Can actions affect perceptual processing?

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Previous studies reported impairments in a perceptual task performed during the selection and execution of an action. These findings, however, always raise the question of whether the impairment actually reflects a reduction in perceptual sensitivity or whether it results only from an unspecific reduction in attentiveness given the perceptual task. Recent studies by the authors indicate that actions can also have a specific impact on perception in a dual-task situation. The identification of a left or right arrow is impaired when it appears during the execution of a compatible left or right keypress. In three experiments Signal Detection Theory is applied to test whether this impairment is also found in the sensitivity measure d' or whether it originates only from a response tendency. The results revealed a general lower d' for the identification of arrows that were compatible to simultaneously executed keypresses than for arrows that were incompatible. The bias measure c was small and/or did not differ between conditions. Additional analyses revealed that the impairment is due to a higher mean perceptual degradation of stimuli in the compatible condition and that it is restricted to the point in time when the central movement command is generated. Thus, actions actually seem able to affect perceptual processing.

Perception and action seem to fulfil different functions: Perception processes pick up and analyse events in our environment by afferent mechanisms, whereas action processes produce and change events in our environment by efferent mechanisms. Although these two mental functions can be highly interactive under most ecological conditions (e.g., in sensorimotor tasks like pointing or grasping), they are often considered to be two self-contained functions that, to a high degree, operate independently. However, some everyday-life observations give reason to doubt this independence. Imagine, you are intensely watching a soccer game on TV, eating away at a bowl of popcorn, when suddenly something happens in the game. Immediately you stop reaching for the popcorn. It is your ''impression'' that during reaching and eating you cannot ''perceive'' in an

adequate manner. The present contribution is concerned with this impression, that is, with the question of whether action processes actually affect perceptual processing.

So far, only a few authors have been interested in the question of whether processing in one task also affects perceptual processing in the other (e.g., De Jong, 1993; De Jong & Sweet, 1994; Kahneman, Beatty, & Pollack, 1967; Ruthruff, Miller, & Lachmann, 1995; for an overview, see Müsseler, 1999). For example, De Jong (1993; De Jong & Sweet, 1994) observed that the identification of a single, foveally presented letter had to be postponed while the observer is engaged in an auditory first task. They reported that "perceptual identification is impeded even when the overlapping task imposes only minimal perceptual requirements" (De Jong & Sweet, 1994, p. 150; see also Pashler, 1989) and concluded that the impairment results from a rather unspecific bottleneck necessary for both the complex perceptual analyses and the response-preparing activities.

However, such demonstrations of rather unspecific perceptual impairments always raise the question of whether they really reflect a reduction in perceptual sensitivity or whether they only result from a reduced attentiveness given the perceptual task. Therefore, a demonstration of *specific* interferences is needed that establishes perceptual differences dependent on the action performed. Recent experiments have revealed such a specific impact of actions on perception. Müsseler and Hommel (1997a) showed that the identification of stimuli in a dual-task-like situation depended heavily on their specific relationship to the response performed in parallel. This was observed in a task in which masked left or right arrows were presented shortly before the execution of an already prepared manual left or right keypress. It was found that the identification of a right arrow was reduced when presented during the execution of a right action as compared to that of a left action and vice versa ("blindness to response-compatible stimuli"; for an overview, see Müsseler, 1999). This finding points to a more specific structural limitation of perceptual processing caused by the temporal overlap during preparation and/or execution of a commensurable action.

Our interpretation of this finding was that initiating an action goes along with a transient insensitivity to a stimulation that shares common codes with the response within the same cognitive system. The structural view underlying this notion regards codes as (task-relevant) features of stimuli and/or responses. The representation of stimuli and responses within a common-coding system is a consequence of the old idea that responses may be cognitively evoked by the (anticipatory) codes of their sensory effects (James, 1890; Lotze, 1852). In other words, the intentions to act emerge from the already existing representations of possible action effects (see also Greenwald, 1970; Tucker & Ellis, 1998). More recently, Prinz (1990, 1997) has indicated that in this case both stimulus codes (i.e., codes of perceived events) and response codes (i.e., codes of to-be-produced events) should be of a commensurable format and refer to- hence, represent- both external events (see also Hommel, 1997; Hommel, Müsseler, Aschersleben, & Prinz, 2000; Müsseler, 1999).

During the last decade, several neurophysiological findings also point to common modules in the brain shared by perception and action control. For example, Sakata and colleagues recorded the activity of neurons in the parietal cortex of monkeys that had been trained to manipulate various types of switch (e.g., push buttons and pull levers, see Sakata, Taira, Murata, & Mine, 1995; Taira, Mine, Georgopoulos, Murata, & Sakata,

1990). Particularly interesting is their finding that a proportion of these neurons is active during the manipulation of a given switch in the dark as well as during the mere observation of that object (Sakata et al., 1995; Taira et al., 1990). Another population of neurons in the inferior premotor cortex of monkeys (area F5) also becomes active, both when monkeys perform a given action, like grasping or holding food, and when they observe a similar action performed by the experimenter (so-called "mirror neurons", see Di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). There are also hints that corresponding observation/execution modules exist in humans, too (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Rizzolatti et al., 1996). In sum, there is considerable evidence of the existence of several populations of neurons that are involved both in perceptual and in motor processing, and which could serve the function of representing a certain action and, possibly, its meaning (Gallese et al., 1996).

If that assumption of a common representation of perception and action is true, specific interferences could originate from confronting perceived events with (to-be-produced) motor events. In other words, an additional activation of a code could be impaired when it is already involved in the selection and programming of an action. This could also be true on a more abstract level, for example, when the RIGHT code is involved in the selection and programming of a right keypress, and, if at that point in time a right-pointing stimulus must be perceived, the perceptibility of the stimulus should be decreased during the preparing period of the central movement command (Müsseler, Wühr, & Prinz, 2000). That is exactly what the blindness phenomenon represents.

However, it is still under discussion whether the blindness effect actually reflects a reduction in the perceptual information available to an observer, or whether it originates from a judgement bias in perceptual unclear situations. Possibly, observers tend only either to contrast or to assimilate their perceptual judgement in respect to the response (R)- whatever the reason for such higher order strategies may be. A possible contrast strategy could be to judge preferably a right (left) stimulus (S), when a left (right) R is executed. This strategy should increase the probabilities of hits and correct rejections in the incompatible condition. An assimilation tendency- that is, when a left (right) R is executed, a left (right) S is preferably judged- should increase the probabilities of hits and correct rejections in the compatible condition. Obviously, the blindness phenomenon could only emerge- if at all- from a contrast strategy.

In order to isolate participants' response tendencies, Müsseler and Hommel (1997a) used additional catch trials where no stimulus was presented at all. The probability of compatible and incompatible judgements did not differ in the catch trials, but compatible stimuli were identified less often than incompatible stimuli in the remaining trials. In another experiment, they observed a blindness effect even though participants only had to detect the presence or absence of stimuli, which could be compatible or incompatible with the overlapping keypress. Thus, the direction of arrows was task irrelevant; nevertheless the blindness effect appeared (Müsseler & Hommel, 1997b). The problem is that in these studies proportion correct (p_c) was used as dependent measure, which can only be interpreted unequivocally if participants' judgements were unbiased.

The Signal Detection Theory (SDT) offers a tool for dealing with this problem (e.g., Green & Swets, 1966; MacMillan & Creelman, 1991; Swets, Tanner, & Birdsall, 1961). SDT allows determination of different statistics for the observers' perceptual sensitivity

in a given task and the observers' bias to prefer one judgement or response alternative to the other. If a reduction in sensitivity (d') is found, it can be concluded that the blindness effect is due to an actual reduction in the information of a compatible item available for report, and not due to a guessing bias. The following experiments, in which the SDT methodology is applied to the task of Müsseler and co-workers, examine whether there is an effect of actions on perception and thus a specific structural influence of action preparation or execution on perceptual processing. In Experiment 1 we introduce an additional S-absent condition with the aim to take into account a higher order strategy in the calculations of d' and c. In Experiment 2 we put a possible response strategy to another test. An actual perceptual impairment by R should depend on the point in time when S is presented, whereas a higher order strategy should not.

EXPERIMENT 1

This experiment was designed to determine the blindness effect to response-compatible stimuli in terms of the sensitivity index d' of SDT. The question of interest is whether observers show differential perceptual processing of a left- or right-pointing stimulus (S) when performing a compatible or incompatible keypress (R). The advantage of d' is its independence of the observer's bias to favour one response over the other, which can be estimated separately by the measure c.

The observers' task was to detect either the presence of left or right arrows or their absence. If observers apply a higher order contrast strategy to perceptual uncertain situations, that is, when a left R is executed, they prefer a right judgement and vice versa; S presentation should not be critical at all. In other words, this strategy should be applied in every perceptual uncertain situation independent from the compatibility relation between R and S. Thus, it should also be applied when no stimulus is presented at all. The detection procedure allows testing for the presence of a contrast strategy in two ways. First, a contrast strategy should increase corresponding judgements also in S-absent trials. Second, the design of this detection experiment allows the computing of a bias measure c for the compatible and incompatible condition that directly reflects the dependence of participants' judgements from R.

There is another question that can be addressed with this detection task. The disadvantage in identifying response-compatible stimuli may result from different perceptual qualities. One extreme is that the mechanism causing the blindness works in a graded fashion: The quality in which participants perceive all stimuli throughout the experiment gradually varies from perfect, over some intermediate states, to very bad quality. The disadvantage of identifying compatible stimuli results from a mean lower perceptual quality in compatible trials than in incompatible trials. Another extreme is that the blindness mechanism works in an all-or-none fashion: Participants either perceive the compatible stimulus quite well or they see nothing. Then the disadvantage of the compatible stimuli results from their higher absolute threshold.

The present task allows us to test between these possibilities. In the experiment no stimulus was presented in one third of all trials, and participants had to detect the presence or absence of left and right arrows, while they performed left or right keypresses R. Participants then could make two qualitatively different errors: One error was to

declare that a compatible stimulus had been presented, when in fact an incompatible stimulus was shown, and vice versa. This will be called a "miss of Type II". The other error was to declare the absence of a stimulus, when in fact a stimulus was present, which will be termed a "miss of Type I". The "graded" and "all-or-none" blindness account makes different predictions for the occurrence of each error type in compatible and incompatible trials. The "graded-quality" account predicts that participants will commit both types of error in compatible and incompatible trials, with a higher proportion of errors in the compatible condition. Conversely, the "all-or-none" account predicts that there will be a selective increase of misses of Type I in the compatible condition- given that the response measure c is almost identical. The assumption of the "all-or-none" account is that misses of Type II do not result from the mechanism causing the blindness effect but from other factors being constant between compatible and incompatible trials. Accordingly, an interaction between error type and compatibility would indicate that the blindness effect emerged from an "all-or-none" impairment.[1] Thus, the outcome of such a detection experiment also sheds more light on the nature of the blindness effect.

Method

Participants

A total of 15 students from the University of Munich participated and received payment. The 4 male and 11 female participants had an average age of 24 years. All participants reported having normal or corrected-to-normal vision.

Materials

The experiment was performed in a dimly lit, soundproof cabin. Stimuli were presented in black-on-white at the centre of a 71-Hz computer screen. The display was positioned at a viewing distance of 50 cm; its luminance was approximately 39 cd/m^2. The observer sat at a table with a chin and forehead rest. To respond, the participants had to press the two switches of a computer mouse with their index and middle fingers of the right hand.

A left or right keypress (R), as indicated by a response cue, was paired with the presentation of a left- or right-pointing arrow or with no stimuli S (see Figure 1). Response cues were dark or white squares measuring 0.6×0.6 degrees of visual angle and were presented $0.75°$ below screen centre until a judgement screen of S appeared (see later). A dark square indicated a to-be-executed left R, a white square a to-be-executed right R. The to-be-identified arrows S ("<" or ">") measured 0.6×1.0 degrees and were presented 0.75 degrees above screen centre for an individually adjusted presentation time. The arrow heads (the empty field in the no-stimulus condition) were replaced by a visual mask, a rectangle of 0.7×1.3 degrees, in which every pixel was set with a probability of .66 in each trial.

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[1] Note that these hypotheses only make sense in the present context by analysing the predicted *hybrid interaction* caused by a selective increase of misses of Type I. An additional assumption is that the criterion c does not differ between conditions. Absolute differences in misses of Types I or II or any other type of interaction, of course, do not allow any conclusions about the perceived degradation of a stimulus.
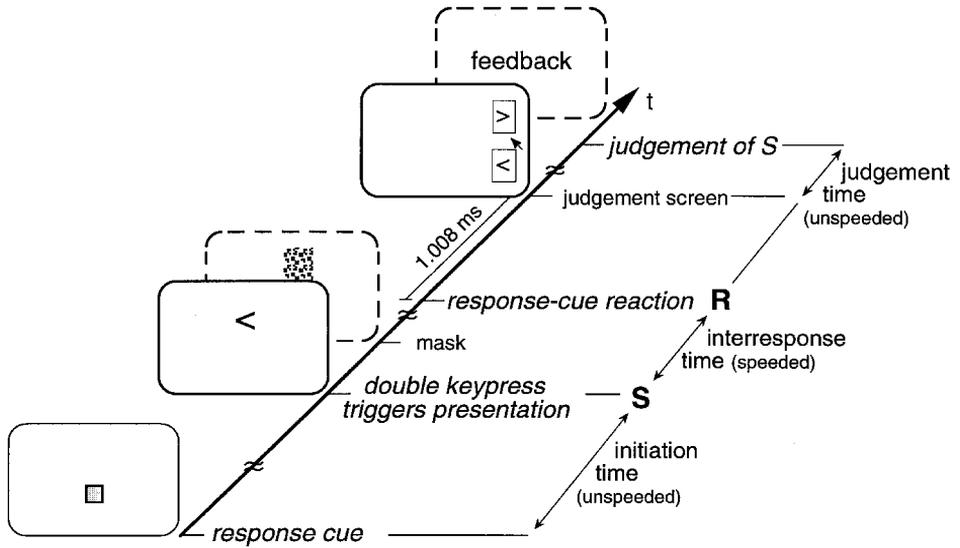
Figure 1. Basic paradigm of the experiments. A response cue (black or white square) indicated to execute a left or right response R. Before executing R, participants pressed both keys simultaneously. While pressing both keys, a masked stimulus S (left- or right-pointing arrow) was shown for an individually adjusted presentation time (between 14 and 70 ms). A trial was completed with an unspeeded judgement of the identity of S.

Design

A left or right R was combined with three stimulus conditions S: either a left or a right arrow or no stimuli were presented with equal probability in random order. A to-be-executed left or right key-press (R) together with the presentation of a to-be-identified left or right arrow (S) yields two compatible (left–left, right–right) and two incompatible (left–right, right–left) combinations. The no-stimulus condition functioned as the "noise" condition in SDT terminology and was used only to calculate the $d's$ for the two different "stimulus + noise" conditions. Thus, the distinction between stimulus-present versus stimulus-absent trials was not an experimental factor, but a necessary aspect of the design in order to calculate $d's$ (cf., Kanwisher, Kim, & Wickens, 1996). In the test phase, participants ran through 234 trials, grouped in 13 blocks with 18 trials each. The identification probabilities of the masked arrows were the main dependent variable, but interresponse times were also analysed.

Procedure

The sequence of events is shown in Figure 1. Each trial started with the presentation of a response cue signalling the execution of a left or right keypress after a simultaneous press of both keys. As soon as this obligatory double keypress had been executed the presentation of the masked S was triggered with the subsequent vertical retrace of the monitor. This ensured that S fell into the execution phase of R. Participants were instructed to prepare- for as long as they wished- the double keypress and R as one sequence in advance, but to perform them as fast as possible after each other. S was presented for an individually adjusted, near-threshold presentation time, which was determined by a pre-test at first and was subsequently adjusted during the experiment. If the participant's error rate in one block was below 10% or above 40%, presentation time decreased or increased by one

vertical retrace of the monitor. On average, *S* was presented for 21 ms in Experiment 1 and 25 ms in Experiment 2.

After an additional blank interval of 252 ms the mask was replaced by a judgement screen 1,008 ms after *R* offset. The judgement screen consisted of a left and right arrow field or an empty field, one above the other, at the margin of the screen. The position of the fields varied randomly. Participants indicated their identification judgement of *S* by selecting a field from the screen with the mouse cursor. Incorrect responses (*R* incorrect, *S*-judgement incorrect, or *R* not within 1 s after double keypress) entailed a beep and an error message.

Results and discussion

A proportion of 6.4% of all trials was excluded from analysis, because participants either gave the wrong *R* or needed more than one second to perform *R* after the double key-press. The following latencies were observed: Participants initiated the double keypress on average 766 ms ($SE = 149$) after response-cue onset; the mean interresponse times before *R* were 182 ms ($SE = 20$); and the mean judgement times were 901 ms ($SE = 36$). None of these latencies was affected by the compatibility relationship between *R* and *S* (all $t < 1$, all $p > .70$, two-tailed); thus, there was no indication of a speed–accuracy trade-off.

Analysis focused on the participants' identification rates. The proportion of correctly identified response-compatible arrows was lower than that of incompatible arrows (.734 vs. .800, $SE = .03$ vs. .02). This difference is statistically significant with $t = 2.40$, $p = .015$, one-tailed, replicating the blindness effect in the proportion-correct values.

The absence of arrows was correctly reported with a mean probability of .776 ($SE = .02$). Thus, false alarms were committed with a mean probability of .224, which were compatible to the performed *R* with a probability of .127 ($SE = .02$) and incompatible with a probability of .098 ($SE = .02$). Although this difference is not significant ($t = 1.46$, *ns*), participants seem to have the tendency to assimilate their judgements with *R* and not to contrast it. A contrast strategy would artificially decrease the "identification" rate in the compatible condition and increase the rate in the incompatible condition independently from perceptual processing. As such a strategy was obviously not applied, a response-bias interpretation of the blindness effect is not very likely. However, this conclusion is based only on the comparison of the *S*-absent trials in both conditions without taking into account the corresponding *S*-present trials. Therefore, an SDT analysis was performed that allowed estimation of participants' tendencies with the whole data set.

In terms of SDT, this experiment was analysed in the following way. The compatible (incompatible) "hit rate" is the proportion of correctly identified *S* during the execution of a compatible (incompatible) *R* (Table 1). "Miss rates" result from the incorrect judgements of arrow direction (misses of Type II) and the absent judgements (misses of Type I) in the compatible and incompatible stimulus-present trials. "False alarms" are the proportions of erroneously reported arrow detections in the stimulus-absent trials, and-consistent with the determination of hits- compatibility of false alarms was determined by the relation of *R* and perceptual judgement. As "correct rejections" are not "compatible" and "incompatible" trials a priori, correctly identified stimulus-absent trials were divided in two, so that the total amount of stimulus-absent trials became identical in the

TABLE 1
Mean judgement rates of S and their assignments to the compatible
and incompatible 2 × 2 tables

	Arrow S	R	<	>	%
			Judgement of S		
compatible	<	1	.753[a] hits	.126[a] misses II	.122[a] misses I
	>	r	.165[a] misses II	.715[a] hits	.121[a] misses I
	abs	1	.138[a]		
		r		.115[a]	.747[a] correct rejections
			false alarms	false alarms	
incompatible	<	r	.787[b] hits	.128[b] misses II	.085[b] misses I
	>	1	.093[b] misses II	.813[b] hits	.094[b] misses I
	abs	1		.091[b]	
		r	.104[b]		.806[b] correct rejections
			false alarms	false alarms	

[a] $d' = 1.38$, c = 0.04; [b] $d' = 1.84$, c = 0.04.
Note: The sensitivity measure d' and the criterion c are averaged across participants. S = masked left- or right-pointing arrow, "<" or ">" respectively; abs = S absent; 1 and r = accompanying critical left or right response (Experiment 1, $N = 15$).

compatible and incompatible 2 × 2 table.[2] Hence, every row in Table 1 is based on the same number of trials.

The SDT analysis yielded a d' of 1.38 ($SE = 0.11$) for the compatible condition and a d' of 1.84 ($SE = 0.12$) for the incompatible condition. The compatible d' was significantly lower than the incompatible d', $t = 2.42$, $p = .015$, one-tailed. The differences between the d's for both conditions and the corresponding differences in the proportion of correct values were significantly correlated, with $r = .701$, $p < .01$, two-tailed.

The bias indices c were 0.04 ($SE = 0.08$) and 0.04 ($SE = 0.09$) for the compatible and the incompatible conditions, respectively. These indices did not differ statistically from

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[2] Another way to analyse the experiment is to treat it as an arrow-detection experiment only, that is, to define hits as the detection of arrows independent of their direction. In that case misses of Type II have to be added to the hit rate. This less restrictive SDT analysis yielded also a significant difference between the d' values for the compatible and for the incompatible condition with d' = 1.93 ($SE = 0.17$) vs. d' = 2.33 ($SE = 0.15$), $t = 2.25$, $p = .021$, one-tailed. The corresponding bias indices c of -0.24 ($SE = 0.05$) and -0.20 ($SE = 0.07$) did not differ statistically from each other ($t < 1$).

each other and from zero (all $t < 1$). A significant positive bias in the compatible condition, together with a significant negative bias in the incompatible condition, would have indicated a contrast tendency. This, however, was obviously not the case.

Participants could make two different errors in the stimulus-present trials. The first error was to report the absence of a stimulus (misses of Type I), the second error to report the arrow wrongly (misses of Type II). Table 1 also shows the proportions of these error types for compatible and incompatible trials separately. A 2 (type) $\times$ 2 (compatibility) analysis of variance (ANOVA)[3] with the mean corresponding error rates of each participant yielded only a main effect of compatibility, $F(1, 14) = 5.72$, $p = .031$, $MSE = 0.003$; that is, the total of both errors was higher in the compatible (.133, $SE = .01$) than in the incompatible condition (.099, $SE = .01$). This result indicates that the blindness effect works in a "graded" manner rather than in an "all-or-none" fashion. Otherwise, a selective increase of misses of Type I should have been observed in the compatible condition, leading to an interaction of both factors, which was not the case ($F < 1$).

To summarize, three main conclusions result from the findings of Experiment 1. First, participants performed worse when identifying a stimulus during the execution of a response that was compatible to it. This impairment was not only expressed in a lower proportion correct, but SDT analysis also revealed a significantly lower sensitivity index d' for the identification of response-compatible stimuli than for the identification of incompatible stimuli. Second, inspection of false alarms and of indices c yielded evidence against an explanation of the blindness effect in terms of a response tendency to contrast judgements with R. Third, a comparison of the relative proportions of misses of Type I and of Type II suggested that the processing of compatible stimuli was impaired in a graded fashion. In other words, there probably was a higher perceptual degradation of the available stimulus information in the compatible condition than in the incompatible condition.

EXPERIMENT 2

Experiment 2 further weighs the response-strategy account against a perceptual interpretation of the blindness effect. According to any response-strategy account, varying the time at which S is presented should be less critical. For example, if the blindness effect originates from the strategy to contrast the judgement in respect to R, this strategy should be applied irrespective of whether S is presented shortly before, simultaneously with, or after R.

As opposed to this, a perceptual account predicts a dependence of the effect on the point of time of presentation. So far, the blindness effect has been interpreted with the idea that initating an action goes along with a transient insensitivity to a stimulation that shares common codes with the response within the same cognitive domain. To be more concrete, it is only when the RIGHT code is involved in the selection and programming of a right keypress, and if at that point in time a right-pointing stimulus must be perceived, that the sensitivity for that stimulus is assumed to be decreased during the generation period of the central movement command. Therefore, this account predicts that the

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[3] All F probabilities of the ANOVAs were Greenhouse–Geisser corrected.

identification performance for compatible stimuli relative to that for incompatible stimuli should vary substantially with the temporal relation between the presentation of S and the execution of R. In particular, the assumption is that the blindness effect is restricted to a short insensitivity period following the generation of the central movement command (for an elaboration of this idea, see Müsseler & Hommel, 1997a,b).

In order to test these alternatives, the temporal relation between the presentation of S and the execution of R is varied in Experiment 2. Two presentation points in time are added to the basic procedure: The to-be-identified S appears not only with the onset of the double keypress before the critical response R, but also with the onset of R, as well as half a second after the offset of R. The first temporal condition should replicate the basic finding of compatible stimuli being less well perceived than incompatible stimuli. If S appears with the onset of R, the outcome can be twofold. On the one hand, in this situation the critical central movement command for R has obviously already been transferred to the muscles, and therefore the LEFT/RIGHT code could become available for perceptual processing again. In that case the blindness effect should decrease markedly. On the other hand, Müsseler and Hommel (1997a) argued that the functional role of the transient insensitivity may be to protect an already performed action from being activated again by the (response-compatible) action effects (cf., perseveration assumption, MacKay, 1986). In that case an increase of the blindness effect is to be expected at the point in time when the action effects occur, that is, when R is executed.

If S is presented late, for example, half a second after the offset of R, compatibility should no longer affect the identification of S. At least, the response-strategy account and the insensitivity-period account make different predictions for this temporal condition. Contrary to the insensitivity account, a response-strategy account predicts a constant disadvantage for compatible stimuli at all three presentation points in time, because there is no reason why participants should alter their strategy within a short period of time.

Method

Participants

Twenty adults with an average age of 29 years served as participants.

Materials, design, and procedure

These were the same as those in Experiment 1 with two modifications. First, we dropped the no-stimulus condition from the design, because we are now mainly interested in differences of the compatibility conditions between stimulus–response-onset asynchrony (SROAs). Thus, a to-be-executed left or right keypress (R) was only paired with the presentation of a to-be-identified left or right arrow (S). Second, the time interval between R and S was varied. As before, S could appear with (the next vertical retrace of the monitor after) the onset of the obligatory double keypress before R, or with the onset of R, or 504 ms after the offset of R. These three intervals of SROA were varied in a complete randomized sequence with the compatibility factor, yielding a 2×3 within-participants design. The experiment consisted of 384 trials (16 blocks of 2 compatibilities $\times$ 3 SROAs $\times$ 4 repetitions).

Results and discussion

If a choice error was observed in R, these trials were excluded from further analysis. This was necessary in 2.0% of the trials and depended neither on the compatibility between S and R nor on the times at which the stimuli were presented (all $p > .25$). The following mean response latencies were observed: The mean initiation times were 952 ms ($SE = 79$), the interresponse times ran up to 149 ms ($SE = 10$), and the judgements required 928 ms ($SE = 31$) on average. None of these latencies was affected by the compatibility factor or by the SROA (all $p > .05$).

The probabilities for identifying the masked arrows S were affected by both factors: When presented with the double keypress, compatible S were less often correctly identified than incompatible arrows (.706 vs. .773, Figure 2 and Table 2). When presented with the onset of R, the disadvantage of the compatible condition was reduced (.765 vs. .792) and even reversed when presented 504 ms after the onset of R (.793 vs. .751). Accordingly, a 2×3 ANOVA indicated only a significant interaction, $F(2, 38) = 3.99$, $p = .029$, $MSE = .0076$ (all other $p > .15$).
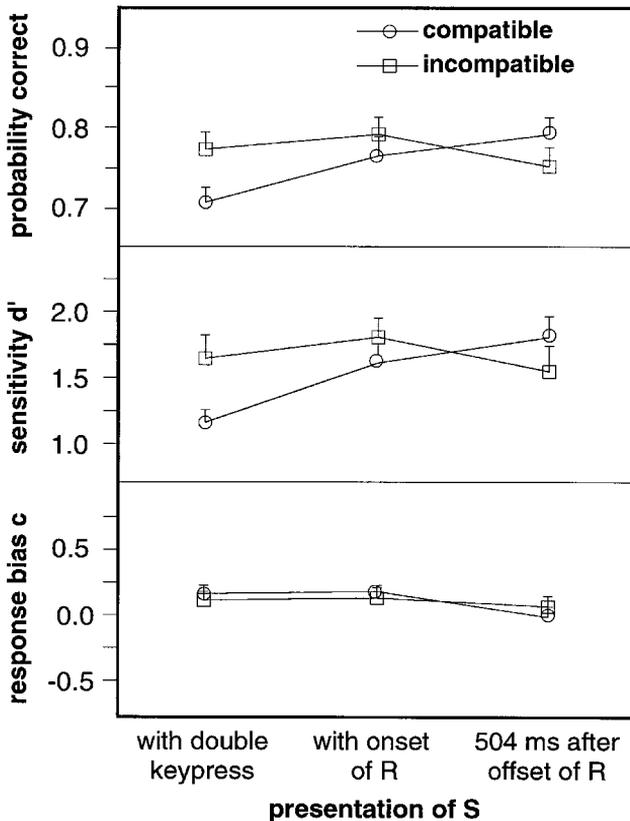

Figure 2. Mean probability correct, sensitivity d' and response bias c (with standard errors between partici-pants) for compatible and incompatible masked arrows S. Arrows S were presented at three points in time relative to the onset of the critical response R (Experiment 2, $N = 20$).

TABLE 2
Mean judgement rates of S for three presentation points in time relative to the onset of R

			Judgement after presentation of S					
			With double keypress		With onset of R		504 ms after offset of R	
	Arrow S	R	<	>	<	>	<	>
compatible	<	l	.655[a] hits	.345[a] misses	.720[b] hits	.280[b] misses	.802[c] hits	.199[c] misses
	>	r	.245[a] false alarms	.755[a] correct rejections	.191[b] false alarms	.809[b] correct rejections	.216[c] false alarms	.784[c] correct rejections
incompatible	<	r	.746[d] hits	.254[d] misses	.762[e] hits	.238[e] misses	.739[f] hits	.261[f] misses
	>	l	.200[d] false alarms	.800[d] correct rejections	.178[e] false alarms	.822[e] correct rejections	.237[f] false alarms	.764[f] correct rejections

[a] $d' = 1.16$, c = 0.15; [b] $d' = 1.62$, c = 0.1; [c] $d' = 1.81$, c = −0.0; [d] $d' = 1.65$, c = 0.12; [e] $d' = 1.80$, c = 0.13; [f] $d' = 1.55$, c = 0.06.
Note: The sensitivity measure d' and the criterion *c* are averaged across participants. S = masked left- or right-pointing arrow, "<" or ">" respectively; l and r = accompanying critical left or right response R (Experiment 2, N = 20).

SDT analysis was performed separately for each SROA. The data of each SROA can be treated as containing two yes–no experiments testing the ability to discriminate between left and right arrows under compatible and incompatible conditions, respectively (see Table 2). The proportion of correct identifications of left arrows presented together with a left accompanying R was treated as the compatible "hit rate". Correspondingly, the proportion of erroneously reported left arrows, when in fact a right arrow was presented before a compatible right R, was considered as the compatible "false alarm rate". The same rationale was applied to the incompatible condition. Of course, alternatively the 2 × 2 tables could be constructed by treating the proportions of correct and incorrect judgements of *right* arrows as compatible "hit rate" and "false alarm rate", respectively, but this rearrangement would not affect the estimation of the SDT parameters.

As can be seen from Figure 2, mean d' nearly paralleled the findings in proportion correct. When presented with the double keypress, the mean d' during the execution of a compatible R was 1.16 ($SE = 0.11$), whereas d' under incompatible conditions was 1.65 ($SE = 0.17$). When presented with the onset of R, the disadvantage of the compatible condition was reduced ($d' = 1.62$ vs. 1.80; $SE = 0.19$ vs. 0.15) and even reversed when presented 504 ms after the offset of R ($d' = 1.81$ vs. 1.55; $SE = 0.16$ vs. 0.20). Accordingly, a 2 × 3 ANOVA indicates a significant interaction, $F(2, 38) = 3.67$, $p = 0.37$, $MSE = 0.38$ (all other $p > .15$). On the contrary, no statistical effect was observed in the response tendencies *c*.

However, it is important to note that in the SDT analysis the statistic c reflects only the degree to which the judgements of the participants depend on the two possible response categories: Do they prefer to judge either "left" or "right"? Nevertheless, evidence for the insensitivity period account comes from the differences in d' between the three intervals of SROA. In particular, this account predicts that the blindness effect is restricted to a short insensitivity period following the generation of the central movement command. That seems to be the case.

To conclude, the identification handicap for response-compatible stimuli S is reduced when presented simultaneously with the onset of R, and even tendentiously reversed when presented 504 ms after its offset. Obviously, the blindness effect occurs only during the generation period of the central movement command. As a consequence of this finding, a higher order response strategy is not very likely to account for the blindness effect.

GENERAL DISCUSSION

The present study was concerned with the phenomenon that, during the execution of an action, participants have problems in identifying stimuli sharing features with that action. In particular, when participants performed a left or right keypress and were asked to identify a left or right arrow in parallel, they performed less well with compatible relationships of keypress and arrow than with incompatible relationships. The experiments were designed to control possible guessing strategies of this phenomenon, according to which one of two alternative responses is preferred, instead of reflecting an error in perception. For example, participants could apply a contrast strategy by preferring a perceptual judgement that is opposite to R. Therefore, in Experiment 1 the observers' task was to detect either the presence or the absence of left or right arrows, while they performed left or right keypresses. This procedure allowed us to compute a d' of SDT robust against guessing strategies and to directly estimate the presence of these strategies in terms of c. The results revealed that the disadvantage for the compatible compared to the incompatible condition did not only show up in differences of percentage correct, but also in differences of the sensitivity indices d', which is evidence against a contrast strategy explanation of the blindness effect. This conclusion was confirmed in Experiment 2. A strategy explanation of any kind would assume that judgements are independent of the points in time of S presentation, but the results showed a clear dependency. In sum, the present study indicates that the blindness effect is not due to strategic factors, but more likely resembles an impairment of perceptual processing.

It is worth pointing out that the study also reveals further information about the possible nature of the blindness effect. First, from the proportion of errors that participants could make in the stimulus-present trials in Experiment 1, namely, to miss stimuli (misses of Type I) or to report wrong stimuli (misses of Type II), it can be concluded that the processing of compatible stimuli is impaired in a graded fashion. Otherwise the amount of misses of Type I should have selectively increased under compatible conditions, which was not the case. Consequently, our observers are not really "blind" to response-compatible stimuli, but they seem to perceive them in a less accurate manner.

Second, Experiment 2 revealed that the blindness effect occurs only during the generation period of the central movement command. According to the initial explanation provided by Müsseler and Hommel (1997a), the transient insensitivity during the generation of a response is caused by a brief refractoriness of cognitive codes, which is shared by representations of stimuli *and* responses. However, what matters is not the level at which the representations of response and stimulus overlap, but only that there are features that they share, whether they are physically or semantically defined (Müsseler, 1999). If they do share such features- and, thus, are cognitively represented by partially overlapping codes- the overlapping part is involved in both executing the response and perceiving the stimulus (cf., the ideomotor notion described later). Under the assumption that after using a particular code for execution, this code is less available for other processings, stimulus perception should be impaired. Our more specific assumption in respect to the present paradigm was that, when the LEFT or RIGHT code is involved in response generation, its sensitivity for a left- or right-pointing stimuli is reduced. This makes the system "perceptually blind" to stimulus events that share the direction feature with the response. This is what the present d' differences could reflect.

Thus, this result gives further evidence for the findings that perceptual processes can be impaired in a dual-task situation (cf., De Jong, 1993; De Jong & Sweet, 1994; Ruthruff et al., 1995). However, the present research is not only another replication of these studies but reveals a specific interference. This points to a direct cross-talk of perception and action at a given processing level, and not so much to an unspecific bottleneck due to a general limitation of attentional resources. However, it is very likely that unspecific and specific interferences are complementary. Indeed, we also found that the present perceptual task is much easier when the masked S is presented alone than when it is presented during the planning or execution of R. Accordingly, single-task performance was better than performance in dual-task trials (Müsseler, 1999). This clearly points also in our experiments to an unspecific impact of response generation upon perceptual identification. Therefore, on the basis of the present results we have no reason to reject the formulation that "the central bottleneck mechanism may be characterised more generally as being involved in the construction of discrete, categorical, or propositional representations" (De Jong, 1993, p. 978). This formulation is already able to integrate findings of specific interferences. The only assumption to add is that unspecific interference originates from a more general level of representation than specific interference. In the present paradigm, for example, unspecific interference might result from the necessity to perform categorical decisions in both tasks or it originates from the simple fact that both tasks refer to the abstract dimension DIRECTION, whereas specific interference needs the overlap in the LEFT or RIGHT code.

Although having a lot in common, it may be critical that the present dual-task situation differs in important aspects from the dual tasks applied in previous studies. Usually dual-task paradigms explicitly aim at the response-*selection* stage, which is achieved by presenting both stimuli in close succession with the instruction to speed up at least the first response (for an overview, see Pashler, 1994). Conversely, the present dual task was developed to show an impairment of stimulus perception during the *execution* of an action. Accordingly, the instruction stressed to prepare R (i.e., the execution of the sequence of double keypress and R) as long as participants wished, and the presentation

of S was realized within the execution phase of R. As can be seen from the rather large initiation times up to the double keypress (about 1 s), participants complied with the instructions. Thus, it is very likely that response-selection processes are not essential for the present blindness effect. Indeed, using a timed-response method, in which participants had to synchronize R with the third of three beeps, Wühr and Müsseler (2000) found the blindness effect for response-compatible stimuli within a period of two seconds before the execution of R. Thus, the blindness effect reflects a conflict that is already apparent during the planning phase of an action.

Crosstalks between perceptual and motor codes have also been found in other research areas. For example, in traditional compatibility research it is well known that facilitation or interference originates from a match or mismatch in stimulus and response features (for overviews, see Hommel & Prinz, 1997; Kornblum, 1992). The ideomotor studies of Greenwald (1970) are also based on the assumption that an overlapping part of stimulus and response can be involved in both perceiving a stimulus and generating a response. He pointed out and was able to show that such overlap can produce S–R compatibility effects naturally. If an actor perceives a stimulus that resembles the effects of a certain action, the effect code is also activated to a certain degree (depending on the extend of stimulus-effect similarity), leading to an activation of the linked motor pattern. Besides the fact that in Greenwald's studies reaction times served as the main dependent variable (and not stimulus-identification rates), and that there are other obvious differences in the experimental procedure that we used, the basic underlying mechanisms might be related to our phenomenon (for a detailed discussion of this point, see Müsseler, 1999).

The idea of explaining perceptual restraints with an insensitivity of codes has also been applied to other perceptual phenomena. The term "repetition blindness", for example, refers to the effect that participants often fail to report the second occurrence of a visually presented stimulus, when it is repeated within a short interval (Hochhaus & Marohn, 1991; Kanwisher, 1987; Kanwisher & Potter, 1990). Repetition blindness has been claimed to be a perceptual phenomenon because it could be obtained under conditions in which memory load was minimal and perceptual sensitivity was assessed independently of response strategies (Hochhaus & Johnston, 1996; Kanwisher et al., 1996).

An interesting interpretation of repetition blindness has been proposed by Hochhaus and Johnston (1996). They used a slightly modified paradigm in which an unmasked precue word was presented for 250 ms, followed by a briefly presented masked target word, which was followed by an unmasked probe word. The participants' task was to indicate whether the probe matched the target word or not. The critical factor was the relationship between precue and target. When the target word repeated the precue word, error rates in the matching task were significantly higher than those in control conditions, in which the precue was either a dummy word (string of Xs) or an unrelated word. Hochhaus and Johnston suggested an explanation for their results, called the "diminishing returns psychophysics", which is an extension of the classical Weber's law. According to this law, the size of the just noticeable difference between two stimuli is a constant fraction of the size of the (smaller) standard stimulus. In other words, a constant increment imposed on a higher baseline level is harder to perceive. The authors proposed that this rule holds for activation in other kinds of domains such as letter or word detectors. Applied to their task, "the difference in activation levels between zero versus one

presentation (baseline condition) is easy to detect, compared with the difference in activa-
tion levels between one versus two prior presentations (repetition condition)" (Hochhaus
& Johnston, 1996, p. 365).

The same logic could hold for features like LEFT and RIGHT in our task. Given that
LEFT/RIGHT stimulus and response codes have a common mental representation, it would
be harder to tell whether this representation has gained a small increment in activation
from the presentation of S, if it has a higher level of activity to start with. This higher
activation may have emerged from preparing a compatible response to the precue. Then,
however, it could also be argued that the activation, which interferes with the perception
of S, does not come from preparing or initiating a response, but from processing the
"meaning" of the response cue. With this conception the blindness effect reflects an
overlap of processing at a mental or memory stage and not so much a direct crosstalk
of perceptual and motor processes in one common code. However, as long as it is not clear
where perceptual processes end and where mental or memory processes start, this objec-
tion is almost universally applicable. Who can really guarantee that d' sensitivity in a pure
perceptual discrimination task (say, with two tones of different pitch) emerges at a per-
ceptual level and does not arise from a later degradation of one piece of information at a
memory stage, whatever the reason might be? Additionally, if a d' effect occurs in an
identification or detection experiment where memory load is low, this "loss of informa-
tion" is not a very convincing explanation (for a similar argumentation concerning repeti-
tion blindness, see Kanwisher et al., 1996; Luo & Caramazza, 1995). Thus, it seems
justified to speak of the blindness effect as a perceptual impairment– at least, because
this view comes closest to what the observers report they have "seen". Thus, in our view,
responses can actually affect perceptual processing.

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