

# Time Course of the Blindness to Response-Compatible Stimuli

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This article examines the time course of a deficit in identifying a stimulus sharing a compatible feature with a response that is executed in parallel ("blindness to response-compatible stimuli," J. Müsseler & B. Hommel, 1997a). In 5 experiments, participants performed a timed response, and the presentation point of time of a to-be-identified stimulus was varied in respect to response execution. A blindness effect was observed when the stimulus was presented between response cue offset and response execution. In contrast, the identification of a stimulus presented before the response cue or after response execution was not affected by stimulus–response compatibility—a finding that rules out a retention-based explanation. These results support an explanation that states that the perceptual processing of a stimulus feature is impaired as long as the shared perception–action feature code is integrated into the representation of a to-be-executed response.

Recent studies have demonstrated an impairment of perceptual identification when the observer was simultaneously engaged in a motor task (e.g., Arnell & Duncan, 1998; De Jong & Sweet, 1994; Dell'Acqua, Turatto, & Jolicœur, in press; Jolicœur, 1999). In these studies, the responses in the motor task and the stimuli in the concurrent identification task typically showed no feature overlap. For example, a left keypress response and a concurrently to-be-identified letter *B* (Jolicœur, 1999) presumably have neither physical nor semantic features in common. Accordingly, the findings were interpreted to reflect an unspecific procedural bottleneck shared by both perceptual and motor processes. Other studies revealed that action-control processes can also have a specific impact on perceptual processing. The perception of a stimulus was found to be additionally impaired when it shared a feature with a response that was executed during stimulus identification (Müsseler & Hommel, 1997a, 1997b). The observation of a specific impairment indicated an interference originating from a structural bottleneck shared by both response preparation and stimulus encoding.

The specific impairment was observed in a task in which participants first pressed two keys simultaneously, then performed a speeded left or right keypress response that was previously signaled by a response cue. The double keypress triggered the presentation of a to-be-identified masked left- or right-pointing stim-

ulus and was introduced as a separation between the preparation of the single keypress response and its execution. It was found that the identification of a stimulus (e.g., a left-pointing arrow) was worse when presented during the execution of a compatible response (e.g., a left response) than when presented during the execution of an incompatible response ("blindness to response-compatible stimuli," Müsseler & Hommel, 1997a).

Our research on this phenomenon has mainly focused on two issues. The first line of research was concerned with whether the effect originates from a perceptual interference between the response cue and the stimulus, that is, from a stimulus–stimulus interference. As the blindness to response-compatible stimuli occurred even with a reversed mapping of the response cues onto responses (Müsseler & Hommel, 1997a) and also with endogenously triggered responses (Müsseler, Wühr, & Prinz, 2000), a stimulus–stimulus source of the blindness effect was ruled out. The second line of research was concerned with whether participants perceive compatible and incompatible stimuli equally well but report a compatible stimulus less often than an incompatible stimulus. This explanation, however, is hard to reconcile with observations of the blindness effect in a  $d'$  analysis (Müsseler, Steininger, & Wühr, 2001) and in a pure detection task, in which the direction of stimuli was irrelevant (Müsseler & Hommel, 1997b). Thus, findings ruled out stimulus–stimulus and response-bias explanations of the blindness effect and, instead, suggested that the response affects the perception of a specific stimulus.

Our interpretation of the phenomenon rests on the assumption that executing an action goes along with a temporary blindness to a stimulation that shares common codes with the response within the same cognitive domain. This notion of cognitive codes common to both perception and action has been proposed by MacKay (1987) as the *mental-node* hypothesis and by Prinz (1990) as the *common-coding* hypothesis (see also Hommel, Müsseler, Aschersleben, & Prinz, in press). The structural view underlying this notion regards cognitive perception–action codes to represent stimulus and response features that can be temporarily combined according to given task requirements. One consequence of this view is that stimulus processing and response preparation can

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overlap temporarily and structurally and, thus, are able to affect each other in a specific manner. If, for example, a keypress with the right hand is required in response to an arrow pointing to the right, the RIGHT code is considered to be the common feature of perception and action; it is used when the stimulus is processed or when the corresponding action is generated (Müsseler, 1999). With this in mind, a functional description of the processes involved in the blindness effect can be sketched as follows: To perform a left or right response, a set of corresponding (perception-action) codes is activated on the cognitive common-coding level. This set of activated codes represents a simple version of an action plan (cf. Hommel et al., in press). The generation of an action plan will be termed *response preparation*. To realize that plan, two additional processes have to take place. The first process is *response initiation*, that is, an internal command is given to start the execution of the response (the fiat in the sense of James, 1890; see also, De Jong, 1993). The second process is *response execution*, which results in an overt movement. In the present context, the distinction between the *initiation* and the *execution* of a response is important because it stresses the fact that the execution of a keypress response begins some time before the key is actually pressed. The initial interpretation of the blindness effect was that, with the initiation of the response, the corresponding codes fall into a brief *refractory period* (MacKay, 1986; for more details, see Müsseler & Hommel, 1997a). The refractoriness of perception-action codes during response execution was assumed to cause the blindness effect. If a stimulus has to be processed by accessing a perception-action code that is in a refractory state, then perception should be impaired.

The idea of code refractoriness has previously been used to explain other perceptual phenomena. The term *repetition blindness*, for example, refers to the observation that participants often fail to detect the occurrence of a repeated item under rapid serial visual presentation (e.g., Bavelier & Potter, 1992; Kanwisher, 1987). Among others, Luo and Caramazza (1995) interpreted this effect as a failure of stimulus encoding because of a brief refractory period of perceptual recognition units (for an alternative interpretation, see Armstrong & Mewhort, 1995). Although the blindness effect discussed here is quite different from the repetition-blindness phenomenon, code refractoriness can be seen as a basic processing principle.

The aim of the present study was to test the refractory hypothesis and several other accounts of the blindness to response-compatible stimuli by analyzing the temporal conditions under which the effect does and does not occur. The refractory hypothesis suggests that after a cognitive perception-action code was involved in preparing a response, this code falls into a brief refractory period during the execution of this response (MacKay, 1986; Müsseler & Hommel, 1997a). Accordingly, this account predicts that the blindness effect should be restricted to stimuli appearing during a brief period around the execution of the response. This prediction was tested in Experiments 1 and 2.

According to a second explanation, the blindness effect emerges from a peculiarity of our procedure. Consider that, before executing the response, participants always had to press both keys simultaneously. Thus, the task required participants to suppress the response until the double keypress had been performed. It is possible that the blindness effect originates from this suppression, which should last, at minimum, until the execution of the double

keypress.<sup>1</sup> Experiment 3 examined the effects of removing the double keypress from the task.

The third account to be tested was whether the blindness effect is a retention-based instead of a perceptual failure. It might be that compatible and incompatible stimuli are encoded equally well, but compatible stimuli are harder to retain or are harder to retrieve from memory. This issue was addressed in Experiments 4 and 5 by comparing identification performance for stimuli presented before and after the response cue. If the blindness effect resembles a memory failure, it should not matter whether the stimulus has to be encoded before or after the response cue.

## Experiment 1

The refractory hypothesis states that the refractoriness of perception-action codes starts with the initiation of a response, reaches its peak with response onset, and then gradually disappears (cf. Müsseler & Hommel, 1997a). Accordingly, the blindness effect should be present only during response execution, whereas no difference between the identification performances for compatible and incompatible stimuli should occur much before and after response execution. To test this idea, we applied the timed-response method. Each trial was provided with an isochronous sequence of three clicks, separated by 700 ms. Participants had to synchronize the response with the third click. This synchronization is known to show a relatively high degree of accuracy (e.g., Fraisse, 1978) and enables the experimenter to present the visual stimuli temporarily with regard to the expected response onset. Five presentation points in time of the visual stimuli, hence five stimulus-response onset asynchronies (SROAs), were tested: -980 ms and -280 ms before the expected onset of the response, simultaneously with the response, and 280 ms and 980 ms after the response.

## Method

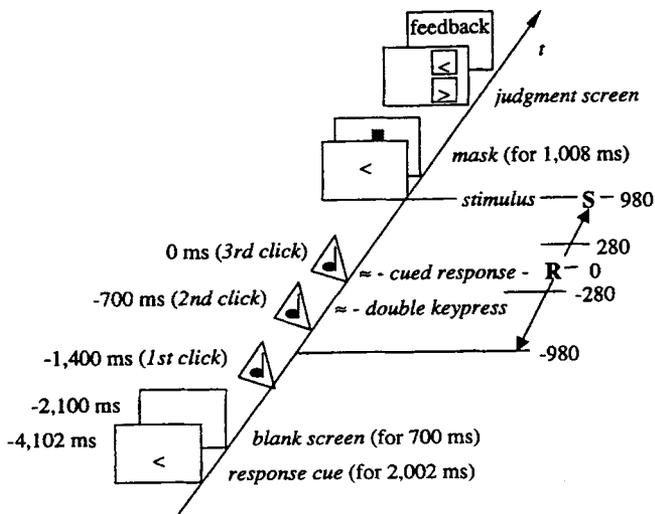
*Participants.* Fifteen volunteers were paid DM 30 (U.S. ~\$15) for their participation in this experiment. They averaged 26 years of age and had normal or corrected-to-normal vision.

*Apparatus and stimuli.* The experiment was performed in a dimly lit, soundproof room on a laboratory computer (rho-prof 200; RhoThron Corp., Homburg, Germany), which controlled stimuli presentation and data acquisition. The participants' heads were placed on a chin rest 50 cm in front of the monitor. Two microswitches of a computer mouse served as response keys that had to be pressed with the index and middle fingers of the right hand.

Visual stimuli were presented in black-on-white and were synchronized with the vertical retrace of a 71-Hz monitor. The monitor's luminance was approximately 39 cd/m<sup>2</sup>. All visual stimuli—the response cues and the to-be-identified stimuli—were arrow heads (“<” or “>”) measuring 0.6° × 1.0°. The mask was a rectangle of 0.7° × 1.3° in which every pixel was black with two-thirds probability on each trial. The auditory stimuli were clicks of 440 Hz with a duration of 40 ms.

*Procedure.* The sequence of events is shown in Figure 1. First, the response cue was shown for 2,016 ms, 1.5° below the screen center. After a blank interval of 700 ms, three clicks appeared with an interclick interval of 700 ms. Participants were instructed to briefly press both mouse keys

<sup>1</sup> We are grateful to Wolfgang Prinz and Carlo Umiltà for suggesting this alternative interpretation.



**Figure 1.** Series of events in Experiments 1–4, in which a timed-response method was applied. Participants had to synchronize responses with isochronously presented clicks. In all experiments, a cued response (a left keypress in the depicted example) had to be performed  $\pm 250$  ms around the third click. In Experiments 1 and 2, a neutral double keypress was to precede the cued response in between 600 and 100 ms before the third click. While doing this, a masked arrow was presented for an individually adjusted time. An arrow could be presented at different points in time relative to the onset of the third click and thus relative to the expected response onset. A trial was completed with an unspeeded judgment of the arrow. R = critical left or right response; S = masked left- or right-pointing arrow.

simultaneously after the second but before the third click, and then to press the one key indicated by the response cue in synchronization with the onset of the third click. Both responses could be realized within overlapping intervals of 500 ms each. The double keypress had to be performed between 600 and 100 ms before the third click's onset to establish a mean response onset asynchrony similar to the previous experiments ( $\sim 350$  ms; e.g., Müsseler & Hommel, 1997a). The single keypress response had to be performed between  $\pm 250$  ms around the onset of the third click. Violations of the first interval resulted in a so-called *double fault*. Missing the second interval was called a *beat mistake*.

The to-be-identified stimuli appeared with 1 of 5 SROAs relative to the onset of the third click (see below). The visual stimulus was presented  $1.5^\circ$  above the screen center for a brief, near-threshold presentation duration. This duration was adjusted individually for each participant in the pretest, and from block to block throughout the whole experiment in order to avoid ceiling or floor effects in identification performance. The duration was increased or decreased by one vertical retrace of the monitor if the identification rate in the last block was below 60% or above 90%, respectively.

The stimulus was replaced by the mask, which stayed on the screen for 1,008 ms after the third click (for SROAs  $\leq 0$  ms) or after stimulus presentation (for SROAs  $> 0$  ms), respectively. After a further blank interval of 256 ms, a left and right arrow appeared, one above the other, at the right margin of the screen (judgment screen). Vertical arrow position varied randomly from trial to trial. Participants judged the direction of the masked arrow by pointing with the mouse to the corresponding arrow and confirming their choice by pressing both mouse keys simultaneously. These judgments were not speeded. Finally, at the end of each trial, participants received different error messages for each kind of error (double faults, beat mistakes, false responses, wrong judgments of visual stimuli) that had occurred in that trial. In the case of error-free perfor-

mance, the next trial started 750 ms after the offset of the judgment response.

Participants were given 20 trials for practice, which were not analyzed. They were instructed to try to accomplish the response task and the identification task as accurately as possible. Additionally, it was stressed that the to-be-performed responses and the to-be-identified stimuli were combined randomly on each trial.

**Design.** Each participant received 640 experimental trials divided in two sessions, with a total duration of approximately 2 hours: 2 (compatibility)  $\times$  5 (SROA)  $\times$  2 (repetitions)  $\times$  16 (blocks)  $\times$  2 (sessions). The left or right keypress response was paired with the presentation of the left- or right-pointing arrow, yielding two compatible (left–left and right–right) and two incompatible (left–right and right–left) combinations. Additionally, five presentation points in time of the visual stimuli, hence five SROAs, were tested ( $-980$ ,  $-280$ ,  $0$ ,  $280$ , and  $980$  ms). Each participant was presented with all combinations in a randomized order.

## Results

One participant was excluded from further analysis because of a high percentage of trials with double faults (32% compared with the mean of 8% [ $SD = 8$ ] for the whole sample). The results are summarized for the remaining 14 participants. The mean presentation time of the stimulus was 49 ms. False responses occurred in 1.2% of the trials, which were not further analyzed.<sup>2</sup> The percentages of double faults and beat mistakes (i.e., performing either the double keypress or the response outside the allowed time window) were 6.3% and 3.5%. In a 2 (compatibility)  $\times$  5 (SROA) analysis of variance (ANOVA), compatibility did not significantly affect the synchronization errors.

More important, stimuli that were compatible with a response showed a lower identification rate (.77) than did incompatible stimuli (.84). This difference resulted in a significant main effect of compatibility in a 2  $\times$  5 ANOVA,  $F(1, 13) = 5.14$ ,  $MSE = 0.036$ ,  $p < .05$ . This main effect has to be interpreted with the SROA variation yielding a significant interaction of both factors,  $F(4, 52) = 4.19$ ,  $MSE = 0.006$ ,  $p < .01$ . As Figure 2 illustrates, the difference between the overall identification rates for compatible and incompatible stimuli was established under negative and zero SROA conditions. For stimuli preceding the response by  $-980$  ms, the identification rate for compatible stimuli was 17% lower than that for incompatible ones. The difference reduced to 9% for stimuli presented  $-280$  ms before response onset and shrank to 7% for stimuli presented with the minimal SROA of approximately 0 ms. Finally, the identification performance with negative SROAs was lower (.73 and .80 for  $-980$  ms and  $-280$  ms SROA, respectively) than with the other SROAs (.85, .83, and .83 for 0 ms,  $+280$  ms, and  $+980$  ms SROA, respectively) yielding a significant main effect of SROA,  $F(4, 52) = 9.40$ ,  $MSE = 0.007$ ,  $p < .001$ .

To test the predictions concerning the appearance or nonappearance of a blindness effect for the different SROA levels, we performed additional  $t$  tests. As expected, the blindness effects were significant for the  $-280$  ms SROA,  $t(13) = 2.41$ ,  $p < .025$ , and for the minimal SROA of approximately 0 ms,  $t(13) = 2.18$ ,  $p < .025$  (both one-tailed). The significant blindness effect was unexpected for stimuli presented nearly 1 s before the onset of the

<sup>2</sup> Note that an error percentage of 1.6% reflects only one error in 64 trials.

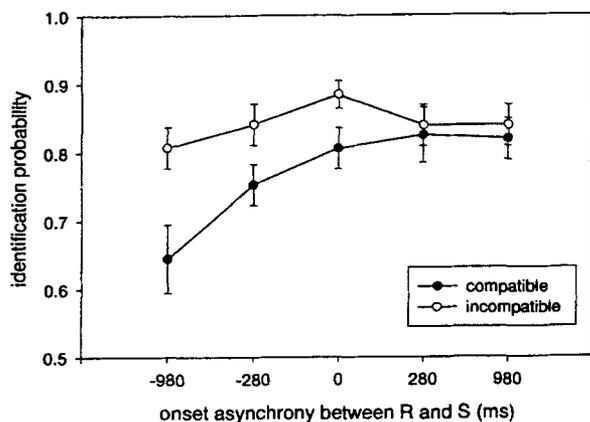


Figure 2. Mean identification probabilities for response-compatible and response-incompatible stimuli in Experiment 1 ( $N = 14$ ; each data point rests on about 800 observations; error bars are standard errors between participants). A left- or right-pointing arrow was presented at five points in time with respect to the execution of a left or right response. Chance level is .5. R = left or right response; S = masked left- or right-pointing arrow.

response,  $t(13) = 2.78$ ,  $p < .025$  (two-tailed). The identification disadvantage for compatible stimuli presented after response onset was equally small and not significant.

The following mean response latencies were observed: The double keypress and the response preceded the onset of the third click by 363 ms and 41 ms, respectively. The difference between both response onsets resembles an asynchrony of 322 ms, which is similar to previous observations (e.g., Müseler & Hommel, 1997a). The mean latency of the judgments, measured from the onset of the judgment screen, was 1,092 ms. None of these measures was affected by compatibility, as corresponding 2 (compatibility)  $\times$  5 (SROA) ANOVAs showed.

### Discussion

The results of Experiment 1 were clear. The identification of a compatible stimulus was impaired until the onset of the response, and this blindness to response-compatible stimuli even increased when the stimulus was presented earlier. In contrast, stimulus identification after response onset was not affected by stimulus-response compatibility.

The results contradict the assumption that the refractory mechanism starts with the execution of the response and is most effective around response onset. Contrary to this assumption, the blindness effect was largest with the SROA of  $-980$  ms and was somewhat reduced with the SROAs of  $-280$  ms and  $0$  ms. Thus, the blindness effect was not restricted to the execution phase of a response. Given that, when does it emerge? The next experiment was designed to examine the temporal limits of the effect.

### Experiment 2

Experiment 2 was aimed to replicate and extend the findings of Experiment 1. In Experiment 1, the largest SROA was  $-980$  ms. In Experiment 2, the stimulus was presented either  $-2,002$  ms,  $-1,400$  ms,  $-630$  ms, or  $-140$  ms before the (expected) onset of

the response. The largest negative SROA corresponded to an interstimulus interval (ISI) of 98 ms between response-cue offset and stimulus onset. Thus, these SROAs covered the complete time range in which the to-be-performed response had to be prepared and maintained.

### Method

**Participants.** Sixteen individuals, average age of 26 years, were paid DM 30 (\$15) for participation. None of them had participated in Experiment 1.

**Apparatus, stimuli, and procedure.** These were identical to Experiment 1, with one exception. With the SROA of  $-2,002$  ms, the onset of the to-be-identified stimulus was temporarily separated from the response-cue presentation by only 98 ms. If response cue and stimulus were presented in such rapid succession, and if they were identical in visual shape, a perceptual-based restraint cannot be excluded (cf. the repetition-blindness effect). To counteract this problem, response cues were now dark or white squares (each  $0.6^\circ \times 0.6^\circ$ ), indicating a left or right response.

**Design.** In this experiment, the SROA factor had four levels ( $-2,002$  ms,  $-1,400$  ms,  $-630$  ms, and  $-140$  ms) resulting in a 2 (compatibility)  $\times$  4 (SROA) within-participants design. The experiment contained 512 trials divided in two sessions: 2 (compatibility)  $\times$  4 (SROA)  $\times$  2 (repetitions)  $\times$  16 (blocks)  $\times$  2 (sessions).

### Results

The masked stimulus was presented for 26 ms on average. False responses occurred in 2.7% of the trials and were not further analyzed. The percentages of double faults and beat mistakes were 10.6% and 4.9%, respectively. Compatibility did not significantly affect the synchronization errors in a 2 (compatibility)  $\times$  4 (SROA) ANOVA.

As can be seen from Figure 3, compatible stimuli were identified less accurately than were incompatible stimuli (.69 vs. .78). This finding was confirmed by a significant main effect of compatibility in a 2  $\times$  4 ANOVA,  $F(1, 15) = 12.95$ ,  $MSE = 0.017$ ,  $p < .01$ . The main effect of SROA was also significant due to a

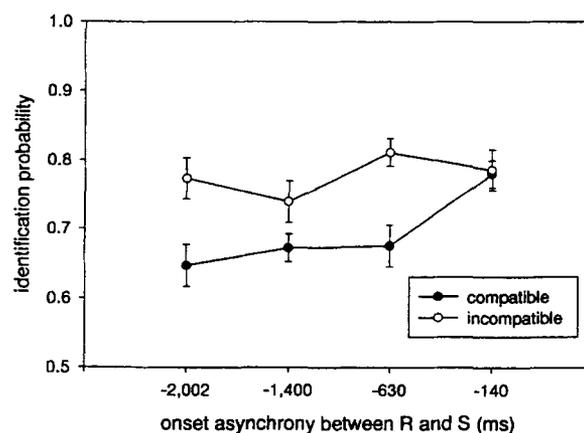


Figure 3. Mean identification probabilities for response-compatible and response-incompatible stimuli in Experiment 2 ( $N = 15$ ; each data point rests on about 790 observations; error bars are standard errors between participants). A left- or right-pointing arrow was presented at four points in time with respect to the execution of a left or right response. Chance level is .5. R = left or right response; S = masked left- or right-pointing arrow.

decreased identification performance with longer (negative) SROAs,  $F(3, 45) = 4.84$ ,  $MSE = 0.008$ ,  $p < .01$ . However, as separate one-way ANOVAs showed, the increase of identification performance with SROA was only significant for the compatible condition,  $F(3, 45) = 6.90$ ,  $MSE = 0.008$ ,  $p < .01$  ( $p > .20$ , for the incompatible condition). For the SROAs of  $-2,002$  ms,  $-1,400$  ms, and  $-630$  ms, the identification of compatible stimuli was always worse compared with the identification of incompatible arrows. Only with the smallest SROA of  $-140$  ms, the identification performance for compatible and incompatible stimuli did not differ. This pattern of results obviously gave rise to a significant interaction of both factors,  $F(3, 45) = 3.05$ ,  $MSE = 0.009$ ,  $p < .05$ .

The following mean latencies were observed: The double keypress was performed 386 ms before the third click, the response followed the third click by 6 ms, and the mean judgment time was 1,106 ms. The asynchronies of the double keypress and the judgment times were not affected by compatibility (all  $ps > .30$ ), but the asynchronies of the response revealed a significant interaction of compatibility and SROA,  $F(3, 45) = 3.35$ ,  $MSE = 79.29$ ,  $p < .05$ . Compatible responses were executed earlier with respect to the third click than incompatible responses were, with the larger SROAs of  $-2,002$  and  $-1,400$  ms, but they were executed later with the smaller SROAs of  $-630$  ms and  $-140$  ms. Because a significant blindness effect had been observed for all three larger SROAs, there was no covariation between worse identification performance and slower response execution in the compatible condition, as compared with the incompatible condition. In addition, none of the differences in the asynchronies was larger than 8 ms.

### Discussion

The results of Experiment 2 confirmed and extended those of Experiment 1. Participants had great difficulties identifying response-compatible stimuli presented over the whole interval between response-cue presentation and the double keypress, ranging from  $-2,002$  to  $-630$  ms. However, there was no blindness effect for stimuli presented  $-140$  ms before the onset of the response. The disappearance of the blindness effect with the  $-140$ -ms SROA might have to do with expectancy. With the arrangement of SROAs in Experiment 2, participants could have learned that the stimulus would appear around the execution of the response if the stimulus had not been presented before the execution of the neutral double keypress. The possibility of expecting the stimulus with the SROA of  $-140$  ms in Experiment 2 could have enabled the participants to better prepare for stimulus processing in that condition (cf. De Jong & Sweet, 1994), which could have weakened the blindness effect.

The results of Experiments 1 and 2 yielded strong evidence against the refractory hypothesis. In particular, the blindness effect was not restricted to the phase of executing the response after the neutral double keypress. In contrast, the perceptual impairment appeared also in earlier phases in which the response had to be prepared and maintained. Which mechanisms are able to account for this time course of the blindness to response-compatible stimuli? Experiment 3 tested two possible explanations. According to the first explanation, the inhibition of perception-action codes is

responsible for the blindness effect, whereas the second explanation attributes the blindness effect to the activation of these codes.

### Experiment 3

So far, in all experiments on the blindness effect, the participants performed a neutral double keypress briefly before they executed the single keypress response (e.g., Müsseler et al., 2000, 2001). Thus, the participants were required to execute the response after the neutral double keypress. This task might be accomplished by preparing and then inhibiting the response until the neutral double keypress was executed. In other words, the activation of the neutral double keypress might temporarily exert an inhibitory impact on the perception-action codes representing the response—similar to a mechanism proposed to account for the problem of serial order in motor control (Estes, 1972; see Rosenbaum, 1991, for a critical discussion). Consequently, the inhibited representation of the response might also affect the left-right code that is necessary for the encoding of the stimulus, thus producing the blindness effect.

This inhibition explanation makes two major predictions. The first prediction is that the blindness effect should be most pronounced before the execution of the neutral double keypress, whereas the effect should quickly disappear after its execution. This prediction fits well with the time course of the blindness effect observed in Experiments 1 and 2. In these experiments, a strong blindness effect was consistently observed before the execution of the neutral double keypress. Between the neutral double keypress and the response, however, the blindness effect became unreliable. It occurred in Experiment 1 (SROA = 0 ms) but not in Experiment 2 (SROA =  $-140$  ms). The second prediction of the inhibition explanation is that the blindness effect should disappear if the participants do not have to perform the neutral double keypress before the response.

According to the second explanation, it is not the inhibition of perception-action codes that interferes with the processing of a stimulus, but the fact that these codes are already in use or occupied by the representation of a response. According to the two-process model of action planning, proposed by Stoet and Hommel (1999), the preparation of a motor response consists of two consecutive stages: first, the activation of perception-action codes, then the integration of these codes (cf. Hommel et al., in press). The important assumption for the present discussion is, once a perception-action code is integrated into the representation (or plan) of a response, this code is occupied. The *occupation* of a perception-action code means that this code is not inhibited, but it is less available for other cognitive activities—for example, for the perceptual processing of a response-compatible stimulus. This occupation explanation predicts a similar time course of the blindness effect as the inhibition explanation described above. However, in contrast to the inhibition explanation, the occupation explanation predicts that the blindness effect should still occur if the participants do not have to perform the neutral double keypress before the response.

### Method

**Participants.** Sixteen volunteers, average age of 25 years, were paid DM 30 (\$15) for their participation in the experiment. None of them had participated in the previous experiments.

**Stimuli, design, and procedure.** These were the same as in Experiment 1 with the following two modifications: First, the execution of the double keypress between the second and third click was removed from the procedure. Second, the responses were recorded with touch-sensitive keys. Two metal plates, each measuring  $1.5 \times 1.5$  cm and separated by 2 cm, were mounted on a board. Participants were instructed to respond by touching the two plates with the index and middle fingers of their right hand. They were told to keep their fingers on the plates throughout each trial and only to lift them, as briefly as possible, to respond simultaneously with the third click. If the fingers did not rest on the plates, the trial was not started. Lifting the responding finger (movement onset) was not allowed until 600 ms before the third click. The response itself (movement offset) had to be performed within  $\pm 250$  ms around the third click.

## Results

Two participants were excluded from the analysis. The first participant was dropped because his performance in the incompatible condition was at chance (50%), whereas his performance was almost perfect in the compatible condition (95%). Thus, it seemed that this participant always judged the stimulus in the same direction as the response. By contrast, the entire group achieved approximately equal performance of 75% in both conditions ( $SD = 8$ , and  $SD = 9$ , for the compatible and incompatible condition, respectively). The second participant was excluded because in 24% of the trials, his fingers did not rest on the keys between response cue presentation and the response interval, whereas the whole sample violated this criterion in only 2% ( $SD = 6$ ) of the trials. The remaining 14 participants performed false responses in 0.4% of the trials, which were not further analyzed. In 4.3% of the trials, beat mistakes occurred, which did not depend on compatibility in a 2 (compatibility)  $\times$  5 (SROA) ANOVA.

A 2  $\times$  5 ANOVA indicated that the identification rates varied with the SROA,  $F(4, 52) = 5.87$ ,  $MSE = 0.006$ ,  $p < .01$  (cf. Figure 4). However, the influence of SROA on identification performance was again limited to the compatible condition,  $F(4,$

52) = 8.79,  $MSE = 0.008$ ,  $p < .001$  ( $F < 1$  for the incompatible condition). Moreover, identification performance was affected by the interaction of SROA and compatibility,  $F(4, 52) = 4.65$ ,  $MSE = 0.04$ ,  $p < .01$ . Planned comparisons localized the only significant difference for the SROA of  $-980$  ms, in which compatible stimuli were identified less accurately than incompatible stimuli,  $t(13) = 3.01$ ,  $p < .01$  (one-tailed; all other  $ps > .30$ ).

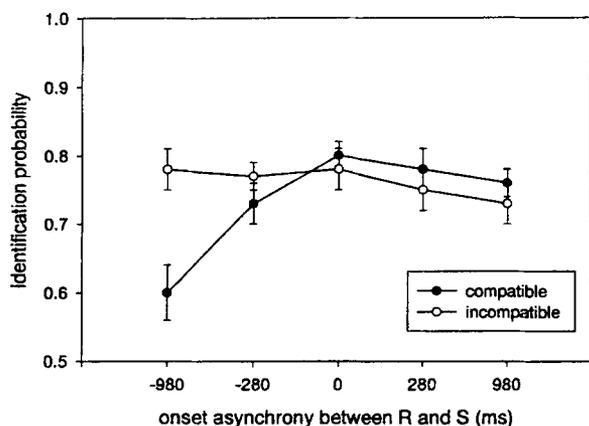
On average, correct responses were given by leaving the sensory plates 252 ms before the third click and by touching them 222 ms later, that is, 30 ms before the third click. Correct judgments were given 946 ms after the onset of the judgment screen. None of these measures depended on compatibility (all  $ps > .35$ ).

## Discussion

The main result of Experiment 3 was a significant blindness to response-compatible stimuli that were presented approximately 1 s before the onset of a single keypress, although this response was not preceded by a neutral double keypress. This result clearly supports the occupation explanation, according to which the integration of perception-action codes into an action plan for a response occupies these codes, and thereby impairs the processing of a response-compatible stimulus, independently from another response that precedes or follows the single keypress. At the same time, the results contradict the inhibition explanation, according to which the neutral double keypress is necessary to obtain the blindness effect.

However, one might argue that in Experiment 3, the necessity to inhibit the response did not emerge from the double keypress but from the necessity to wait for the occurrence of the third click. There are at least two arguments against this modified inhibition assumption. First, the blindness effect was also observed in studies in which the timed-response method was not used (e.g., Müsseler & Hommel, 1997a). In these studies, participants were allowed to execute the response whenever they wanted. The only constraint was to execute the double keypress before the response. Second, the blindness effect also occurred in experiments in which the participants responded to the response cue as quickly as possible (Müsseler & Wühr, in press). Therefore, in the latter experiments, a temporary suppression of the response was not necessary at all. These findings speak against an inhibition explanation of the blindness effect while supporting the occupation explanation.

Finally, another result of Experiment 3 needs to be discussed. In this experiment, the blindness effect was only observed with the earliest presentation of the stimulus ( $-980$  ms SROA). In contrast, in Experiment 1, a smaller but significant blindness effect was also observed with stimuli presented  $-280$  ms before or almost simultaneously with the response. The main difference between these experiments was that the response was preceded by a double keypress in Experiment 1 but not in Experiment 3. One may argue that this difference encouraged the participants of Experiment 1 to maintain a cognitive representation of the response for a longer time than the participants of Experiment 3 did. In particular, after the double keypress, which was performed approximately 350 ms before the third click, the participant must choose the finger with which to repeat the keypress. If, however, only a single keypress is demanded—as in Experiment 3—the corresponding finger could already be lifted at least 500 ms before the third click. Once the finger is lifted, a cognitive representation of the response might no



**Figure 4.** Mean identification probabilities for response-compatible and response-incompatible stimuli in Experiment 3 ( $N = 14$ ; each data point rests on about 850 observations; error bars are standard errors between participants). A left- or right-pointing arrow was presented at the same points in time as in Experiment 1. Participants had to perform only a left or right response by briefly lifting their finger from a touch-sensitive metal plate. Chance level is .5. R = left or right response; S = masked left- or right-pointing arrow.

longer be necessary. Thus, in the latter case, stimuli appearing less than 500 ms before the third click may no longer be affected by the response task, whereas in the former case they are still likely to appear while the response (sequence) is cognitively represented.

Whereas the first three experiments were concerned with possible sources of the blindness effect, Experiments 4 and 5 were concerned with the possible locus of the blindness effect. That is, the examination of whether the blindness effect is a failure to encode the stimulus or a failure to memorize it.

### Experiment 4

Until now, the findings indicated that the blindness effect resembles a failure to encode stimuli caused by the simultaneous preparation and maintenance of a compatible response. On the other hand, the time course of the blindness effect observed in Experiments 1–3 indicated an increase in the size of the blindness effect with increasing SROA. In other words, the blindness effect seemed to increase with the duration of the retention interval. This observation suggests that the blindness effect is not a failure of perceptual encoding but a failure of (short-term) memory. A memory-failure account of the blindness effect states that compatible and incompatible stimuli are equally well encoded, but compatible stimuli have a higher risk to be forgotten during the remainder of the task.

Research on human memory has shown that the similarity between items has a detrimental effect on memory of these items. For example, the recall of repeated items in a string of digits or letters is known to be poorer than the recall of nonrepeated items, even if the individual items are shown long enough to warrant correct perceptual encoding (Ranschburg effect; Ranschburg, 1902; for an overview, see Henson, 1998). Among other ideas, the Ranschburg effect has been explained by a bias against guessing repeated items.

The purpose of Experiments 4 and 5 was to examine the plausibility of a memory-based explanation of the blindness effect. Participants identified a stimulus when it was presented before the response cue or—as in the previous experiments—when it occurred between response-cue presentation and response onset. The critical condition was the presentation of the stimulus before the response cue. In this case, the to-be-performed response may obviously not affect the perceptual encoding of the stimulus. However, if the blindness effect is due to a memory failure, then interference should be even stronger in this condition because the retention interval is longer compared with the condition in which the stimulus is presented after the response cue.

### Method

**Participants.** Fifteen volunteers, average age of 22 years, were paid DM 15 (\$7) for participation. None of them had participated in the previous experiments.

**Apparatus and stimuli.** This experiment ran on a Macintosh IIci computer (Apple, Cupertino, CA) with a 17" color monitor of 75 Hz. Otherwise, presentation conditions were the same as in Experiments 1–3, with the following modifications: The response cue was a 500-Hz tone that was presented for 100 ms either to the left or right ear by headphones. The tone indicated a to-be-synchronized left or right response (see below). The to-be-identified arrowheads measured  $0.8^\circ \times 1.6^\circ$  of visual angle, and the mask was a rectangle of  $1.0^\circ \times 2.0^\circ$  that consisted of randomly arranged rods with the orientation of the arrowheads.

**Procedure.** The response cue was presented either to the left or right ear. Following the tone's onset by 1,400 ms, a sequence of three clicks appeared with an interclick interval of 700 ms. Participants were instructed to press a key ipsilateral to the response-cue tone in synchronization with the third click. Asynchronies larger than  $\pm 250$  ms were considered an error. As in Experiment 3, participants did not have to perform a neutral double keypress before the response.

The presentation time of the visual stimulus was adjusted from block to block according to the same rule as in Experiments 1–3. However, the presentation times for visual stimuli presented before and after the response cue were adjusted independently in order to achieve comparable degrees of difficulty. Another modification of the experiment was that the trials in which participants made errors in the response task (false responses, beat mistakes) were repeated once at the end of the block. The intertrial interval was 2,106 ms and the experiment was run in one session.

**Design.** The to-be-identified stimulus was presented with equal probability before or after the response cue, that is, the stimulus appeared 1,400 ms before the onset of the response cue, or it was presented 1,800 ms or 2,293 ms after the response cue. These conditions corresponded to SROAs of  $-4,200$  ms,  $-1,000$  ms, and  $-507$  ms, respectively. Compatibility and SROA were crossed in a  $2 \times 3$  design. Each participant received 320 experimental trials in randomized order.

### Results

The mean presentation times for visual stimuli presented before and after the response cue were 56 and 46 ms, respectively. This difference was significant,  $t(14) = 2.93$ ,  $p < .01$  (two-tailed). Participants performed false responses in 0.8% and beat mistakes in 1.7% of the trials. These low error rates were not further analyzed.

Collapsed across compatibility, participants yielded an identification rate of .76 for stimuli presented before the response cue. For stimuli presented after the cue, identification rates were .77 and .78 for the SROAs of 1,000 ms and 507 ms, respectively. Collapsed across SROA, identification rates were identical for the compatible and the incompatible condition (.77). The main effects of both factors in a  $2 \times 3$  ANOVA were not significant (both  $F$ s  $< 1$ ). However, the interaction was significant,  $F(2, 28) = 4.83$ ,  $MSE = 0.002$ ,  $p < .05$ . This interaction was due to the fact that compatible stimuli were identified less accurately than incompatible stimuli (.75 vs. .80) only when the stimuli were presented after the response cue and preceded the response by 1,000 ms,  $t(14) = 2.40$ ,  $p < .025$  (one-tailed; all other  $t$ s  $< 1$ ; see Figure 5).

On average, participants performed the response 30 ms after the onset of the third click. A  $2 \times 3$  ANOVA on the asynchronies between the responses and the third click showed no significant effect.

### Discussion

In Experiment 4, the judgment of a visual stimulus was not affected by stimulus–response compatibility when the stimulus was presented before the response cue. In contrast, when the stimulus occurred between the response cue and the response, response-compatible stimuli were reported less frequently than response-incompatible stimuli. If the blindness effect originates from an interference in short-term memory, then the disadvantage in reporting response-compatible stimuli should have been more pronounced in the former condition, because in this condition the retention interval was more than twice as large as in the latter

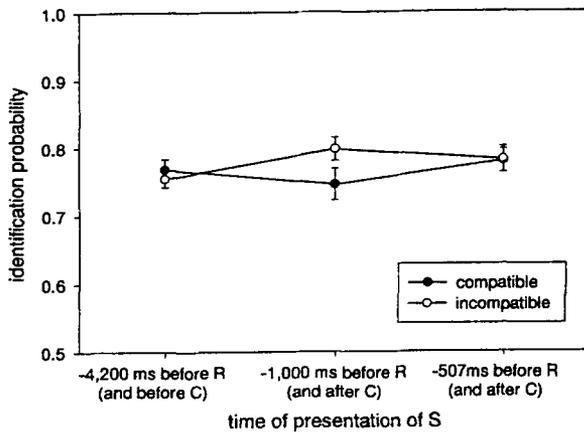


Figure 5. Mean identification probabilities for response-compatible and response-incompatible stimuli in Experiment 4 ( $N = 15$ ; error bars are standard errors between participants). A left- or right-pointing arrow was presented with equal probability either before the response cue (about 1,200 observations per data point) or between the cue and a timed response (about 600 observations per data point). No double keypress had to be performed. Chance level is .5. C = response cue; R = left or right response; S = masked left- or right-pointing arrow.

condition. Thus, the results suggest that the blindness effect is more likely a failure to encode response-compatible stimuli than a failure to memorize them.

On the other hand, the blindness effect for stimuli presented between the response cue and the response was restricted to an SROA of  $-1,000$  ms, that is, no blindness effect was observed for an SROA of  $-507$  ms. In addition, the blindness effect observed with the SROA of  $-1,000$  ms was—although significant—rather small: only 5% compared with 17% and 15% in Experiments 1 and 3, respectively (for SROAs of  $-980$  ms). Therefore, we performed Experiment 5 to get converging evidence for the results of Experiment 4.

### Experiment 5

The aim of Experiment 5 was to replicate the results of Experiment 4 and to extend the general scope of the findings. Therefore, the to-be-identified stimulus was again presented either before the response cue or between the response cue and the response. The prediction was that the blindness effect occurs only in the latter condition. This result would suggest that the blindness effect is a failure to perceptually encode response-compatible stimuli. In contrast to Experiments 1–4, the response task was no longer a timed-response task but a speeded reaction-time task in response to a go signal. This change was designed to examine any peculiarities in the results of the previous experiment(s) resulting from the use of the timed-response task.

### Method

**Participants.** Sixteen volunteers, average age of 26 years, were paid DM 15 (\$7) for their participation. None of them had participated in any of the previous experiments.

**Apparatus and stimuli.** The apparatus and stimuli were identical to Experiment 4. Instead of three clicks, with which participants had to synchronize their response, only one beep was presented as a go signal.

**Procedure and design.** The response cue was a tone presented either to the left or to the right ear. After an interval of 1,506 ms, the go signal was presented binaurally. Participants were instructed to press the key ipsilateral to the response-cue tone on the occurrence of the go signal as quickly as possible. A reaction time larger than 1 s was considered an error.

The stimulus onset asynchronies (SOAs) between the go signal and the to-be-identified stimulus were  $-2,507$  ms,  $-1,000$  ms, and  $-507$  ms, respectively. The stimulus appeared 1 s before the onset of the response cue with the  $-2,507$ -ms SOA, and it appeared  $\frac{1}{2}$  s or 1 s after the onset of the response cue with the  $-1,000$  ms and  $-507$  ms SOAs, respectively. As in Experiment 4, the largest SOA occurred in 50% of the trials, whereas the two other SOAs had a probability of 25% each. The entire experiment lasted between 75–90 min, including short breaks.

### Results

One participant was excluded from the analysis because he violated the reaction time criterion ( $RT < 1$  s) in half of the trials (47% compared with 15% [ $SD = 14$ ] of the whole sample). The identification rates of the remaining 15 participants increased with decreasing SOA between the go signal and the stimulus from .74 ( $-2,507$ -ms SOA) to .76 ( $-1,000$ -ms SOA), and finally to .81 ( $-507$ -ms SOA),  $F(2, 28) = 10.34$ ,  $MSE = 0.004$ ,  $p < .001$ . More important, compatible stimuli were recognized less accurately than incompatible stimuli (.75 vs. .79),  $F(1, 14) = 7.18$ ,  $MSE = 0.005$ ,  $p < .05$ , and the disadvantage in the identification of compatible stimuli was limited to stimuli presented after the response cue yielding a significant interaction of both factors,  $F(2, 28) = 5.52$ ,  $MSE = 0.003$ ,  $p < .01$  (cf. Figure 6). Planned comparisons revealed only a significant blindness effect for stimuli presented  $-507$  ms before the go signal,  $t(14) = 4.49$ ,  $p < .001$  (one-tailed).

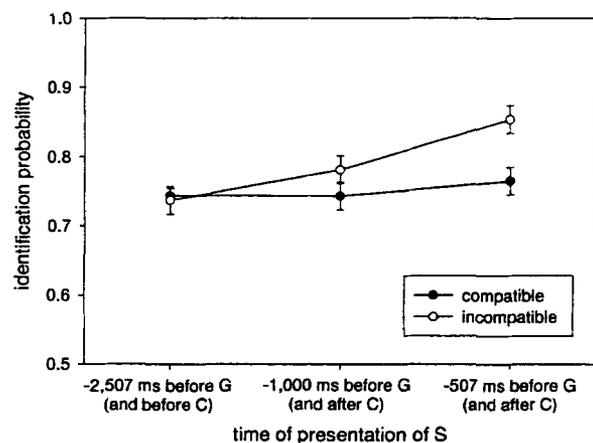


Figure 6. Mean identification probabilities for response-compatible and response-incompatible stimuli in Experiment 5 ( $N = 15$ ; error bars are standard errors between participants). A left- or right-pointing arrow was presented with equal probability either before a response cue (about 1,150 observations per data point) or between the cue and a go signal (about 550 observations per data point). No double keypress had to be performed. Chance level is .5. C = response cue; G = go signal; S = masked left- or right-pointing arrow.

The mean presentation times were 55 ms and 52 ms for stimuli presented before and after the response cue, respectively. This difference was not significant,  $t(14) = 1.48, p > .10$  (two-tailed). False responses occurred in 0.9% of the trials, which were not further analyzed. Reaction times were too long in 13% of the trials. This latency error increased from 8% to 21% with decreasing SOA; that is, the more both tasks were performed in temporal neighborhood, the more latency errors were made,  $F(2, 28) = 10.57, MSE = 145.17, p < .001$ . Mean reaction time was 492 ms. Latencies increased substantially with decreasing SOA between the go signal and the stimulus (405 ms, 478 ms, 594 ms),  $F(2, 28) = 57.26, MSE = 4,774.96, p < .001$ . This result was paralleled by the increase in latency errors with decreasing SOA mentioned above. Compatibility had no significant effect on reaction times.

### Discussion

The results clearly replicated the major finding of Experiment 4. Again, the judgments of a stimulus preceding the response cue did not depend on stimulus–response compatibility. If, however, the stimulus appeared between the response cue and the response, compatible stimuli were again less frequently reported than incompatible stimuli. Together, the findings of Experiments 4 and 5 are strong evidence against the hypothesis that the blindness effect is due to some interference in short-term memory between similar (compatible) items. Instead, they support the hypothesis that the blindness effect is a failure to perceptually encode response-compatible stimuli.

One could argue, however, that the task of memorizing an arrow presented before the response cue is different from the task of identifying an arrow following the response cue in that the sequence of the to-be-memorized events is reversed (stimulus–response in the first case, response–stimulus in the second case). This might be critical because the Ranschburg effect is more likely to affect the second instance of two repeated items (e.g., Jahnke, 1969). When the arrow precedes the tone, however, participants have to interchange the relative positions of the two items in short-term memory in order to respond in the correct order. Thus, the arrow would again be the second instance of the repeated items in memory.

### General Discussion

The present study rests on the assumption of common perception–action codes that are involved both in the perception of stimuli and in the control of actions. Under this assumption, the preparation or execution of a response can be expected to affect the processing of a (compatible) stimulus that shares a feature with the response. Indeed, the execution of a left- or right-side keypress response impaired the identification of a simultaneously presented response-compatible arrow as compared with the identification of an incompatible stimulus. The main purpose of this article was to assess the temporal conditions under which this blindness to response-compatible stimuli does occur, and, on the basis of the results, to evaluate different explanations of the phenomenon.

Experiments 1 and 2 revealed that the identification of a response-compatible stimulus was impaired when it was briefly presented at different points in time between the presentation of a response cue and the timed onset of the response. However, the

blindness effect disappeared as soon as the response was executed. The observation that the blindness effect occurred for a period of nearly 2 s before response onset argues against our original refractory explanation of the blindness effect (Müsseler & Hommel, 1997a). According to our original explanation, the blindness effect is the result of a brief insensitivity of perception–action codes that only occurs during the execution phase of a response.

Experiment 3 tested two alternative explanations. According to the inhibition explanation, the blindness effect critically depends on the neutral double keypress or, more precisely, on the need to inhibit the critical response until the execution of the double keypress. The double keypress preceded the response in Experiments 1 and 2, as well as in all previous experiments on the blindness effect. In contrast, according to the occupation explanation, it is not the inhibition of perception–action codes that interferes with the processing of a stimulus but, rather, the occupation of these codes by processes that prepare or maintain a response in memory. In particular, the occupation explanation states that the integration of a set of activated perception–action codes, which is established to represent a response, makes these codes less available for other processes. Thus, when a specific code is occupied by the representation of a response, perceptual processing of a response-compatible stimulus is assumed to be impaired (cf. Hommel et al., in press). Whereas the inhibition account predicts that the blindness effect disappears when the double keypress is omitted from the task, the occupation account predicts that the blindness effect should nevertheless occur. Consistent with the latter, in Experiment 3, we observed the blindness effect without a double keypress in the response task.

Finally, Experiments 4 and 5 investigated whether the blindness effect arises at the level of perceptual encoding or in short-term memory. In other words, it was tested whether the preparation of a response interferes with the encoding of a compatible stimulus or whether it interferes with memorizing a compatible stimulus. Therefore, in Experiments 4 and 5, a visual stimulus was not only presented between the response cue and the response but also before the response cue. In the latter case, the preparation of the response cannot affect the perceptual encoding of the stimulus, it can only interfere with the retention of the stimulus. In both experiments, however, a blindness effect was only observed for stimuli appearing between the response cue and the response, suggesting that the blindness effect arises at the stage of perceptual encoding.

In summary, the results of the present experiments support the notion that the occupation of cognitive perception–action codes, because of their integration into a representation of the response, makes them less available for perceptual processing and, thus, impairs the encoding of response-compatible stimuli. However, it might be necessary to justify why we dismiss the concept of code inhibition and prefer the concept of code occupation. From a functional point of view, there is an important difference between an inhibited code and an occupied code. An inhibited code is—by definition—not active and, thus, cannot be used by any cognitive process(es). In contrast to this definition, an occupied code is an active code that is integrated with other active codes and, therefore, it cannot be used by another cognitive process. In our view, the concept of code occupation is well suited to explain the present findings as well as the findings of other dual-task experiments.

In the task used in the experiments of this study, participants do have to inhibit the execution of the response until the presentation of a go signal. At the same time, however, the participants also have to maintain the cognitive representation of the response (an action plan) active. In other words, while the participants maintain an active cognitive representation of the response, they prevent this action plan from gaining control over the motor system until the go signal appears. Thus, in our view, not the inhibited motor response but, rather, the active cognitive representation of the response (i.e., a set of integrated perception–action codes) interferes with the perception of a compatible stimulus.

The same explanation applies to the dual-task experiments of Stoet and Hommel (1999), in which the participants had to maintain an already prepared Response A active while they had to perform a second Response B. It was observed that Response B was slower when it was compatible with the already prepared Response A than when it was incompatible. In addition, in the dual-task experiments of Wühr and Müsseler (in press; see also, Müsseler & Wühr, in press; Wühr, 2000), participants had to perform the response immediately on the presentation of the response cue. Thus, when the response cue occurred, participants had to activate the corresponding response and to execute it right away, but nevertheless, a blindness effect was observed.

The blindness effect seems to be inconsistent with recent observations reported by Craighero, Fadiga, Rizzolatti, and Umiltà (1999). These authors had participants prepare a grasping movement to a bar rotated 45° to the left or right. The execution of the movement was signaled by the picture of a bar that served as a go signal. Although the orientation of the go signal was irrelevant to the task, movements were started more quickly if the orientation of the go signal was compatible with the planned action, that is, if it matched the orientation of the to-be-grasped bar. In one experiment, participants had to grasp the object only in two thirds of the trials, whereas they had to press a key with the foot in the remaining trials. Nevertheless, keypresses with the foot were faster when the go signal was compatible with the prepared—but now to-be-inhibited—grasping response. This observation led Craighero et al. to conclude that the prepared response facilitated the processing of the congruent go signal, and not vice versa. This conclusion seems to be at odds with the conclusion that was drawn from the blindness effect.

However, there are important differences between the task used by Craighero et al. (1999) and the task used to investigate the blindness effect. Most important, in the Craighero et al. study, participants only had to detect the go signal (or to discriminate between two rather dissimilar stimuli). According to our account, however, the occupation of an active code, due to its integration into an action plan, does not mean that this code cannot be activated further. The occupation of a code only interferes with attempts to integrate the same code into a second representation. However, such an attempt was not necessary in the Craighero et al. study because the go signal only had to be detected, but it did not have to be reported later on. Accordingly, our explanation of the Craighero et al. results is that the pre-activation of perception–action codes, because of the preparation of the grasping response, helped to detect some features of the go signal. Of course, this interpretation needs empirical validation and future research is needed to further specify the mechanisms, which operate on the shared perception–action codes.

Another difference between the motor-visual facilitation effect reported by Craighero et al. (1999) and the blindness effect is that the former effect was found in reaction times, whereas the latter effect was observed in the accuracy of unspeeded perceptual judgments. There is evidence that similar experimental conditions can differentially affect the reaction time of speeded responses and the accuracy of unspeeded judgments. On the one hand, B. A. Eriksen and C. W. Eriksen (1974) observed that speeded responses to a target stimulus were facilitated by the presentation of identical (i.e., compatible) stimuli that flanked the target stimulus. On the other hand, Bjork and Murray (1977) observed that the unspeeded judgment of a target stimulus was impaired by the presence of an identical distractor stimulus in a masked display. These observations led Santee and Egeth (1982) to conclude that accuracy and reaction time are not (always) converging measures of the same processes. In particular, they argued that accuracy appears to be more sensitive to interactions between perceptual processes under constrained viewing conditions, whereas RT appears to be more sensitive to interactions between response-related processes under constrained and unconstrained viewing conditions.

To conclude, a feature overlap between two stimuli or between two tasks cannot always be expected to affect accuracy and reaction times in the same way, even under seemingly similar experimental conditions. Rather, the given task demands need to be carefully analyzed in order to improve our understanding of how the feature overlap between two tasks can affect the perception of stimuli and the control of actions.

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