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Action-Effect Codes in and Before the Central Bottleneck: Evidence From the Psychological Refractory Period Paradigm

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Voluntary motor actions aim at and are thus governed by predictable action effects. Therefore, representations of an action's effects normally must become activated prior to the action itself. In 5 psychological refractory period experiments the authors investigated whether the activation of such effect representations coincides with the response selection stage of information-processing theories. Participants performed 2 choice reaction tasks, separated by variable stimulus onset asynchronies. The authors varied the compatibility between responses and forthcoming sensorial effects (Experiments 1, 2, 3, and 5) or between responses and effect-resembling stimuli (Experiments 4 and 5) in one of the tasks. They observed that compatibility influences from forthcoming (anticipated) response effects were located within the response selection bottleneck, whereas compatibility influences from action-preceding (perceived) effects were due to processes before the bottleneck. These results point to a crucial role of the endogenous activation of action-effect representations for the selection of voluntary motor responses.

Keywords: action control, anticipated action effects, psychological refractory period

It is a major interest of cognitive psychology to understand the mental processes that enable humans to produce adaptive motor behavior. Broadly speaking, two different approaches to this central issue can be identified. Sensorimotor approaches, on the one hand, conceptualize behavior as a reaction to external stimulation. Reactions are considered as the end product of a chain of processing stages that somehow translate stimuli into stimulus-assigned motor patterns (e.g., Massaro, 1990; Sanders, 1980, 1998; Smith, 1968; Sternberg, 1969). The main translation work is assumed to occur in a response selection stage. Ideomotor (IM) approaches, on the other hand, are concerned with the mechanisms needed to achieve intended goals. These approaches emphasize that in order to produce a desired outcome, it is necessary that codes of intended future percepts (action effects) rather than codes of actual percepts (stimuli) are linked to adequate motor patterns. Goal-oriented action thus necessarily presupposes the activation of action-effect representations prior to the action itself. Of course this can occur only after links between motor actions and their effects have been acquired. But after such links have been established, so IM theory assumes, actions become exhaustively represented by their effects, so that there is no other way to select an action than by recollecting its sensory effects (Greenwald, 1970; Hoffmann, 1993; Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890; Lotze, 1852; Prinz, 1987).

The purpose of the present article was to make a step toward reconciling the apparently separated views of sensorimotor and IM approaches of action control. By combining paradigms from both camps, we hoped to bring together advantageous aspects of both approaches. Sensorimotor approaches are not very explicit about the type of processing occurring in the "black box" called response selection. But these approaches offer elaborated methods to localize this process in the time course between stimuli and responses. By contrast, IM approaches make the clear suggestion that motor actions are "selected" by recollecting their sensory effects, but they have not cared too much about the relative point in time that this recollection occurs. We studied whether the response selection stage proposed in sensorimotor approaches coincides with the anticipation of action effects, which according to IM approaches mediates action production. More specifically, we located the activation of action-effect codes relative to the response selection bottleneck evident in dual-task performance (Pashler, 1984, 1994; Welford, 1952). In short, we confirm that the activation of effect codes actually takes place during this processing bottleneck. Moreover, we demonstrate that this inference holds when effect codes are endogenously activated by the performer but not when they are exogenously activated by external stimulation. We be-

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lieve that these results help to better understand constraints in dual-task performance and motor control in general.

Effect Codes and IM Approaches of Motor Control

Effect Codes and IM Approaches of Motor Control The key assumption of the IM models is the representation of motor actions by codes of their sensory effects—that is, the proprioceptive effects, tactile effects, visual effects (and so forth) brought about by the motor action. Therefore, movements of the body cannot be controlled directly by setting up an efferent motor command (Keele, 1968) or motor program (Schmidt, 1975) but only indirectly by activating codes of their outcomes that in turn activate associated motor patterns. Although this is a strong claim, it has come to receive some support, mostly from tasks that varied the compatibility of motor actions and produced action effects. There are two brands of this approach, which can be classified as relying on either exogenous or endogenous activation of effect codes.

Exogenous Activation of Effect Codes

The first, "induction" approach assumes that if actions are selected by means of their sensory effects, then stimuli resembling these effects should facilitate the selection of the effect-eliciting response (Greenwald, 1970). In other words, perceiving an action effect should "induce" the motor patterns that normally produce these effects. To illustrate this idea, let us consider a recent series of experiments by Hommel (1996) and Elsner and Hommel (2001). In these studies, participants began with an introductory learning phase, in which responses triggered artificial action effects (e.g., a left response produced a high-pitched tone and a right response triggered a low-pitched tone). After a practice period a test phase followed that used the previous action effects as imperative stimuli for the very same responses. The mapping of stimuli and responses was either compatible, so that stimuli matched the former action effects of the required response (e.g., a high-pitched tone affording a left response), or incompatible, so that stimuli matched the action effects of the alternative response (e.g., a high-pitched tone affording a right response). Reaction times (RTs) were faster with stimuli that were effect compatible rather than effect incompatible. This influence of stimulus– effect compatibility suggests that stimuli resembling action effects do indeed have the power to activate the motor patterns that previously produced them.

Endogenous Activation of Effect Codes

Induction studies thus suggest that effect codes basically have the power to affect response production. But are such effect codes spontaneously generated and used to intentionally produce a motor pattern? There is another line of evidence suggesting that this is so. These studies focus on the impact of action effects that follow actions in time rather than preceding them, as in induction studies. The idea is that if action effects become anticipated prior to the action itself, they might leave a trace in observable performance. As an example, consider motor actions that produce feature-overlapping action effects, such as left or right keypresses that switch on a light on the left- or right-hand side. A response might be easy to generate when it produces a compatible action effect (e.g., a left response producing a left-sided effect), as the activation of the effect codes during response generation might automatically prime a compatible motor action. By contrast, an anticipation of action effects would be less helpful (and possibly harmful) if an action produced an incompatible effect (e.g., a left response producing a right-sided effect). Here, the activated effect codes would prime a different response than the one actually requested. There is now converging evidence for such an influence of compatibility between responses and their forthcoming effects (hence response– effect, or R-E, compatibility). For example, producing a spatial response proceeds faster when the response is followed by a spatially compatible visual effect instead of an incompatible one (e.g., a left response flashing a light on the left side instead of the right side; Hommel, 1993; Kunde, 2001). Similarly, a forceful keypress proceeds faster when followed by an auditory effect of compatible instead of incompatible intensity (e.g., a forceful keypress that produces a loud tone instead of a quiet tone; Kunde, 2001). Because all response effects were presented only after the response was actually carried out, such influences of R-E compatibility must originate from effect codes internally generated during action production.

Altogether, the compatibility effects obtained with exogenously as well as endogenously activated effect codes provide clear support for a role of effect codes in action production. Yet it is less clear whether the activation of such codes should be equated with what information-processing models label as "response selection." This need not necessarily be so. For instance, it might be that the activation of effect codes is not capacity limited and could thus be done to some extent prior to a response selection bottleneck (see, e.g., automatic response activation vs. response selection; Hommel, 1998). Alternatively, action effects might be predicted only after the response is selected (during the initiation of a response) instead of being used for response selection itself. Such a result would limit or at least qualify the explanatory power of the IM approaches.

Previous Studies on Effect Code Activation and Response Selection

Although the locus of effect code activation has not been a primary concern of empirical investigation, tentative hints come from studies that have addressed the boundary condition of the response selection bottleneck in dual tasks. On the basis of the induction logic (described above), Greenwald (1972) argued that the capacity-limited response selection process could be bypassed if the stimuli closely resembled the action effects from the required response. These IM-compatible tasks, such as vocally imitating an auditorily presented letter or moving a joystick in the direction of an arrow, would allow "perfectly efficient timesharing" (Greenwald, 1972, p. 52), that is, simultaneous performance without slowing of or interference between tasks. There is some controversy as to whether perfect time-sharing can be obtained (Greenwald, 1972, 2003; Greenwald & Shulman, 1973) or whether small dual-task costs remain even with two IM-compatible tasks (Lien, McCann, Ruthruff, & Proctor, 2005; Lien, Proctor, & Allen, 2002). Nevertheless, the remarkable reduction of dual-task costs, which are otherwise robust even with highly compatible or overlearned stimulus–response (S-R) mappings (cf. Lien & Proctor, 2002), points to a close connection of effect code activation and the response selection bottleneck. It is important to note, however, that IM-compatible tasks represent an exceptional case of choice reaction. At present it is unclear which processes are shortened or eliminated compared with tasks using arbitrary S-R mappings (Lien et al., 2005). Also, the failure to replicate perfect time-sharing with only one IM-compatible task of two concurrent tasks indicates that some capacity-limited processes are still involved even with stimuli strongly resembling action effects (Klapp, Porter-Graham, & Hoifjeld, 1991; Lien et al., 2002).

Design and Rationale of the Present Study

Given this inconclusive evidence with IM-compatible tasks, our approach was not to eliminate the response selection bottleneck altogether. We intentionally left it in the task but asked at what point in time, relative to the bottleneck, effect codes exert their impact. We used a well-established method to localize the time point of an experimental manipulation in the processing between stimulus presentation and response execution, namely, the paradigm of the psychological refractory period (PRP). In a PRP experiment, participants are required to perform two different choice reaction tasks with speeded responses to two successive stimuli. The interval between the presentation of the two stimuli (stimulus onset asynchrony [SOA]) is varied, resulting in different temporal overlap of the two tasks. Typically, RTs of Task 1 are barely affected by the SOA, whereas RTs of Task 2 are severely prolonged with short SOAs. This PRP effect is attributed to a response selection bottleneck, be it either structural (Pashler, 1984; Pashler & Johnston, 1989) or strategic (Logan & Gordon, 2001; Meyer & Kieras, 1997).[1]. Accordingly, response selection in Task 2 is delayed with short SOA, leading to a pause in processing ("cognitive slack"; Schweickert, 1978) and a subsequent increase in RTs.

The response selection bottleneck model allows clear predictions of interactions of SOA with other experimental factors influencing different stages of information processing, as expressed in the "locus-of-slack" logic (McCann & Johnston, 1992; see Figure 1). Because these predictions have been described in more detail elsewhere (Lien & Proctor, 2002; Pashler, 1994), we will remain brief here. First, the impact of factors located before the bottleneck of Task 2 is reduced with very short SOAs, because a slowing of prebottleneck processes occurs during the waiting period of Task 2 and thus does not increase RT (cf. Figure 1). Hence, an underadditive interaction of prebottleneck manipulations with SOA ensues. Second, factors affecting the bottleneck stage of Task 2 itself cannot be absorbed into the slack and thus impact RTs at all SOAs to a similar extent, thereby producing an effect additive to SOA. Third, the influence of factors located at or before the bottleneck in Task 1 fully propagates to Task 2, given sufficient task overlap. Fourth, any influences on processes after the bottleneck in Task 1 will not appear in Task 2. Applying this logic to effect-based compatibility effects leads to the following predictions: If the activation of effect codes affects the response selection stage, influences of effect-based compatibility should (a) be additive to SOA when manipulated in Task 2 and (b) fully propagate to Task 2 when manipulated in Task 1. If an activation of effect codes affects processes before response selection, compatibility effects in Task 2 should be diminished or absent at short SOAs. If an activation of effect codes affects processes after response selection, compatibility effects in Task 1 should not propagate to Task 2.

We tested these assumptions for both endogenously and exogenously activated effect codes in five dual-task experiments. The goal of Experiments 1–3 was to scrutinize the locus of an endogenous activation of effect codes. In Experiments 1 and 2, we varied the R-E compatibility between responses and contingent postresponse effects in Task 2 (see Table 1). In Experiment 1, responses and effects overlapped on the physical dimension of intensity, whereas Experiment 2 replicated Experiment 1 with an abstract form of R-E compatibility. In Experiment 3, we reversed the order of Task 1 and Task 2 to exclude effects related to the initiation or execution of the responses. Experiments 4 and 5 extend the findings to exogenously activated effect codes according to the induction logic. In Experiment 4, effectlike stimuli were presented prior to the response, and we varied the compatibility between perceptually stimulated effects and effects produced by afforded responses. Finally, in Experiment 5 we varied both the compatibility of postresponse effects with the responses and the stimuli, which allowed us to examine the locus of an exogenous as well as an endogenous activation of effect codes within a single experiment.

Experiment 1

The purpose of Experiment 1 was to localize the influence of R-E compatibility between responses and forthcoming (hence endogenously activated) response effects. Participants performed two choice reaction tasks. First, they responded to a high or low tone with a left or right keypress using the index or middle finger of the left hand. The crucial manipulation was applied in Task 2. Here, participants responded to a visually presented letter with either a soft or

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[1] Although other theoretical accounts differ regarding the explanation of the bottleneck (e.g., assume a graded capacity sharing between both tasks; Navon & Miller, 2002; Tombu & Jolicoeur, 2003), they do not differ regarding the prediction for interactions of the PRP effect with other experimental factors (for a discussion, see Miller & Reynolds, 2003)

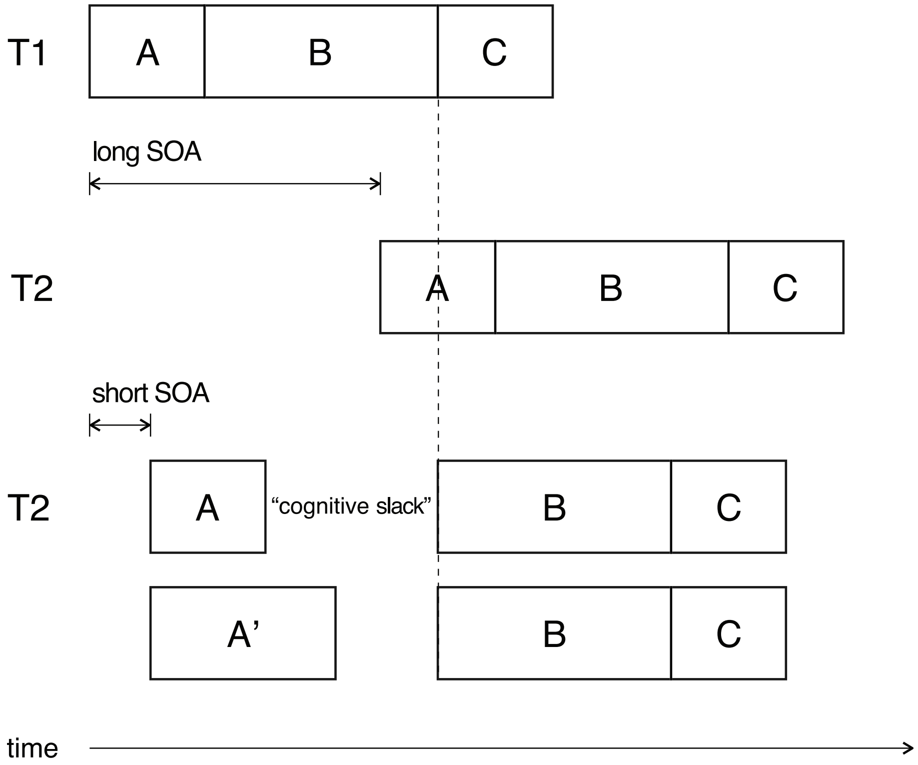

Figure 1. The "locus-of-slack" logic. Response selection represents the bottleneck (Stage B); with high processing overlap, response selection in Task 2 (T2) does not start until response selection in Task 1 (T1) is finished. Processes before and after the bottleneck (A, C) can proceed in parallel. With short stimulus onset asynchrony (SOA), manipulations of Task 2 processes before response selection (A') are absorbed into the emerging "slack."

Table 1
Overlapping Dimensions of Stimuli, Responses, and Response-Contingent Action Effects Used in Experiments 1–5.

Experiment	Task	Stimuli	Responses	Action effects
1	2		Force	Intensity
2	2		Color	Color
3	1		Force	Intensity
4[a]	2	Size		Size
5	2	Frequency	Duration	Frequency and duration

[a] Test phase.

a forceful keypress using the index finger of the right hand. These responses produced auditory effects that, in different blocks, were either compatible with the response (soft keypress– quiet tone, forceful keypress–loud tone) or incompatible (soft keypress– loud tone, forceful keypress– quiet tone). We expected this manipulation to produce influences of R-E compatibility sizable enough to allow for some variation with SOA.

A further manipulation was included in Experiment 1 as a type of control variable: In Task 2, the stimuli were either masked or unmasked. According to previous research, we should obtain an effect of masking that is underadditive with SOA (Pashler & Johnston, 1989). This would reassure us that the present paradigm was not exceptional in any important respect.

To summarize, our expectations were as follows: First, RTs of Task 2 should be prolonged at short SOA (the PRP effect). Second, masking should exert an influence that is underadditive with SOA. Third, responses should be slower with forthcoming incompatible effects than with compatible effects (R-E compatibility effect). Fourth, if R-E compatibility effects are located at the response selection bottleneck, they should be additive to the SOA.

Method

Participants. Forty-eight undergraduates participated either in fulfillment of course credit requirements or for a payment of €6 (∼U.S.$8). They were not familiar with the purposes of the experiment. Apparatus and stimuli. Stimulus presentation and data collection were controlled by an IBM-compatible PC and a 17-in. VGA display. Viewing distance was approximately 60 cm. Manual responses (Task 1) were executed with the index and middle fingers of the left hand on two external keys, with the key midpoints separated by approximately 30 mm. Responses of varying force (Task 2) were executed with the index finger of the right hand on a pressure-sensitive response key. The response force was measured in a range from 0 cN to 3,000 cN, with the maximum force of 3,000 cN depressing the plate by approximately 0.5 mm. The response force was sampled by the computer at a rate of 500 Hz. Participants were instructed to rest the index finger on the key registered as permanent force of 20–200 cN. Responses to stimuli were to be either soft ($<$ 800 cN) or forceful ($>$ 800 cN) presses of brief duration. RT was defined as the interval between stimulus onset and the point in time at which the response force was above 200 cN. The peak force was registered when the response force was equal to or lower than any force within the past 8 ms.

Stimuli of Task 1 (the pitch discrimination task) were computergenerated sinus tones (300 or 900 Hz, 56 ms duration) preceded by a warning click (500 Hz, 20 ms). Stimuli of Task 2 (the letter discrimination task) were the letters *H* and *S*. Letters were 15 mm in height and were presented in the center of the screen within a circle (30 mm diameter). In half of the trials, the letters were masked with an *X* (15 mm in height). All visual stimuli were presented in white on a gray background. Response effects of Task 2 were quiet (65 dB) or loud (78 dB) tones (300 Hz) presented by two loudspeakers positioned on the left and on the right of the pressure-sensitive response key (right of body midline). Loudness rose and decayed over 500 ms, resulting in the impression of a gong sound.

Design and procedure. The experiment consisted of a single session lasting approximately 50 min, containing six blocks separated by short rests. A block consisted of 64 trials that resulted from the combination of the factors stimulus in Task 1 (high or low tone), stimulus in Task 2 (letter *H* or *S*), masking of stimulus in Task 2 (masked or nonmasked), and SOA between the two stimuli (80, 150, 400, or 1,500 ms); trials were repeated once and presented in random order. Aggregated over stimuli and blocks, the 16 combinations of SOA, masking, and R-E compatibility consisted of 24 trials each. R-E compatibility was varied between blocks. After the first three blocks, the mapping of responses and effects was switched. The mapping of stimuli and responses as well as the order of compatible and incompatible R-E mappings was randomly chosen for the participants and balanced between them.

Each trial began with a warning click. Following an interval of 500 ms, a low-pitched or high-pitched tone was presented. After one of the four SOAs, the letter H or S was presented for 500 ms. Participants first had to respond to the tone with a keypress using the index or middle finger of the left hand and then had to respond to the letter with either a soft or a forceful keypress using the right index finger. Immediately after the response force peaked, a response effect (the gong sound) was presented. With a compatible R-E mapping, a loud gong sound followed a forceful response and a quiet gong sound followed a soft response. With an incompatible mapping, the R-E mapping was reversed. In the case of a response omission or error in one of the two tasks or the wrong order of responses, participants received a compatible feedback message. If no response was registered within 5,000 ms, the trial was aborted. The next trial began after an intertrial interval of 2,000 ms.

Participants were explicitly instructed to respond first to the tone and then to the letter as fast as possible without making too many errors. After 32 practice trials without response effects, participants were informed that in the following experiment every press on the pressure-sensitive response key would produce a tone of varying intensity. Participants were again instructed to respond as fast as possible without making too many errors, regardless of the correspondence between responses and subsequent effects.

Results

RTs. All trials with omissions or errors in one of the two tasks or the wrong order of responses (9.1% of responses) were eliminated from RT analyses. The remaining trials were screened for outliers separately for each SOA × Masking × R-E compatibility condition and participant. Outlier elimination for this and all subsequent experiments was based on the nonrecursive shifting z-score procedure by Selst and Jolicoeur (1994) using an SPSS syntax by Thompson (2006). In total, 4.8% of correct responses across all participants in Experiment 1 were identified as outliers. The mean RTs of the remaining trials were entered into an analysis of variance (ANOVA) for repeated measures with within-subject variables SOA (80, 150, 400, or 1,500 ms), masking of stimulus in Task 2 (masked or nonmasked), and R-E mapping (compatible or incompatible). Where necessary, p values were Greenhouse-Geisser corrected.

Task 1. The mean RT in Task 1 (RT1) increased monotonously with reduction of SOA, $F(3,141) = 20.73$, $p < .001$. RT1s were 8 ms higher with masked stimuli in Task 2, $F(1,47) = 4.93$, $p = .04$. This cross-talk effect, which was numerically present only at short SOAs (cf. Figure 2), possibly indicates a simultaneous degradation of perceptual processing (Pashler, 1989). No other effects reached significance (all *p*s$>$ .25).

Task 2. The mean RT in Task 2 (RT2) increased monotonously with reduction of SOA, $F(3,141) = 700.93$, $p < .001$. RT2s were 14 ms higher with masked stimuli in Task 2, $F(1,47) = 13.71$, $p < .01$. This effect of masking decreased with reduction of SOA, $F(3,141) = 5.11$, $p < .01$, for the interaction of SOA and masking (see Figure 2). Ef-

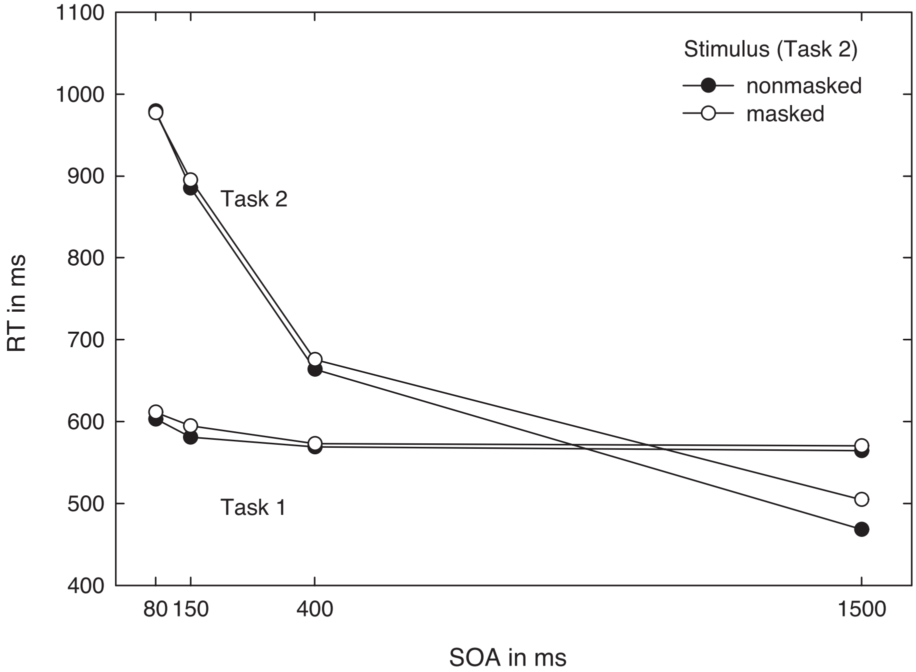

Figure 2. Mean reaction times (RTs) for Task 1 and Task 2 in Experiment 1 as a function of stimulus onset asynchrony (SOA) and stimulus masking.

fect sizes were –2, 10, 12, and 36 ms for 80-, 150-, 400-, and 1,500-ms SOAs, respectively.

RT2 was 45 ms higher with incompatible response effects than with compatible response effects, $F(1,47)$=11.75, $p < .01$. Of primary interest was the finding of no systematic interaction between SOA and R-E compatibility, $F(3,141)$=0.12; effect sizes were 41, 48, 46, and 46 ms for the four SOA levels (see Figure 3). No other effects reached significance (all ps> .29).

Error rates. The mean error rate in Task 1 (PE1) was 3.0%. PE1 increased monotonously with reduction of SOA, $F(3,141) = 4.92$, $p < .01$. Error rates were 3.6%, 3.1%, 3.1%, and 2.3% for 80-, 150-, 400-, and 1,500-ms SOAs. No other effects reached significance (all ps> .10).

The mean error rate in Task 2 (PE2) was 6.7%. There was a significant main effect of SOA, $F(3,141) = 29.70$, $p < .01$. PE2 rates were 3.5%, 4.0%, 4.8%, and 9.8% for 80-, 150-, 400-, and 1,500-ms SOAs. The high error rate at the longest SOA may be attributable to a speed–accuracy trade-off. No other effects reached significance (all ps> .20).

Discussion

Experiment 1 revealed several clear findings. First, there was a delay of RT2 when SOA decreased—hence, the expected PRP effect. Second, the effect of masking the Task 2 stimulus was underadditive with SOA, which replicates previous results on the interaction of factors affecting stimulus processing (Pashler & Johnston, 1989). Third, we found an R-E compatibility effect of comparable size to single-task conditions as reported by Kunde (2001). Most interesting, the influence of R-E compatibility was additive to SOA, which indicates that anticipated action effects do not exert their influence before the response selection bottleneck. This conclusion is also in accordance with the observed independence of stimulus masking and R-E compatibility, which, following the logic of additive factors (Sternberg, 1969), implies that these factors affect different processes.

However, a note of caution is in order regarding these inferences. Response selection processes for continuous, force-varying keypresses might differ from more ballistic, discontinuous responses like spatial keypresses or vocal responses typically used in choice reaction tasks. For that reason we wanted to replicate the additive influence of R-E compatibility to SOA with responses and effects overlapping on a more abstract dimension.

Experiment 2

The aim of Experiment 2 was to replicate Experiment 1 with responses and effects that overlapped on the conceptual feature of color (cf. Koch & Kunde, 2002). In Task 2, participants had to respond to a digit (*1*, *2*, *3*, or *4*) by saying a color word aloud (“blue,” “yellow,” “green,” or “pink”). Each vocal response immediately triggered the presentation of a color word (*blue*, *yellow*, *green*, or *pink*) in its corresponding color. Similar to Experiment 1, responses and effects were mapped either compatibly or incompatibly. For example, with a compatible mapping the vocal response “green” was predictably followed by the word *green* presented in green color. With an incompatible mapping, it would instead be followed by the word *red* presented in red. We expected to

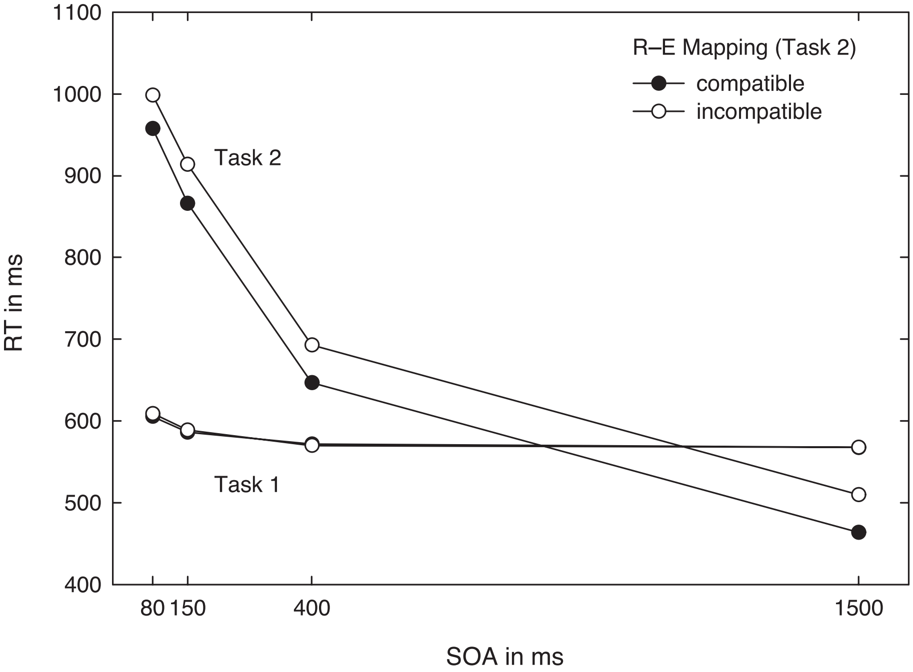

Figure 3. Mean reaction times (RTs) for Task 1 and Task 2 in Experiment 1 as a function of stimulus onset asynchrony (SOA) and response– effect (R-E) compatibility.

replicate the main result of Experiment 1, that is, additive effects of R-E compatibility and SOA.

Method

Participants. Forty-eight undergraduates participated either in fulfillment of course credit requirements or for payment of €8 (~U.S.$ 10.50). They were not familiar with the purposes of the experiment.

Apparatus and stimuli. Stimulus presentation and data collection were controlled by an IBM-compatible PC and a 17-in. VGA display. The viewing distance was approximately 60 cm. Manual responses (Task 1) were executed with the index and middle fingers of the right hand on a mouse connected to the parallel port of the computer. Vocal responses (Task 2) were recorded with a headset microphone that triggered a voice key. The identity of each response was registered by the experimenter after presentation of the response effects using the keyboard of the PC. The online coding of verbal responses allowed immediate error feedback. In Task 1 (the pitch discrimination task) the same stimuli were used as in Experiment 1. Stimuli of Task 2 (the digit discrimination task) were the digits *1*, *2*, *3*, and *4*. Digits were 15 mm in height and were presented in the center of the screen within a circle (30 mm diameter). In half of the trials, the digits were masked with an *X* (15 mm in height). All stimuli were presented in white on a gray background. The response effects of Task 2 were color words (the German words *gelb*, *grün*, *blau*, and *pink*, meaning yellow, green, blue, and pink), presented in their corresponding color. All words were presented in uppercase letters measuring approximately 45 mm in width and 15 mm in height in the bottom part of the screen.

Design and procedure. The experiment consisted of a single session lasting approximately 50 min, containing eight blocks separated by short rests. A block consisted of 64 trials, one for every possible combination of the following variables in a random sequence: stimulus in Task 1 (high or low tone), stimulus in Task 2 (digit *1*, *2*, *3*, or *4*), masking of stimulus in Task 2 (masked or nonmasked), and SOA between Task 1 and Task 2 (80, 150, 400, or 1,500 ms). Aggregated over stimuli and blocks, this resulted in 32 trials each for the 16 combinations of SOA, masking, and R-E compatibility. R-E compatibility was varied between blocks. After the first four blocks, the mapping of responses and effects was switched. The mapping of stimuli and responses as well as the order of compatible and incompatible mappings was randomly chosen for all participants and balanced between them.

Each trial began with the warning click followed by the low- or high-pitched tone. After one of the four SOAs, the digit *1*, *2*, *3*, or *4* was presented for 500 ms. Participants first had to respond to the tone with a mouse click using the index or middle finger of the right hand and then had to respond to the digit by saying a color word (“yellow,” “green,” “blue,” or “pink”). Immediately after the vocal response, the response effect was presented for 500 ms. With a compatible R-E mapping, a vocal response triggered the presentation of the color word identical to the color afforded by the digit. With an incompatible mapping, a color word different from the afforded response was presented.

In the case of a response omission or error in one of the two tasks or the wrong order of responses, participants received a corresponding feedback message. If no response was registered within 5,000 ms, the trial was aborted. The next trial began 2,000 ms after the experimenter specified the vocal response, resulting in a variable intertrial interval.

Participants were explicitly instructed to respond first to the tone and then to the letter as fast as possible without making too many errors. After 32 practice trials without response effects, participants were informed that in the following experiment every vocal response would trigger the presentation of a color word. Participants were again instructed to respond as fast as possible without making too many errors, regardless of the correspondence between responses and subsequent words.

Results

RTs. All trials with omissions or errors in one of the two tasks or the wrong order of responses (4.6% of responses) were excluded from RT analyses. In total, 5.0% of correct responses across all participants were identified as outliers according to the criteria described in Experiment 1. Mean RTs of the remaining trials were entered into an ANOVA for repeated measures with within-subject variables SOA (80, 150, 400 or 1,500 ms), masking of stimulus in Task 2 (masked or nonmasked), and R-E mapping (compatible or incompatible).

Task 1. RT1 increased monotonously with reduction of SOA, $F(3,141) = 35.14$, $p < .001$. The interaction of SOA × Masking of Stimulus in Task 2 × R-E Compatibility approached significance, $F(3,141) = 2.52$, $p = .06$. Post hoc Tukey honestly significant difference tests (with *p*s set at .10) revealed no pairwise comparison tending toward significance. Because we did not find similar effects in Experiment 1, we do not consider this a reliable interaction. No other effects reached significance (all *p*s> .33).

Task 2. RT2 increased monotonously with reduction of SOA, $F(3,141) = 229.16$, $p < .001$. RT2s were 21 ms higher with masked stimuli in Task 2, $F(1,47) = 18.02$, $p < .001$. This effect of masking increased with SOA, $F(3,141) = 4.77$, $p < .01$, for the interaction of SOA and masking (cf. Figure 4); effect sizes were 7, 4, 31, and 41 ms for 80-, 150-, 400-, and 1,500-ms SOAs. RT2 was 33 ms higher with incompatible response effects than with compatible response effects, $F(1,47) = 3.97$, $p < .05$. Of note, there was no alteration of the R-E compatibility effect across SOA, $F(3,141) = 0.55$ (cf. Figure 5). No other effects reached significance (all *F*s< 0.92).

Error rates. The mean error rate in Task 1 was 1.6%. PE1 increased monotonously with reduction of SOA, $F(3,141) = 12.71$, $p < .001$; error rates were 2.7%, 1.6%, 1.3%, and 0.9% for the 80-, 150-, 400-, and 1,500-ms SOAs. PE1 was 0.5% higher with masked stimuli in Task 2, $F(1,47) = 8.73$, $p < .01$. No other effects reached significance (all *p*s> .29).

The mean error rate in Task 2 was 3.4%. No effects reached significance (all *p*s> .23).

Discussion

The results of Experiment 2 closely mirror those of Experiment 1. We found a PRP effect as well as an influence of stimulus masking, which was diminished at the short SOAs. Furthermore, the influence of R-E compatibility, this time based on a conceptual overlap of responses and response effects, again was additive to SOA. This clearly supports the conclusion that R-E compatibility effects do not result from processes before the response selection bottleneck. However, we cannot rule out that there are effects located after the bottleneck that might account for the observed additivity with SOA. We therefore conceived another experiment to exclude any effects related to the initiation or execution of the responses.

Experiment 3

The aim of Experiment 3 was to test whether R-E compatibility effects are located at or after the response selection bottleneck. We changed the order of tasks of Experiment 1 and moved the manipulation of R-E compatibility to Task 1. We had two expectations (as noted earlier in the *Design and Rationale* section): First, responses in Task 1 should be slower with forthcoming incompatible effects than with compatible effects, independent of SOA.

Second, if the activation of effect codes does indeed start at the response selection stage, effects of R-E compatibility in Task 1 should fully propagate to Task 2 at sufficiently short SOAs. However, if the activation of effect codes occurs after response selection (i.e., during response initiation or execution), effects of R-E compatibility in Task 1 should be diminished or absent in Task 2.

Method

Participants. Twenty-four undergraduates participated either in fulfillment of course credit requirements or for payment of €6 (∼U.S.$8). They were not familiar with the purposes of the experiment.

Apparatus and stimuli. The same apparatus was used as in Experiment 1. Responses of varying force (Task 1) were executed with the index finger of the right hand on a pressure-sensitive response key. Manual responses (Task 2) were executed with the index, middle, and ring finger of the left hand on three external keys, with the key midpoints separated by approximately 30 mm. The stimuli in Task 1 (the pitch discrimination task) were the same as in Experiment 1. Stimuli of Task 2 (the color discrimination task) were circular colored dots (yellow, green, and blue). The dots (45 mm in diameter) were presented in the center of the screen on a gray background. Response effects of Task 1 were the tones used as response effects in Task 2 of Experiment 1.

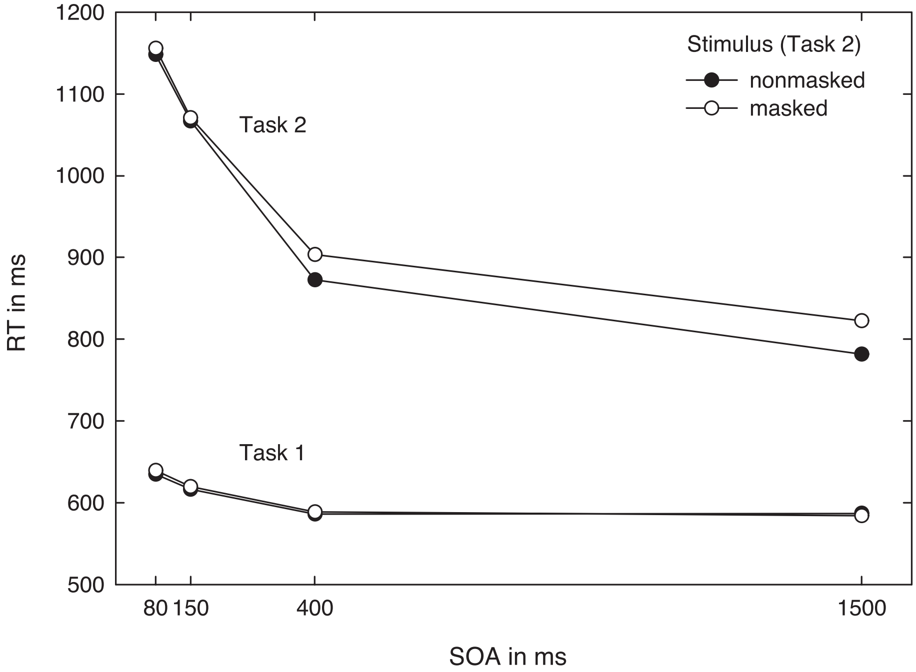

Figure 4. Mean reaction times (RTs) for Task 1 and Task 2 in Experiment 2 as a function of stimulus onset asynchrony (SOA) and stimulus masking

Design and procedure. The experiment consisted of a single session lasting approximately 50 min, containing eight blocks separated by short rests. A block consisted of 48 trials that resulted from the combination of the factors stimulus in Task 1 (high or low tone), stimulus in Task 2 (yellow, green, or blue dot), and SOA between the two stimuli (80, 150, 400, or 1,500 ms), which were repeated twice and presented in random order. Aggregated over stimuli and blocks, the six combinations of SOA and R-E compatibility consisted of 64 trials each. R-E compatibility was varied between blocks. After the first four blocks the mapping of responses and effects was switched. The mapping of stimuli and responses as well as the order of compatible and incompatible R-E mappings was randomly chosen for the participants and balanced between them.

Each trial began with the warning click followed by the lowpitched or high-pitched tone. After one of the four SOAs the color dot was presented for 500 ms. Participants first had to respond to the tone with a soft or forceful keypress using the right index finger and then had to respond to the color dot with a keypress using the index, middle, or ring finger of the left hand. Immediately after the response force peaked, a gong sound was presented. With a compatible R- E mapping, a loud tone followed a forceful response and a quiet tone followed a soft response. With an incompatible mapping, the R-E mapping was reversed. In the case of a response omission or error in one of the two tasks or the wrong order of responses, participants received a corresponding feedback message. If no response was registered within 5,000 ms, the trial was aborted. The next trial began after an intertrial interval of 2,000 ms.

Participants were explicitly instructed to respond first to the tone and then to the color dot as fast as possible without making too many errors. After 24 practice trials without response effects, participants were informed that in the following experiment, every press on the pressure-sensitive response key would produce a tone of varying intensity. Participants were again instructed to respond as fast as possible without making too many errors, regardless of the correspondence between responses and subsequent tones.

Results

RTs. All trials with omissions or errors in one of the two tasks or the wrong order of responses (7.6% of responses) were excluded from RT analyses. In total, 4.8% of correct responses across all participants were identified as outliers according to the criteria described in Experiment 1. Mean RTs of the remaining trials were entered into an ANOVA for repeated measures with within-subject variables SOA (80, 150, 400, or 1,500 ms) and R-E mapping (compatible or incompatible).

Task 1. The mean RT in Task 1 increased monotonously with reduction of SOA, $F(3,69) = 4.66$, $p = .02$. RT1s were 43 ms higher with incompatible response effects than with compatible response effects, $F(1,23) = 5.85$, $p = .02$ (see Figure 6). The interaction of both factors was far from significance, $F(3,69) = 0.18$.

Task 2. The mean RT in Task 2 increased monotonously with reduction of SOA, $F(3,69) = 183.06$, $p < .001$. RT2 was 63 ms higher with incompatible response effects than

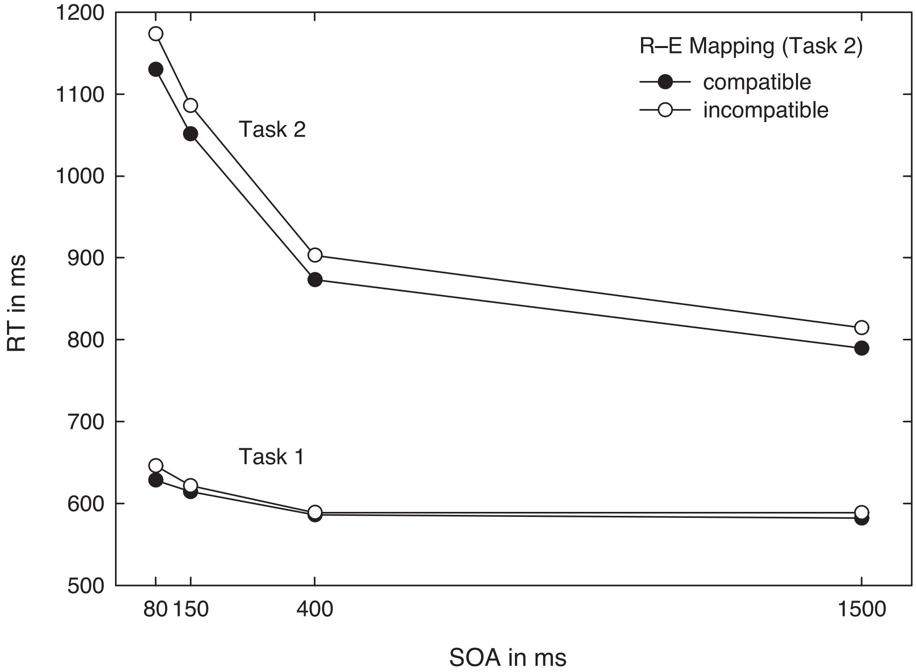

Figure 5. Mean reaction times (RTs) for Task 1 and Task 2 in Experiment 2 as a function of stimulus onset asynchrony (SOA) and response– effect (R-E) compatibility.

with compatible response effects in Task 1, $F(1,23) = 5.99$, $p = .02$ (see Figure 6). The interaction of both factors did not reach significance, $F(3,69) = 1.27$, $p = .29$. Of primary interest, the influence of R-E compatibility did not differ in effect size for both tasks, $F(1,23) = 1.81$, $p = .19$. Except at the longest SOA, effects were numerically even larger in Task 2 than in Task 1; that is, with sufficient temporal overlap, effects of Task 1 did fully propagate to Task 2.

Error rates. The mean error rate in Task 1 was 4.6%. No effect reached significance (all ps$>$ .23). The mean error rate in Task 2 was 3.7%. There was a significant main effect of SOA, $F(3,69) = 5.76$, $p < .01$. PE2s were 3.1%, 2.7%, 3.9%, and 5.1% for 80-, 150-, 400-, and 1,500-ms SOAs. No other effects reached significance (all ps$>$ .20).

Discussion

The main findings of Experiment 3 show that when R-E compatibility was manipulated in Task 1, effects of comparable size to Task 1 also occurred in Task 2, although there was no dimensional overlap of stimuli or responses between both tasks. The effect propagation from Task 1 to Task 2 indicates that the processes influenced by anticipated action effects are completed before the response selection bottleneck is released. Taken together with Experiment 1 and 2, these results support the idea that R-E compatibility effects arise entirely during the response selection bottleneck.

Experiment 4

As explained in the introduction, there is a second approach to studying the role of action effects in response production, namely, the induction paradigm. Experiment 4 investigated whether the same inferences about endogenously activating effect codes obtained from Experiments 1–3 can apply to exogenously stimulated effect codes. For this purpose, we used an induction task as Task 2 in the PRP paradigm.

The experiment was divided into a learning phase and a test phase (see, e.g., Elsner & Hommel, 2001; Hommel, 1996). In the learning phase, the participants were required to respond to a neutral stimulus with a freely chosen keypress with the index or middle finger of the right hand. Each response was contingently followed by certain visual effects. For example, a keypress with the index finger triggered a small circle, whereas a keypress with the middle finger triggered a large circle filling the whole screen. Theories of action-effect learning (e.g., Elsner & Hommel, 2001) predict that motor patterns producing a particular effect become automatically integrated with the cognitive codes of their resulting effects. Accordingly, in our example, keypresses with the right index finger should now be associated with small circles, and keypresses with the right middle finger, with large circles.

The test phase was similar to Experiments 1 and 2 in that two choice reaction tasks were combined into a PRP paradigm. Task 1 was the familiar pitch discrimination task. In Task 2, the participants had to respond to the border color of a circle with the index and middle fingers of the right hand.

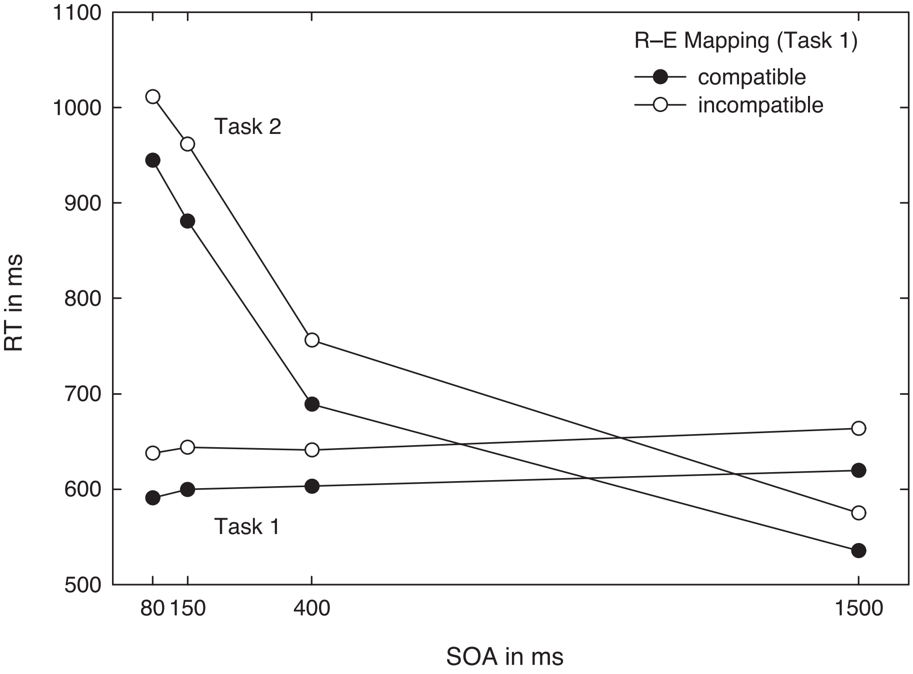

Figure 6. Mean reaction times (RTs) for Task 1 and Task 2 in Experiment 3 as a function of stimulus onset asynchrony (SOA) and response–effect (R-E) compatibility

Of crucial importance was that the size of the circle was identical to the response effects of the learning phase. As circle size varied independently of border color, we varied the compatibility between the stimulated response effects and the response effects associated with the actual responses signaled by the border color—hence, stimulus– effect (S-E) compatibility. For example, in a compatible trial a small circle with a red border afforded a keypress with the index finger, which in the learning phase triggered the presentation of a small circle. With a small circle and a green border, however, an incompatible trial resulted, because now a keypress with the right middle finger was signaled, which produced a large circle.

Externally stimulated response effects are generally assumed to influence response selection processes. Therefore, we expected a result similar to those of Experiments 1 and 2, that is, the resulting S-E compatibility effect should be additive to SOA.

Method

Participants. Forty-eight undergraduates participated either in fulfillment of course credit requirements or for payment of €6 (∼U.S.$8).[2] They were not familiar with the purposes of the experiment.

Apparatus and stimuli. Stimulus presentation and data collection were controlled by an Apple iMac with integrated 15-in. VGA display using PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993). The viewing distance was approximately 60 cm. Manual responses were executed with the index and middle fingers of the left and right hands using the keyboard response keys A or S and 5 or 6 of the numeric keypad, respectively. The neutral stimulus to trigger the free response in the learning phase and the fixation cross in the test phase was a centrally presented plus sign (12 mm in height). The stimuli of Task 1 (the pitch discrimination task) were the same tones as in Experiment 1. The stimuli of Task 2 (the color discrimination task) were small or large white circles (10 mm and 190 mm in diameter) with a red or green border (5 mm) presented in the center of the screen. The response effects were small or large white circles (10 mm and 190 mm in diameter) with a gray border (5 mm) presented in the center of the screen. All visual stimuli were presented on a black background.

Design and procedure. Each experimental session was divided into a learning phase and a test phase. Blocks within both phases were separated by short rests.

Learning phase. The learning phase consisted of four blocks of 50 trials each. All trials started with the plus sign presented for 200 ms. Participants were instructed to respond after the plus sign with a freely chosen keypress using the index or middle finger of the right hand. Each keypress triggered the presentation of a circle for 200 ms starting 50 ms after the onset of the keypress. The mapping of responses and effects was randomly chosen for participants and bal-

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[2] A total of 5 participants had to be excluded, as they did not follow the instruction in the acquisition phase and responded with either repetitive patterns (4 participants) or a highly unbalanced response ratio of left-to-right keypresses (1 participant). Their data were replaced by those of 5 new participants.

anced between them. For half of the participants, a keypress with the index finger triggered a small circle, and a keypress with the middle finger, a large circle. For the other half of the participants this mapping was reversed. If participants responded before the onset of the plus sign, an error message was displayed and the trial was restarted. The next trial began after an intertrial interval of 1,500 ms. After each block, visual feedback was presented displaying the total response count so far. Participants were explicitly instructed to use both keys in random order with roughly equal frequency. The experimenters pointed out that exclusively pressing one key was not acceptable. Participants were informed that every keypress would trigger the presentation of a small or large circle on the screen. They were told that they should recall the relation between keypresses and appearance of the circles during the experiment. Participants completed 8 practice trials and 200 learning trials in total.

Test phase. The test phase consisted of two blocks of 64 trials. To obtain a reasonable number of trial repetitions per factor combination with a trial number in the range of previous induction studies, we reduced the number of SOAs and left out the masking of stimulus in Task 2. Within each block, every combination of the following variables was presented four times in a random sequence: stimulus in Task 1 (low or high tone), color of stimulus in Task 2 (red or green border), size of stimulus in Task 2 (small or large diameter), and SOA (50 or 1,500 ms). Aggregated over tone, circle size, and blocks, this resulted in 32 repetitions for the four possible combinations of SOA and S-E compatibility.

Each trial began with the plus sign presented as a fixation point for 200 ms, followed by the tone. After one of the two SOAs a small or large circle with a red or green border was presented for 500 ms. Participants first had to respond to the tone using the index or middle finger of the left hand and then had to respond to the color of the circle border using the index or middle finger of the right hand. For half of the participants, each right-hand keypress triggered the same response effects as in the learning phase (i.e., a small or large circle with a gray border). For the other half of the participants, no response effects were presented in the test phase.[3] In the case of a response omission or error in one of the two tasks, or when the wrong order of responses was given, participants received a corresponding feedback message. The next trial began after an intertrial interval of 2,000 ms.

Participants were explicitly instructed to respond first to the tone and then to the color of the circle border. They were told to consider the size of the circles irrelevant and to respond as fast as possible without making too many errors. Participants completed 32 practice trials followed by 128 test trials.

Results

Learning phase. In total, 4.3% of the responses were excluded from analyses as outliers. The mean number of responses using the index versus middle finger did not differ (index finger, $M = 95.7$; middle finger, $M = 95.9$; sign test $Z = .15$, $p = .88$). The mean RT was 410 ms and did not differ between the two responses (408 ms and 413 ms for index and middle finger), $t(47) = 0.87$, $p = .39$.

Test phase. Trials with omissions or errors in one of the two tasks or the wrong order of responses (7.6%) were eliminated from RT analyses. In total, 4.1% of correct responses across all participants were identified as outliers using the criteria described in Experiment 1. The mean RTs of the remaining trials were submitted to an ANOVA for repeated measures with within-subject variables SOA (50 or 1,500 ms) and S-E compatibility (compatible or incompatible).

RTs. The RTs in Task 1 and Task 2 are displayed in Figure 7. RT1 increased with reduction of SOA, $F(1,47) = 11.35$, $p = .01$. No other effects reached significance (all ps$> .19$). RT2 increased with reduction of SOA, $F(1,47) = 784.18$, $p = .001$. RT2 was 24 ms higher with incompatible stimuli than with compatible stimuli, $F(1,47) = 4.64$, $p = .04$. Most interesting, there was an interaction between SOA and S-E compatibility, $F(1,47) = 4.86$, $p = .03$, indicating an influence of S-E compatibility with long SOA (51 ms) but not with short SOA (–4 ms).

Error rates. The mean error rate in Task 1 was 4.4%. PE1 increased with reduction of SOA, $F(1,47) = 22.31$, $p < .001$; error rates were 5.6% and 3.1% for 50- and 1,500-ms SOAs. No other effects reached significance (all Fs< 0.87). The mean error rate in Task 2 was 3.4%. No effect reached significance (all ps$> .17$).

Discussion

In Experiment 4 we aimed to complement the preceding experiments by using the induction paradigm. We found an influence of compatibility governed by perceived action effects, that is, faster responding with a stimulus that mirrored the action effect of the required response than with a stimulus that mirrored the action effects of an alternative response. However, this S-E compatibility influence differs from the R-E compatibility effect with regard to its relationships to SOA: It was underadditive with SOA. So, following the locus-of-slack logic, the S-E compatibility exerts its impact prior to the response selection bottleneck.

Before discussing this result in more detail, it is necessary to consider two alternative explanations. First, it could be argued that the stimulated effect codes decay quickly over time and therefore have less chance to affect the motor system the later the response is emitted (i.e., with high RTs at a short SOA). Such a time course has been found for the irrelevant spatial codes in the Simon task (De Jong, Liang, & Lauber, 1994; Eimer, Hommel, & Prinz, 1995; Ridderinkhof, 2002) and has been used to explain the underadditive interaction of the Simon effect and the PRP effect (McCann & Johnston,

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[3] This manipulation was initially included to test for an extinction of response–effect associations in the test phase. However, because it turned out that in all analyses computed subsequently this manipulation was entirely ineffective, we report only the data collapsed across both groups.

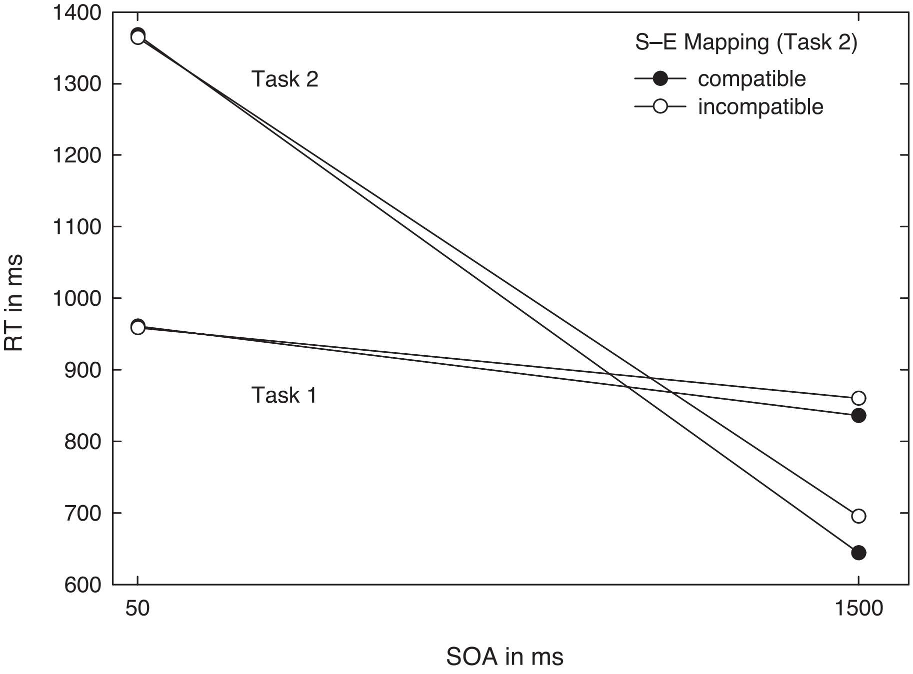

Figure 7. Mean reaction times (RTs) for Task 1 and Task 2 in Experiment 4 as a function of stimulus onset asynchrony (SOA) and stimulus– effect (S-E) compatibility.

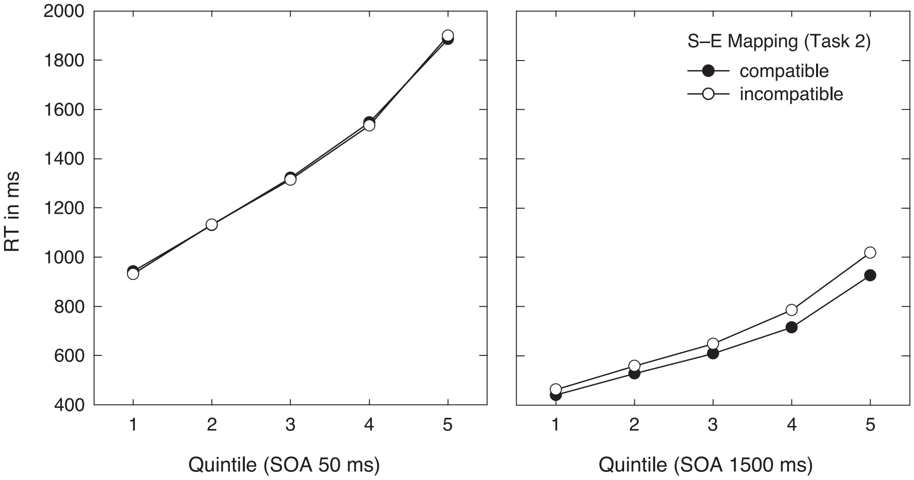

Figure 8. Mean reaction time (RT) quintiles for Task 2 in Experiment 4 as a function of stimulus onset asynchrony (SOA) and stimulus– effect (S-E) compatibility.

1992; but see Lien & Proctor, 2000). It therefore seems necessary to consider that decay of stimulated effect codes could also account for the present underadditive effect.

However, a closer examination of the temporal dynamics of the present compatibility effect indicated no decay of effect code activation at all. In fact, S-E compatibility effects increased significantly with increasing RT—$F(4, 188) = 4.02$, $p = .02$, for the interaction of S-E compatibility effect and RT quintile—which is also consistent with similar time courses in a previous study on action induction (Hommel, 1996). As can be seen in Figure 8 , with comparable RTs, the effect was clearly present at long SOA but absent at short SOA. Post hoc quintile analyses may not completely rule out decay of effect codes, but without additional assumptions, decay does not appear to be a plausible explanation of the present results.

A second alternative explanation is based on backward compatibility between responses at short SOA (see, e.g., Hommel, 1998. Because both tasks afford left–right responses, an activation of a response in Task 2 by perceived response effects might prime the corresponding response in Task 1. Given that this activation is actively eliminated for both tasks after the response is selected in Task 1 but before response selection in Task 2 starts (Logan & Gordon, 2001), any priming by perceived response effects might be eliminated in Task 2 at short SOA. Instead, we should find faster responses in Task 1 with stimuli resembling the response effects of the corresponding response in Task 2. Yet this was not the case: $F(1,47) = 0.78$ for the main effect of backward compatibility on RT1; $F(1,47) = 0.13$ for the interaction of backward compatibility and SOA. Nevertheless, in Experiment 5 we eliminated any possibility for backward compatibility between both responses by using tasks without any dimensional overlap.

Experiment 5

Experiment 4 revealed an important difference between anticipated (endogenously activated) and stimulated (exogenously activated) effect codes: Whereas the anticipation of effect codes starts during the response selection bottleneck, stimulated effect codes seem to influence processes before the response selection bottleneck. However, one must be cautious with drawing inferences across experiments because there may be confounding differences in the methods or stimuli used. For instance, in Experiment 4 we had to limit the number of SOAs to get a reasonable number of trial repetitions as compared with Experiments 1–3. The number and distribution of SOAs are known to influence task-scheduling strategies of participants (Miller, Ulrich, & Rolke, in press).

With Experiment 5 we therefore aimed to replicate the dissociations found between stimulated and anticipated response effects in a single experiment. The manipulation of R-E and S-E compatibility again took place in Task 2 (cf. Table 1). Participants had to respond to a left or right tone with keypresses of long or short duration. Each response immediately triggered the presentation of a tone of long or short duration. Responses and effects were mapped either compatibly or incompatibly. For example, with a compatible mapping, the long keypress predictably produced a long tone. With an incompatible mapping, it would instead produce a short tone. Similar to Experiments 1 and 2, we expected slower responses with forthcoming incompatible effects than with compatible effects (temporal R-E compatibility; Kunde, 2003, independent of SOA.

To manipulate the compatibility between stimuli and response effects, the tones used as stimuli and responses also varied in their frequency. Frequency of response effect tones was related consistently to their duration; for example, short tones were always of low frequency and long tones of high frequency. The frequency of stimuli, however, varied randomly from trial to trial, thereby producing S-E compatible trials, in which stimulus and response effect tones were of the same frequency, and S-E incompatible trials, in which stimulus and response effect tones were of different frequency. Similar to Experiment 4, we expected slower responses with incompatible than with compatible stimulus and effect tones (S-E compatibility; see, e.g., Hommel, 1996, but confined to the long SOAs only.

Method

Participants. Forty-eight undergraduates participated either in fulfillment of course credit requirements or for payment of €6 (∼U.S.$8). They were not familiar with the purposes of the experiment.

Apparatus and stimuli. Stimulus presentation and data collection were controlled by an Apple Power Mac G3 and a 19-in. VGA display using PsyScope (Cohen et al., 1993). The viewing distance was approximately 60 cm. Vocal responses (Task 1) were recorded with a microphone that triggered a voice key. The identity of each response was registered by the experimenter after presentation of the response effects using an external button box. Manual responses (Task 2) were executed with the index finger of the right hand on a single external key, positioned centrally in front of the participants. Keypresses were to be either of short duration (release of the key less than 200 ms after pressing the key) or long duration (release of the key between 200 ms and 500 ms after pressing the key). RT was defined as the interval between stimulus onset and pressing of the key.

Stimuli of Task 1 (the letter discrimination task) were the letters *H* and *S* preceded by a centrally presented *plus* sign. The letters and the sign were 15 mm in height and were presented in the center of the screen on a black background. Stimuli of Task 2 (the tone discrimination task) were sinus tones (300 or 900 Hz) of medium duration (250 ms), which were presented through one of two loudspeakers positioned left and right of the display. The response effects were sinus tones (300 or 900 Hz) of short or long duration (125 or 400 ms) presented through both loudspeakers.

Design and procedure. The experiment consisted of a single session lasting approximately 50 min, containing six blocks separated by short rests. A block consisted of 64 trials that resulted from the combination of the factors stimulus in Task 1 (letter *H* or *S*), location of stimulus in Task 2 (left or right speaker), frequency of stimulus in Task 2 (300 or 900 Hz), and SOA between the two stimuli (80, 150, 400, or 1,500 ms), which were repeated twice and presented in random order. Aggregated over stimuli and blocks, the 16 combinations of SOA, R-E compatibility, and S-E compatibility consisted of 24 trials each. R-E compatibility was varied between blocks. After the first three blocks the mapping of responses and effects was reversed. The mapping of stimuli and responses and of responses and effects, as well as the order of compatible and incompatible R-E mappings, was randomly chosen for the participants and balanced between them.

Each trial began with a plus sign presented as a fixation point for 200 ms, directly followed by a letter (200 ms). After one of the four SOAs, the tone was presented for 250 ms. Participants first had to respond to the letter by saying a color word (the German word “rot” or “grün” for red or green). They then had to respond to the location of the tone with a keypress of long or short duration using the index finger of the right hand. Immediately after releasing the key, a response effect tone was presented. With a compatible R-E mapping, a long tone followed a long keypress and a short tone followed a short keypress. With an incompatible mapping, the R-E relation was reversed. To ensure a fixed intertrial interval, the experimenter had to specify the identity of the vocal response within 2,000 ms after presentation of the response effects. In the case of a response omission or error in one of the two tasks, or when the wrong order of responses was given, participants received a corresponding feedback message. The next trial began after an intertrial interval of 2,000 ms.

Participants were explicitly instructed to respond first to the letter and then to the tone as fast as possible without making too many errors. After 32 practice trials without response effects, participants were informed that in the following experiment, every press on the response key would produce a tone of varying duration and frequency. Participants were again instructed to respond as fast as possible without making too many errors, regardless of the correspondence between responses or stimuli and subsequent tones.

Results

RTs. All trials with omissions or errors in one of the two tasks or the wrong order of responses (8.2% of responses) were excluded from RT analyses. In total, 4.0% of correct responses across all participants were identified as outliers according to the criteria described in Experiment 1. Mean RTs of the remaining trials were entered into an ANOVA for repeated measures with within-subject variables SOA (80, 150, 400, or 1,500 ms), R-E mapping (compatible or incompatible), and S-E compatibility (compatible or incompatible).

Task 1. The mean RTs in Task 1 were 5 ms higher in S-E incompatible trials than in S-E compatible trials, $F(1,47) = 5.28$, $p = .03$. No other effects reached significance (all ps$= .12$).

Task 2. The mean RT in Task 2 increased monotonously with reduction of SOA, $F(3,141) = 387.34$, $p = .001$. RT2s were 8 ms higher in S-E incompatible than compatible trials, $F(1,47) = 5.85$, $p = .02$. This effect of S-E compatibility decreased with reduction of SOA, $F(3,141) = 3.05$, $p = .04$, for the interaction of S-E compatibility and SOA (see Figure 9); effect sizes were –2, 1, 12, and 21 ms for 80-, 150-, 400-, and 1,500-ms SOAs. RT2 was 31 ms higher with incompatible than with compatible R-E mapping, $F(1,47) = 4.35$, $p = .04$. Of note, there was no alteration of the R-E compatibility effect across SOAs, $F(3,141) = 0.62$ (cf. Figure 10).

We also examined the temporal dynamics of S-E compatibility effects to check whether decay of stimulated effect codes can account for the absence of any effects at short SOA (cf. discussion of Experiment 4). Quintile analyses indicated no decreasing effects with increasing RTs, $F(4,188) = 0.13$ for the interaction of S-E compatibility effect and RT quintile, with S-E compatibility effects numerically even increasing with increasing RTs.

Error rates. The mean error rate in Task 1 was 0.9% and therefore too low for a meaningful analysis. The mean error rate in Task 2 was 4.9%. No effects reached significance (all ps$> .07$).

Discussion

In Experiment 5 we aimed to replicate the specific interactions of SOA with R-E and S-E compatibility effects, respectively, found in Experiments 1, 2, and 4 within a single experiment. The results fully support our previous inferences. The influence of R-E compatibility was additive to SOA, therefore replicating Experiments 1 and 2. We also found an influence of perceived auditory action effects that was present only at the longest SOAs, therefore replicating Experiment 4. Furthermore, R-E and S-E compatibility effects did not interact at long SOA, supporting the idea that anticipated and stimulated response effects exert their influence at different time points during response preparation, that is, within and before the response selection bottleneck.

General Discussion

The purpose of the present study was to make a step forward toward reconciling IM and sensorimotor models of action control. We investigated whether the anticipation of an action's sensory consequences, which according to IM models mediates action generation, coincides with the response selection stage of sensorimotor models. We conducted five PRP experiments in which the compatibility between responses and sensorial response effects was varied. In Experiments 1–3 the manipulated response effects were presented only after the response was actually carried out. Conceivably, the ensuing compatibility effects are mediated by internally anticipated action effects. By contrast, in Experiments 4 and 5 action effects were also presented prior to the responses, and the ensuing compatibility effects were therefore caused by externally stimulated effect representations. With response-effect anticipation, compatibility effects corresponded to the response selection bottleneck, whereas with response-effect stimulation, compatibility effects were located before the bottleneck. We now discuss the implications of these results

Action Effects Are Anticipated During Response Selection

The interpretation of results is straightforward with anticipated response effects. The anticipation of action effects in action production occurs at a relative point in time that information processing theories denote as response selection. This result is generally consistent with existing effect-based models of action control (e.g., Hommel, 1997). However, our results lead us to scrutinize the impact of anticipatory effect codes in two respects. First, the additive influences of R-E compatibility to SOA in Experiments 1 and 2 suggest that an endogenous activation of effect codes does not start before stimulus processing is completed. This inference is corroborated by the additive relationship between effects

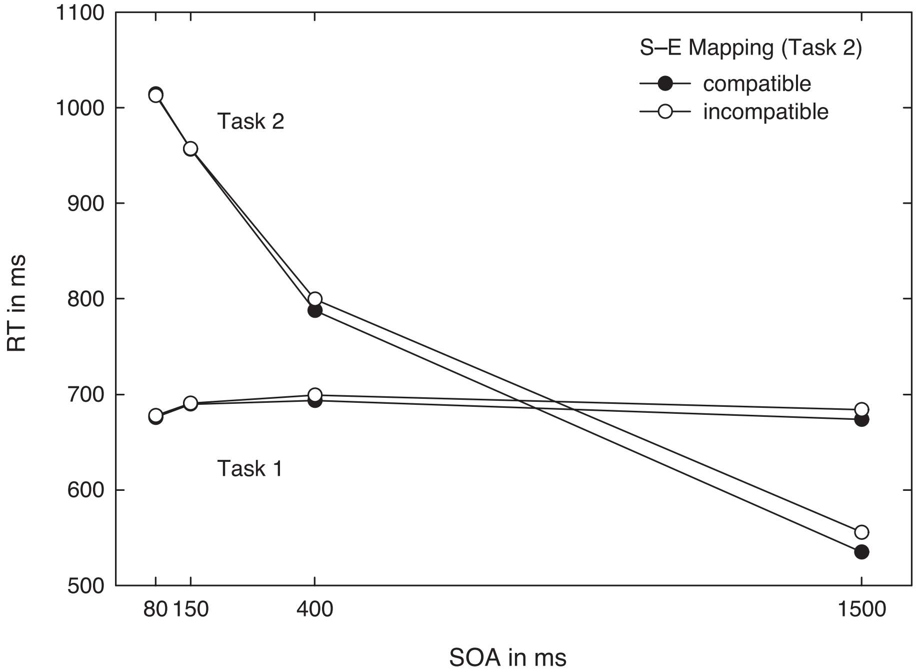

Figure 9. Mean reaction times (RTs) for Task 1 and Task 2 in Experiment 5 as a function of stimulus onset asynchrony (SOA) and stimulus– effect (S-E) compatibility.

of R-E compatibility and stimulus masking. Second, the full propagation of R-E compatibility effects from Task 1 to Task 2 in Experiment 3 further indicates that the activation of effect codes is completed before a response is initiated. These observations can be reconciled with an activation-accumulation model of R-E compatibility effects (Kunde, Koch, & Hoffmann, 2004), which assumes that relevant as well as irrelevant response effects are anticipated in parallel during response selection. Similar to comparable models of S-R compatibility effects (Kornblum, Hasbroucq, & Osman, 1990; Kornblum, Stevens, Whipple, & Requin, 1999), differences in RTs between compatible and incompatible R-E mappings are assumed to result from mutual priming or interference during the activation of dimensionally overlapping effect codes at this stage. In the case of compatible effects, the activation of irrelevant effect codes primes relevant effect codes, leading to faster buildup of code activation. With noncorresponding response effects the mutual priming is detrimental, in that to-be-inhibited movements become activated too, leading to a delay in activation of the requested response or the execution of an erroneous response.

If we assume that response selection in Task 1 also affords an endogenous activation of effect codes, our results further imply that this activation does proceed only serially for different responses and might thus constitute a major bottleneck in dual-task situations (see Greenwald, 1972; Greenwald & Shulman, 1973. This allows for some interesting predictions for future research on dual-task performance. For example, PRP effects might be reduced for responses that lead to similar rather than dissimilar effects, if the necessary activation of such codes in the first task could transfer to the selection of a response in the second task. Preliminary support for this claim stems from the observation that subjects were faster to prepare a response that produced an auditory effect when a concurrently prepared action predictably produced the same auditory effect (Kunde, Hoffmann, & Zellmann, 2002). Of interest, this correspondence influence was highest at the short SOA. A plausible interpretation of this pattern would be that a match of the effects of the two tasks reduces the PRP effect. Furthermore, when actors are actually forced to produce motor actions with both hands at the same time (bimanual coordination tasks), this is much easier when the concurrent actions aim at the same rather than different manipulatory effects (Hazeltine, 2005; Hazeltine, Diedrichsen, Kennerley, & Ivry, 2003; Kunde & Weigelt, 2005).

Action Induction Affects Processes Before Response Selection

The interpretation of results with an exogenous activation of effect codes is more challenging. In Experiments 4 and 5, an external stimulation of action effects yielded a significant underadditive interaction with the PRP effect. Given that decay of effect code activation, at least without additional assumptions, does not appear to be a very probable explanation of this result (cf. discussion of Experiment 4), it seems that externally stimulated effects do influence prebottleneck processes. There are two interpretations that in our view would be generally consistent with the data.

First, stimulated response-effect codes might impact stimulus processing instead of response selection. In the present instance of S-E compatibility, it could be that all events be-

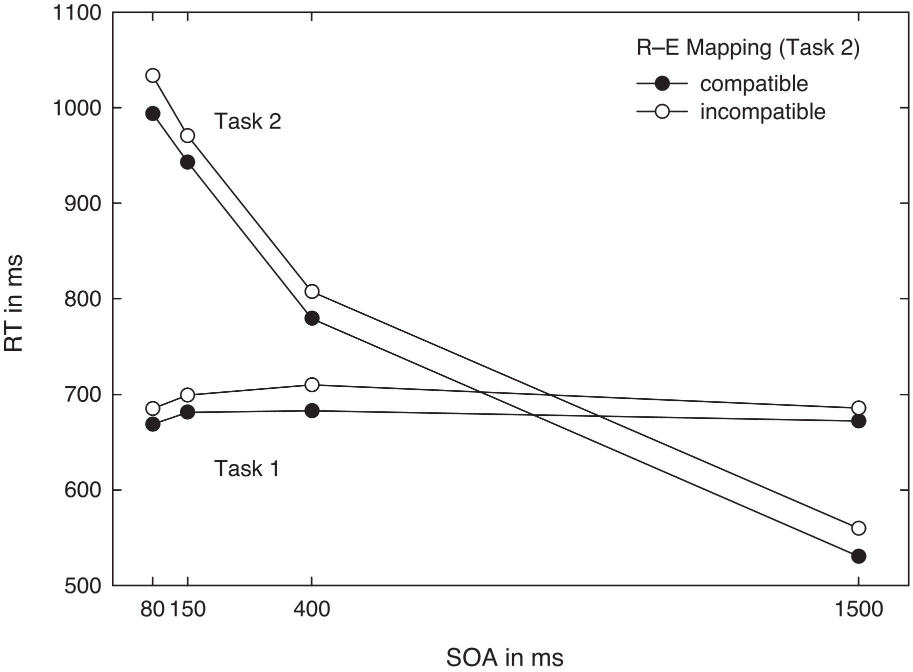

Figure 10. Mean reaction times (RTs) for Task 1 and Task 2 in Experiment 5 as a function of stimulus onset asynchrony (SOA) and response– effect (R-E) compatibility

longing to a certain response (e.g., its assigned stimulus feature and its response effect) become linked to each other. If such triple links among stimuli, responses, and effects existed, stimuli and response effects would prime each other mutually. To illustrate this, consider a compatible trial in the test phase of Experiment 4: A red stimulus color (the imperative signal for a left keypress) is presented concurrently with a large circle (the response effect of a left keypress). If direct links between stimulus color and response effects emerge, the perception of a large dot would prime the encoding of the color red. A compatible response effect would not only prime the corresponding response but also speed up the processing of the stimulus assigned to that response. By contrast, an incompatible effect would not benefit the encoding of the presented stimulus color but the color of the alternative response.

Given the empirical evidence against stimulus-based accounts in general (Hommel, 1995; Lu & Proctor, 1994) and neuropsychological findings on presupplementary motor area activation by perceived action effects in particular (Elsner et al., 2002), a pure stimulus-processing account seems unlikely. Yet a significant contribution of direct stimulus– effect links to S-E compatibility effects would have implications for the use of induction paradigms as a means to study effect-based action control. Those versions that combine imperative stimuli with action effects might overestimate the contribution of these effects to actual response selection compared with stimulus identification (Beckers, De Houwer, & Eelen, 2002; Drost, Rieger, Brass, Gunter, & Prinz, 2005; Hommel, 1996, 2004; Ziessler & Nattkemper, 2002; Ziessler, Nattkemper, & Frensch, 2004).

The second prebottleneck interpretation, which is generally consistent with our results, preserves the response-activating power of perceived action effects but affords an extension of the classic response selection bottleneck model with response-related processes running in parallel before the bottleneck. Such an extension was advocated by Hommel (1998) and Lien and Proctor (2000, 2002). These authors assume that response selection contains two components, response activation and response selection. The automatic translation of stimuli into response activation starts directly after stimulus identification and is completed before the subsequent response selection bottleneck. Because response activation occurs in parallel for both tasks, translation of stimuli for Task 2 does not have to wait until response selection in Task 1 is completed. The locus-of-slack logic therefore predicts an underadditive interaction with SOA for any factors influencing response activation.

Within this model, the observed underadditive interaction of S-E compatibility effects with SOA can be easily explained without referring to perceptual processes or decay of stimulated effect codes: Stimuli resembling action effects directly activate the corresponding response features, in parallel to response activation based on S-R mapping rules. This leads to a faster buildup of response activation in S-E compatible compared with S-E incompatible trials, because both processes then activate the very same responses. With short SOA, however, a slack ensues between response activation and response selection, leading to a reduction of S-E compatibility effects.

According to this account, perceived action effects do activate their associated actions. Yet some capacity-limited process, which Lien and Proctor (2002) termed "final" response selection, is necessary before the response can ultimately be carried out. This is probably true even with extensively preactivated responses (see the persisting PRP effects with IM-compatible tasks; Lien et al., 2005). As our results with anticipated response effects suggest, this final response selection coincides with an endogenous activation of effect codes. Thus, the anticipation of action effects— or, to use James's (1890) terms, "thinking the act"—represents an intentional component in action control even with responses seemingly determined by imperative stimuli.

To summarize, we attempted to link two approaches of action control that have tended to some extent to run separately. Our results suggest that the "black box" in information-processing theories labeled "response selection" can be filled with psychological concepts borrowed from IM theories of action control. In this way, we believe that the present experiments provide a fruitful step toward reconciling original ideas of introspective psychology with more modern information-processing approaches.

References

Beckers, T., De Houwer, J., & Eelen, P. (2002). Automatic integration of non-perceptual action effect features: The case of the associative affective simon effect. *Psychol Res*, *66*(3), 166–173.

Cohen, J., MacWhinney, B. M., Flatt, M., & Provost, J. (1993). Psyscope: An interactive graphic system for designing and controlling experiments in the psychology laboratory using macintosh computers. Behavior Research Methods, Instruments, and Computers, *25*, 257–271.

De Jong, R., Liang, C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *J Exp Psychol Hum Percept Perform*, *20*(4), 731–750.

Drost, U., Rieger, M., Brass, M., Gunter, T., & Prinz, W. (2005). Action-effect coupling in pianists. *Psychol Res*, *69*(4), 233–241.

Eimer, M., Hommel, B., & Prinz, W. (1995). S–r compatibility and response selection. *Acta Psychol (Amst)*, *90*, 301–313.

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *J Exp Psychol Hum Percept Perform*, *27*(1), 229–240.

Elsner, B., Hommel, B., Mentschel, B., Drzezga, A., Prinz, W., Conrad, B., & Siebner, H. (2002). Linking actions and their perceivable consequences in the human brain. *Neuroimage*, *17*, 364–372.

Greenwald, A. (2003). On doing two things at once: Iii. confirmation of perfect timesharing when simultaneous tasks are ideomotor compatible. *J Exp Psychol Hum Percept Perform*, *29*(5), 859–868.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychol Rev*, *77*(2), 73–97.

Greenwald, A. G. (1972). On doing two things at once: Timesharing as a function of ideomotor compatibility. *J Exp Psychol*, *94*(1), 52–57.

Greenwald, A. G., & Shulman, H. G. (1973). On doing two things at once: Ii. elimination of the psychological refractory period effect. *J Exp Psychol*, *101*(1), 70–76.

Hazeltine, E. (2005). Response-response compatibility during bimanual movements: evidence for the conceptual coding of action. *Psychon Bull Rev*, *12*(4), 682–688.

Hazeltine, E., Diedrichsen, J., Kennerley, S. W., & Ivry, R. B. (2003). Bimanual cross-talk during reaching movements is primarily related to response selection, not the specification of motor parameters. *Psychol Res*, *67*, 56–70.

Hoffmann, J. (1993). *Vorhersage und erkenntnis: Die funktion von antizipationen in der menschlichen verhaltenssteuerung und wahrnehmung [anticipation and cognition: The function of anticipations in human behavioral control and perception].* Göttingen: Hogrefe.

Hommel, B. (1993). Inverting the simon effect by intention: Determinants of direction and extent of effects of irrelevant spatial information. *Psychol Res*, *55*, 270–279.

Hommel, B. (1995). Stimulus-response compatibility and the simon effect: Toward an empirical clarification. *Journal of Experimental Psychology: Human Perception & Performance*, *21*(4), 764–775.

Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychol Res*, *59*(3), 176–186.

Hommel, B. (1997). Toward an action-concept model of stimulus-response compatibility. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility* (p. 281–320). Amsterdam: North-Holland.

Hommel, B. (1998). Automatic stimulus-response translation in dual-task performance. *J Exp Psychol Hum Percept Perform*, *24*, 1368–1384.

Hommel, B. (2004). Coloring an action: Intending to produce color events eliminates the stroop effect. *Psychol Res*, *68*, 74–90.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (tec): A framework for perception and action planning. *Behav Brain Sci*, *24*, 849–937.

James, W. (1890). *The principles of psychology (vols. 1–2).* Cambridge, MA: Harvard University Press.

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychol Bull*, *70*, 387–403.

Klapp, S. T., Porter-Graham, K. A., & Hoifjeld, A. R. (1991). The relation of perception and motor action: Ideomotor compatibility and interference in divided attention. *J Mot Behav*, *23*, 155–162.

Koch, I., & Kunde, W. (2002). Verbal response-effect compatibility. *Memory*
Cognition, *30*(8), 1297–1303.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—a model and taxonomy. *Psychol Rev*, *97*, 253–270.

Kornblum, S., Stevens, G. T., Whipple, A., & Requin, J. (1999). The effects of irrelevant stimuli: 1. the time course of stimulus-stimulus and stimulus-response consistency effects with stroop-like stimuli, simon-like tasks, and their factorial combinations. *J Exp Psychol Hum Percept Perform*, *25*, 688–714.

Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *J Exp Psychol Hum Percept Perform*, *27*(2), 387–394.

Kunde, W. (2003). Temporal response-effect compatibility. *Psychol Res*, *67*, 153–159.

Kunde, W., Hoffmann, J., & Zellmann, P. (2002). The impact of anticipated action effects on action planning. *Acta Psychol (Amst)*, *109*, 137–155.

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *Quarterly Journal of Experimental Psychology*, *57A*(1), 87–106.

Kunde, W., & Weigelt, M. (2005). Goal congruency in bimanual object manipulation. *J Exp Psychol Hum Percept Perform*, *31*(1), 145–156.

Lien, M., McCann, R., Ruthruff, E., & Proctor, R. (2005). Dual-task performance with ideomotor-compatible tasks: is the central processing bottleneck intact, bypassed, or shifted in locus? *J Exp Psychol Hum Percept Perform*, *31*(1), 122–144.

Lien, M.-C., & Proctor, R. W. (2000). Multiple spatial correspondence effects on dual-task performance. *J Exp Psychol Hum Percept Perform*, *26*(4), 1260–1280.

Lien, M.-C., & Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychon Bull Rev*, *9*(2), 212–238.

Lien, M.-C., Proctor, R. W., & Allen, P. A. (2002). Ideomotor compatibility in the psychological refractory period effect: 29 years of oversimplification. *J Exp Psychol Hum Percept Perform*, *28*(2), 396–409.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychol Rev*, *108*(2), 393–434.

Lotze, H. (1852). *Medicinische psychologie oder physiologie der seele*. Amsterdam: E. J. Bonset.

Lu, C., & Proctor, R. (1994). Processing of an irrelevant location dimension as a function of the relevant stimulus dimension. *J Exp Psychol Hum Percept Perform*, *20*(2), 286–298.

Massaro, D. W. (1990). An information-processing analysis of perception and action. In O. Neumann & W. Prinz (Eds.), *Relationships between perception and action: Current approaches* (pp. 133–166). Berlin: Springer.

McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *J Exp Psychol Hum Percept Perform*, *18*(2), 471–484.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part ii. accounts of psychological refractory-period phenomena. *Psychol Rev*, *104*(4), 749–791.

Miller, J., & Reynolds, A. (2003). The locus of redundant-targets and nontargets effects: evidence from the psychological refractory period paradigm. *J Exp Psychol Hum Percept Perform*, *29*(6), 1126–1142.

Miller, J., Ulrich, R., & Rolke, B. (in press). On the optimality of serial and parallel processing in the psychological refractory period paradigm: Effects of the distribution of stimulus onset asynchronies. *Cognit Psychol*.

Navon, D., & Miller, J. (2002). Queuing or sharing? a critical evaluation of the single-bottleneck notion. *Cognit Psychol*, *44*(3), 193–251.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *J Exp Psychol Hum Percept Perform*, *10*(3), 358–377.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychol Bull*, *116*(2), 220–244.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology*, *41A*(1), 19–45.

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

Ridderinkhof, K. R. (2002). Activation and suppression in conflict tasks: Empirical clarification through distributional analyses. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action. attention & performance, vol. xix* (p. 494–519). Oxford: Oxford University Press.

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

Sanders, A. F. (1998). *Elements of human performance: Reaction processes and attention in human skill* (F. S. Andries, Ed.). Mahwah, N.J.: Erlbaum.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychol Rev*, *82*, 225–260.

Schweickert, R. (1978). A critical path generalization of the additive factor method: Analysis of a stroop task. *Journal of Mathematical Psychology*, *18*(2), 105–139.

Selst, M. van, & Jolicoeur, P. (1994). A solution to the effect of sample size on outlier elimination. *Quarterly Journal of Experimental Psychology*, *47A*(3), 631–650.

Smith, E. E. (1968). Choice reaction time: An analysis of the major theoretical positions. *Psychol Bull*, *69*(2), 77–110.

Sternberg, S. (1969). The discovery of processing stages: Extensions of donders' method. *Acta Psychol (Amst)*, *30*, 276–315.

Thompson, G. L. (2006). An spss implementation of the nonrecursive outlier deletion procedure with shifting z-score criterion (van selst & jolicoeur, 1994). *Behavior Research Methods, Instruments, and Computers*, *38*, 344–352.

Tombu, M., & Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *J Exp Psychol Hum Percept Perform*, *29*(1), 3–18.

Welford, A. T. (1952). The 'psychological refractory period' and the timing of high-speed performance: A review and a theory. *British Journal of Psychology*, *43*, 2–19.

Ziessler, M., & Nattkemper, D. (2002). Effect anticipation in action planning. In W. Prinz & B. Hommel (Eds.), *Attention and performance xix. common mechanisms in perception and action* (p. 646–672). Oxford: Oxford University Press.

Ziessler, M., Nattkemper, D., & Frensch, P. A. (2004). The role of anticipation and intention for the learning of effects of self-performed actions. *Psychol Res*, *68(2-3)*(2-3), 163–175.