the error rates, it might point to a different processing strategy in the compatible group. To test this, RT medians from error trials were computed as a function of target-distractor congruency and target-effect compatibility. Six, 7, and 11 participants from the three compatibility groups (compatible, control, and incompatible respectively) made errors in all three congruency conditions. An ANOVA on these data and RT medians as a comparison produced a main effect of measure, $F(1,21) = 7.51$, $p < .05$, indicating that error RTs tended to be somewhat shorter than RTs in valid trials, and a main effect of target-distractor congruency, $F(2,42) = 3.23$, $p < .05$. However, all other effects were far from significance and the error RTs showed a very similar pattern to the RTs from valid trials: 403, 400, and 477 ms in target-distractor congruent, neutral, and incongruent conditions respectively. Thus, there is no evidence for different processing strategies in the three groups.

**Table 1** Error rates (percentage of incorrect response decisions) in Experiment 2 as a function of target-effect compatibility and target-distractor congruency

| Target-effect compatibility | Target-distractor congruency | | |
|---|---|---|---|
| | Congruent | Neutral | Incongruent |
| Compatible | 2.5 | 3.3 | 5.4 |
| Control | 3.2 | 3.9 | 5.3 |
| Incompatible | 7.3 | 8.4 | 11.3 |

## Discussion

The purpose of Experiment 2 was to see whether acquired color effects of manual actions affect performance in a Stroop task. Two types of effects were considered to be diagnostic: Main effects of target-effect mapping on the one hand and influences of this mapping on the Stroop effect on the other hand. With regard to the former there is evidence in RTs that the compatible target-effect mapping facilitated performance compared with the control and incompatible groups, which did not differ from each other. Thus, the results follow an asymmetric pattern indicative of a more strategic interpretation of action-effect use. In particular, the lack of a RT difference between the incompatible and the control group is inconsistent with the idea that reacting to color stimuli is a sufficient condition to spontaneously recode one's manual actions in terms of color. (I will get back to the error effect in the general discussion section.) Apparently, people employ action effects to recode their actions only if this is of some use, as it was in the compatible group.

Effect mapping also impacted the Stroop effect, which in the compatible-mapping group was even eliminated, at least in RTs. This observation is difficult to combine with a strictly perceptual interpretation of the manual Stroop effect along the lines of Kornblum and colleagues (Kornblum, 1994; Kornblum et al., 1999), as this interpretation would leave no room for any impact of post-response events—unless action effects are accorded the same status as features of the action. Also, the disappearance of the Stroop effect in the compatible group does not seem fit with expectations of the original version of the dimensional overlap model (Kornblum et al., 1990) or the interactive activation approaches of Cohen et al. (1990) or Phaf et al. (1990)—if anything, these accounts imply a stronger role of distractors as the feature overlap between stimuli and responses increases. In contrast, translation models have no problem accounting for the present findings. These models suggest that acquiring an association between responses and visual color patches provides people with an alternative, nonlinguistic way of coding their response, which keeps linguistic distractors out of the processing pathway and renders them ineffective. As the relationship between color effects and actions was useful only with a target-compatible effect mapping, only participants in the compatible group can be expected to employ the coding alternative and, indeed, the Stroop effect vanished in this group.

The observation that the manual Stroop effect disappears if target stimuli and responses are made to look more similar is not new. McClain (1983), Virzi and Egeth (1985), and Sugg and McDonald (1994) were able to eliminate the effect by signaling response locations through target-compatible color patches. However, as Simon and Sudalaimuthu (1979) had noted earlier, this technique is likely to "reduce the task to a low-level color-matching procedure" (p. 178), the more so as the mapping of colored response labels to response locations was frequently changed during the experiments or even from trial to trial. Indeed, no study to date has been successful in demonstrating that the manual Stroop effect can be eliminated by using colored response labels if the relationship between colors and responses remains fixed (Sugg & McDonald, 1994). The present findings extend these previous observations in two ways. Firstly, they show that the manual Stroop effect can be eliminated even if response-color relations are fixed and, secondly, they show that this is possible even if low-level color-matching can be ruled out—simply because the response "labels" appeared only after the response was carried out. Thus, if color effects did serve as response labels it must have been their anticipation that guided response selection, just as the ideomotor approach to action control suggests. At this point, we can only speculate why earlier studies were less successful in eliminating the effect with fixed response labels. As Sugg and McDonald (1994) pointed out, it may be that using fixed color labels encourages participants to verbally recode their actions, hence, to address their responses via verbal color names, which opens the door for word distractors. If we assume that verbal coding strategies are developed and play their major role at the beginning of a new task (Goschke, 2000), verbal color coding may be particularly tempting if colored response labels are visible during instruction and task preparation, i.e., if color labels are available while participants rehearse the instructions and implement their task set, they may spontaneously use verbal representations of the response labels, e.g., because these are easier to rehearse. Obviously, this was not possible in the present Experiment 2, where no response-related color was visible, or even mentioned, before the first response was actually carried out. However, more research is necessary to test these speculations.

Interestingly, the error rates show that some impact of the Stroop effect was retained. The finding that RTs and errors were affected differently fits well with the increasing evidence that the error Stroop effect is unrelated to, and thus can be dissociated from the RT Stroop effect (e.g., Kane & Engle, 2003a; Spieler, Balota, & Faust, 1996). Accounts of this dissociation refer to the use and frequency of congruent target-distractor combinations. Note that for congruent pairings there is no way of determining whether participants react to the color or the word, suggesting that at least some of the (seemingly) correct responses in the congruent condition are actually faulty responses to the word (MacLeod & MacDonald, 2000). If so, it needs to be assumed that the error Stroop effect is overestimated (if not an artifact), because some errors in the congruent conditions are counted as correct responses. The degree of overestimation will vary with the number of trials in which participants forget the actual goal of the task (goal neglect: Duncan, 1993, 1995) and, hence, respond to the more over-learnt word stimulus (Kane & Engle, 2003a). As this number is unlikely to be related to the action-effect manipulation and its impact on performance, there is indeed no reason to assume that the error Stroop effect should vary with target-effect compatibility. Hence, the observation of a reliable Stroop effect in errors does not contradict the elimination of the effect in RTs.

## Experiment 3

Experiment 2 shows that acquiring a target-compatible response-contingent color effect basically eliminates the impact of color-word congruency, i.e., the Stroop effect in a manual task. According to the suggested translation-related account this is because colored action effects, and the integration of their codes with the accompanying response, provide people with a means of addressing and selecting their actions in a nonlinguistic fashion, which again blocks out linguistic distractors. An obvious way to test this account is to replace the color patches that served as action effects in Experiment 2 with the corresponding color words. Semantically speaking, this does not change the picture: Responses still produce effects that match or do not match the meaning of the target stimulus. However, as the effects are linguistically defined they should no longer be effective at blocking out distractor words, so that a full-fledged Stroop effect would be expected even in the compatible-effect group. Experiment 3 tested whether this expectation was fulfilled.

## Method

### Participants

Forty native Dutch speakers were paid to participate in single sessions of about 30 min. They were randomly assigned to the two experimental groups (*compatible* and *incompatible*), so that 20 participants were tested in each group.

### Stimuli and apparatus

These were as in Experiment 1, with two exceptions. The target set was adapted to Dutch language, resulting in the words "Blauw", "Groen", and "Tocht" (Dutch for blue, green, and tour). Action effects consisted of the words "blauw" and "groen" (blue and green) presented in gray in the center of the screen.

### Procedure

The procedure was exactly as in Experiment 2, except that action effects were color words and that there was no control group.

## Results

Trials with response omissions (<1%) were excluded and mean RTs and PEs were calculated and analyzed analogously to Experiment 2. The RT analysis produced only a main effect of target-distractor congruency, $F(2,76) = 23.61, p < .001$, while the main effect of target-effect compatibility missed the significance criterion, $p < .11$, and the interaction was far from significance, $F < 1$. Figure 3 shows the result. Both groups exhibit standard effects of target-distractor congruency, i.e., RTs increasing from the congruent and neutral to the incongruent condition. Importantly, the effects proved to be reliable even if tested separately for each group, and the differences between congruent and incongruent conditions in the two groups are of comparable size.

The PE analysis also revealed only a main effect of target-distractor congruency, $F(2,76) = 5.42, p < .01$, whereas the main effect of target-effect compatibility and the interaction were far from significance, $F < 1.4$ (see Table 2). As with RTs, performance decreased from the congruent and neutral to the incongruent condition (4.6%, 4.6%, and 6.2% respectively).

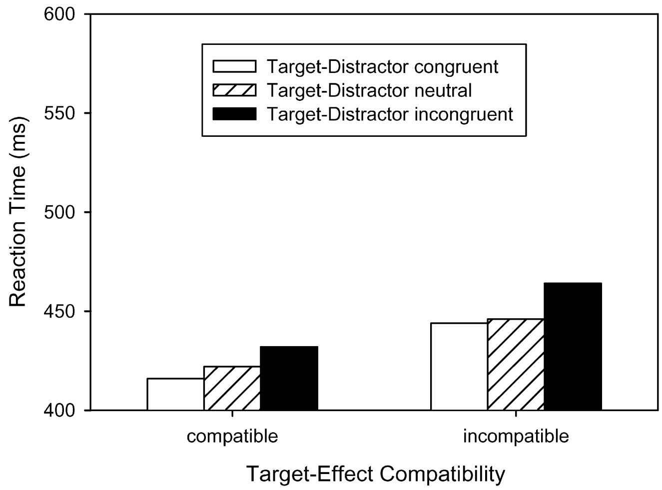


**Fig. 3** Mean RTs in Experiment 3 as a function of target-effect-compatibility group and target-distractor congruency

**Table 2** Error rates (percentage of incorrect response decisions) in Experiment 3 as a function of target-effect compatibility and target-distractor congruency

| Target-effect | Target-distractor congruency | | |
|---|---|---|---|
| Compatibility | Congruent | Neutral | Incongruent |
| Compatible | 4.2 | 3.6 | 6.1 |
| Incompatible | 4.9 | 5.7 | 6.4 |

## Discussion

Replacing the color patches employed in Experiment 2 with words denoting these colors in Experiment 3 produced two clear-cut effects. Firstly, there was no longer evidence in RTs or PEs of a main effect of target-effect compatibility. This is interesting as it suggests that, whichever factors were responsible for such effects in Experiment 2, their impact seems to depend on the format of the action effects (color vs. word) but not on their meaning.

Secondly, target-distractor congruency was no longer affected by compatibility, i.e., a standard Stroop effect was obtained in both groups. The latter observation favors an account of the interaction of compatibility and congruency in Experiment 2 in terms of translation or privileged access. Acquiring action effects affords alternative ways of coding one's actions, but in a Stroop task this helps to block out distractors only if the alternative codes are nonlinguistic, as they were in Experiment 2. In contrast, linguistic effects are inefficient. In view of evidence that linguistic effects (and words, in particular) are acquired as automatically as nonlinguistic effects (Hommel et al., in press), this does not seem to reflect the inability of participants to use the color-word effects in Experiment 3 but, instead, the little utility an effect-based coding strategy would have had in Experiment 3.

## General discussion

The purpose of the present study was to investigate the relationship between color-related action effects and the Stroop phenomenon. Three questions guided the study. The first was whether task-irrelevant color-related effects are acquired and integrated with manual actions at all. Indeed, Experiment 1 showed that experiencing responses to produce visual events of a particular color turned irrelevant stimuli sharing those colors into effective primes of the respective response. This provides evidence that the codes of response-produced colors became associated with representations of the action producing them, so that activating the color code by means of a prime stimulus spread activation to the associated action and thus facilitated its selection. Hence, the basic logic underlying ideomotor theory in general and the action-concept approach (Hommel, 1997a) in particular also applies to manual actions that produce color effects—actions can become "mentally colored."

The second question was whether coding manual responses in terms of their color-related effects is a spontaneous, obligatory process or a result of a context-sensitive strategy. If it were an automatic process a symmetric effect pattern would have been expected—better performance with compatible effect mapping, and worse performance with incompatible effect mapping compared with the control group—and a mapping effect in both Experiments 2 and 3. However, the effect of mapping compatibility was confined to speeding up RTs in the compatible-mapping group of Experiment 2. The fact that no mapping effect was found in Experiment 3 suggests that it does not rely on abstract, semantic codes but, instead, on the perceptual qualities of the action effects. What seems to have mattered for the facilitation effect was the identity of color targets and color effects with respect to both content *and* format, which was given in Experiment 2 but not in Experiment 3. This double identity apparently provided participants with a processing shortcut that made the S-R translation faster and, as the (lack of) congruency effects demonstrate, less sensitive to word distractors. Indeed, from an action-concept approach only color effects guarantee the use of the same representational structure for coding the color target and the response, and it is this dual use of identical cognitive codes that should create the strongest association between stimulus and action events. This need not exclude semantically mediated effects. In fact, the main problem underlying the Stroop effect obviously derives from the semantic relation—and overlap in meaning—between target colors and irrelevant color words. Thus, the intention to react to color stimuli (and, probably, to recode them verbally) must be sufficient to prime color words to sneak in and compete with colors for response selection. Similarly, acquiring the words DOG and CHAIR as effects of manual actions has been demonstrated to transfer to other, semantically close action effects like ANIMAL and FURNITURE or CAT and TABLE (Hommel et al., in press), suggesting that action-effect associations include or generalize to semantically related concepts. And yet, in the present Experiment 3 semantic overlap was not enough.

These observations suggest a somewhat complicated relationship between automatic and strategic processes, but the emerging picture fits nicely into the ideomotor framework in general and Elsner and Hommel's (2001) two-stage model of action control in particular. On the one hand, action effects are indeed picked up automatically. This is demonstrated by both the priming effect in Experiment 1 and the main effect of effect compatibility in Experiment 2. Although there is no way to tell from the data obtained, Hommel et al.'s (in press) demonstration of the automatic acquisition of word effects strongly suggests that even the color words employed in Experiment 3 were learned. On the other hand, however, the *use* of acquired action effects for action control is intentional and strategic, i.e., dependent on and controlled by the goals of the actor. If so, people have no choice but to acquire the action-effect episodes they are facing, but once that has been done they may or may not make use of particular action effects, or semantically close concepts, to code their actions.

Figure 4 provides a sketch of how this reasoning applies to Experiment 2. Let us consider two motor patterns, $m_l$ and $m_r$, which drive the left- and right-hand key press actions respectively. Each key press produces, among others, two types of effects, one of them being feedback on the left or right side and the other consisting of a blue or green color patch (see Fig. 4A; the example refers to the situation in the compatible-effect group). As the activations of $m_l$, the code *left* and the code *blue* for one action and of $m_r$, *right* and *green* for the other overlap in time, associations are created between them (see Fig. 4B).[2] If people have no means of controlling the way they code their actions, the left-hand action, say, would always be coded as both left and blue, so that left stimuli and blue stimuli would make equally good action primes. However, given the finding that instructing people in a particular fashion can make them code a left-hand action as RIGHT, and vice versa (Hommel, 1993), we need to assume that actors have considerable control over how actions are coded. If so, participants in the present experiments must have had a choice between "attending" either the location features or the color features of their key presses (i.e., of the key press-contingent perceptual events; see Hommel, 1993, 2003a). In Fig. 4, this choice is implemented by means of category or domain nodes that can be activated to

[2] It is an interesting question whether the codes for left and blue (and for right and green) can also become directly associated. This hypothesis is not only suggested by a generalization of the action-concept approach (Hommel, Müsseler, Aschersleben, Prinz, 2001), it also seems to stand empirical testing (Hommel Colzato, in press; Hommel, 1998b, 2003b).

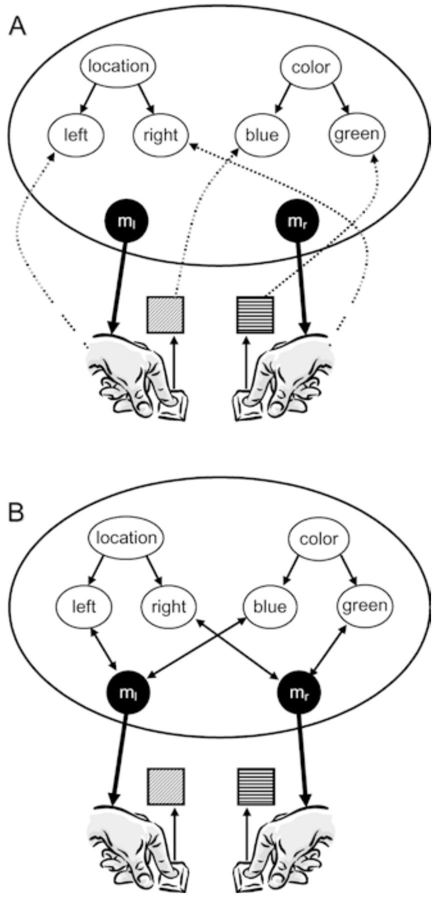


**Fig. 4A, B** Sketch of the major theoretical assumptions to account for the impact of target-effect compatibility on general performance and on target-distractor congruency effects. **A** exemplifies the acquisition phase, the codes and mappings refer to the compatible group of Experiment 2. Performing the key presses (achieved via motor patterns $m_l$ or $m_r$) is assumed to activate codes of both spatial and color-related action effects. As shown in **B**, this creates bilateral associations between motor patterns and effect codes, rendering spatial and color stimuli effective primes of the associated action. Codes of a particular effect domain (location or color) can be preactivated (task-primed) to various degrees via corresponding domain or dimension nodes

prime (and make task-relevant) either location codes or color codes.

Now, given the task instruction to press left and right keys and the naturalness of spatial coding of manual actions it is likely that participants had "switched on" their LOCATION node by default. This would lead actions to be coded in terms of left and right, hence, in terms of features that do not overlap with any stimulus in the task. The question is whether the color code is switched off entirely. At least two factors can be suspected of being significant for this question: Task relevance and usefulness. If a task does not relate to color at all there would be little reason to choose a color coding of one's actions, even if those codes were available. Yet a Stroop task does bring in color as a task-relevant dimension, so that some degree of activation of the COLOR node may be difficult to prevent. Usefulness has more to do with the benefits of coding one's actions in a particular way. Let us compare, for instance, the compatible-effect and the incompatible-effect groups in Experiment 2. Coding actions in terms of the colors they produce would render the target color a 100%-valid action prime in the compatible group and a 100%-invalid action prime in the incompatible group. Accordingly, if participants had any control over the dimensions used for action coding it would have made much more sense to go for color in the compatible group than the incompatible group. And this is what the main effect of effect compatibility indicates: Faster responses for the compatible group than the incompatible group and the control group (which had no alternative to location coding anyway).

These considerations also help to interpret the findings of Experiment 1, where the color primes were task-irrelevant but primed the correct response in 50% of the trials, i.e., they were more valid (and useful) than in the incompatible group but less valid than in the compatible group of Experiment 2. Assume that people were able to match the degree to which a particular dimension node contributes to action coding (i.e., the degree to which it primes codes of the dimension) to the usefulness of doing so—an idea introduced and discussed by Meiran (2000a, 2000b). If so, participants in Experiment 1 would have been expected to have activated the COLOR code to a lesser degree than members of the compatible group but to a greater degree than members of the incompatible group of Experiment 2. And this is in fact what the findings suggest. Let us take the impact of prime-effect compatibility in Experiment 1 and compare it with the difference between the neutral congruency conditions of the compatible-effect group and the control group, and the difference between the neutral congruency conditions of the incompatible-effect group and the control group. This gives a pronounced 58-ms effect for the compatible group of Experiment 2, a still reliable effect of 8 ms in Experiment 1, and an insignificant 3-ms effect for the incompatible group of Experiment 2—effect sizes that at least are ordered according to the actual use of "having colored" one's actions under the respective conditions.

The outcome of Experiment 3 also makes sense if task relevance and usefulness of color coding are considered. On the one hand, the semantic overlap between target colors and the presumably acquired color-word effects would have provided an opportunity to ease the task for people in the compatible-effect group. On the other hand, however, the action effects were words, not colors, so that bringing them into play would have required the activation not of the COLOR node but of a COLOR-WORD node (omitted in Fig. 4). This again would be likely to interfere with the standard Stroop instruction, to respond to the color and to ignore the word-aspect of the target stimuli. Thus, increasing the attention to the action effects would have involved further increasing the impact of the nominally irrelevant dimension of the target stimulus—which would be likely to create more confusion than help for response selection.

The third question guiding the study was whether acquiring color-related action effects has any impact on the Stroop effect. The answer is clear-cut: It had an effect but only if targets and effects matched in format. This observation has considerable theoretical consequences. One is that it renders stimulus-based accounts of the Stroop effect implausible. If the manual Stroop effect resulted from direct interactions between stimulus codes (of color and word meaning) before the target is identified, as Kornblum and colleagues (Kornblum, 1994; Kornblum et al., 1999) claim, it is difficult to see, without additional assumptions, how postresponse manipulations can eliminate the effect altogether. More interactive models along the lines of Cohen et al. (1990), Kornblum et al. (1990), and Phaf et al. (1990) also seem to be insufficiently equipped to explain why and how the manual Stroop effect can be prevented from occurring by merely learning to associate actions with the consequences they produce. The main shortcoming of these models seems to be that they have little to say about how actions are represented and even less to say about how action representations are tailored to the task context. Better suited for this purpose are translation or privileged access models as suggested by Virzi and Egeth (1985), Glaser and Glaser (1989), or Lu (1997). As they predict, providing a target-compatible, nonlinguistic response code enabled participants to effectively block out distracting words in the compatible group of Experiment 2. Apparently, then, acquiring color effects allowed or motivated them to (re) code their actions in a more nonverbal fashion than participants would normally do, thereby minimizing access to and impact from linguistic processing systems.

More generally, the observed interaction between action-effect manipulations and a phenomenon that is commonly associated with response-selection processes lends further credit to the ideomotor approach to action control. This approach claims that selecting an action involves some sort of anticipation (not necessarily a conscious process) of which events the action about to be selected would create or modify. In everyday life almost all actions can be carried out for multiple reasons and, thus, are experienced to create multiple effects. If these effects are all learned and stored, as modern versions of the ideomotor approach suggest, there must be some sort of mechanism that tailors the way an action is represented to the contextual requirements and the actor's current goals and needs (Hommel, Pösse, & Waszak, 2000). As proposed here, one means of doing this is to prime the task- and goal-relevant dimensions so that the contextually relevant features of an action are more likely to contribute to the action's current cognitive representation than less relevant features (Hommel et al., 2001). Thus, the same action can be represented differently, depending on contextual demands and requirements, and which features are highlighted in a particular context is at the actor's disposal.

Some final considerations about the two dissociations of RT and error effects observed in Experiment 2 are in order. The first relates to the effect-compatibility manipulation, which produced a benefit in the compatible group (compared with the control group) that showed up in RTs and interference in the incompatible group that showed up in PEs. The second consideration relates to the effect of target-distractor congruency, which depended on effect compatibility in RTs but was unaffected by compatibility in PEs. As there was no evidence of any speed-accuracy trade-off or changes in speed-accuracy strategies, the question remains as to what these dissociations reflect. To account for the latter, I suggested an interpretation in terms of goal neglect, taking up a line of reasoning from Kane and Engle (2003a). These authors point out that Stroop-type effects are likely to be produced by two different factors, or their interactions. One refers to the action goal. Stroop tasks are so challenging because they require the more uncommon of two possible responses to color-word compounds: Responses to the color, not to the color name. Working against the more natural tendency to react to the name requires one to continuously remind oneself of the task, which translates into the need to constantly maintain a representation of the task goal in working memory (Duncan, 1995). As discussed already, failures to maintain the goal (goal neglect) lead to word-related reactions, which produce an error in an incongruent trial but a valid response in a congruent trial, thereby underestimating the congruence error rates. The second factor comes into play only if the goal is correctly maintained and only if word and color are incongruent. In that case, two conflicting responses are activated and this conflict has to be resolved somehow. This resolution takes time, which should prolong incongruence RTs but not produce an error.

Indeed, a number of observations support Kane and Engle's (2003a) two factors account. For instance, Alzheimer's patients, who are likely to suffer from a high degree of goal neglect, show considerable increases in error rates in incongruent trials (Spieler et al., 1996). Error rates in incongruence conditions are also associated with measures of the individual working memory span, a parameter that is likely to be related to the frequency of goal neglect (Kane & Engle, 2003a). Interestingly, this relationship between memory span and incongruence errors is only found if the Stroop task includes congruent trials, suggesting that these trials provoke or reward goal neglect in particular (Kane & Engle, 2003b).

As discussed in Experiment 2, considering that RT and error Stroop effects may reflect contributions from different factors provides an explanation for the finding that in this experiment effect compatibility eliminated the impact of target-distractor congruency on RTs but not on error rates. By helping to shield stimulus-response translation from the impact of linguistic processing systems, the compatible-action-effect manipulation was likely to decrease response conflict in incongruent trials—thereby reducing the RT congruency effect. But this should not affect the likelihood of goal neglect and the measure it is reflected by—hence, no impact on PEs. Interestingly, a similar line of reasoning may account for the other dissociation of RTs and errors. According to the account sketched in Fig. 4, the way actions are coded is controlled by the weighting or relative activation of dimensional nodes (LOCATION and COLOR); hence, by the amount of "attention" used on action-contingent features of one or the other dimension. Weighting these nodes in a particular fashion is assumed to reflect the current task goal, which, according to Duncan (1993, 1995) and others, may be neglected now and then. Goal neglect may therefore result in coding actions in terms of features that are not intended, i.e., in spatial terms if color coding is actually preferred, and vice versa. In the compatible-effect group it does not matter whether a blue target is translated into a LEFT response or whether it triggers the color-compatible BLUE response, the result is the same. Hence, if acquiring the target-compatible effects has any impact on performance, it can only be on RTs. Not so with incompatible effects. Here, "forgetting" to translate a blue target into a LEFT response would lead to the BLUE response being triggered, which, however, is the RIGHT response and therefore incorrect. Hence, if acquiring the target-incompatible effects has any impact on performance, it can only be on PEs, which is what the findings reflect.

To sum up, the findings support the assumption of ideomotor approaches that experiencing action-contingent events leads to the automatic creation of bilateral action-effect associations. Once formed, these associations are employed in a strategic, context-sensitive fashion, presumably by priming goal-related feature domains. As a consequence, features from primed and, hence, goal-related dimensions contribute more strongly to the task-specific cognitive coding of respective actions. This task-specificity of action representations determines the ease of stimulus-response translation and, as a side effect, the sensitivity of response selection to competition from irrelevant distractor stimuli. In other words, the way we code our actions determines what can activate them.

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