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RESEARCH ARTICLE

Perceptual criterion and motor threshold: a signal detection analysis of the relationship between perception and action

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Abstract Although a large number of studies have demonstrated that a motor response to a visual stimulus is, at least to some extent, independent of the perceptual response, little effort has been spent on the investigation of the explicit characteristics of this independency. In the present experiment, observers were presented with an S1–S2 stimulus-pair, with S1 within the threshold range and with S2 highly suprathreshold. S2 was displayed either at the same location as S1 (masked condition), or some degree to the left or right of S1 (non-masked). Both the observers' sensitivity to S1 and simple RTs elicited by the stimulus pair were jointly assessed on a trial-by-trial basis. Response times decreased with increasing S1 contrast for perceptual Hits both when S1 was masked by S2 and when it was not, but for Misses only when S1 was masked, though to a lesser extent than for Hits. When RTs are collapsed across perceptual Hits and Misses for any given S1-contrast, they were independent of whether S1 was masked or not. The data indicate that the motor system has a fixed, high-energy threshold, whereas the perceptual system has a d'-dependent criterion that can either be higher or lower than the motor threshold—depending on the particular conditions.

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Introduction

It is indisputable that the relationship between perception and action is more complex than what folk psychology usually assumes: perception does not inform and generate action. The demise of this classical input-output view of the perception-action couple (e.g., Neisser 1967) is the result of a number of studies suggesting that action might be controlled by visual information that is *not* present in conscious perceptual experience (see Rossetti and Pisella 2002). To name only two of a large number of examples: Bridgeman et al. (1979) showed that pointing movements toward visual stimuli relocated during the action remain accurate even if the observer does not consciously perceive the displacement; Aglioti et al. (1995) demonstrated that when subjects grasp the central circle of an Ebbinghaus illusion, grip size is determined by the true size of the circle to be grasped and not by its illusory size. However, as for this latter dissociation, for example, some studies suggest that it was mostly due to methodological artifacts (see Franz 2001). Thus, the matter at hand is in dispute.

Milner and Goodale (1995) originally accounted for the perception-action dissociation in terms of the two visual processing streams—ventral and dorsal—isolated by Ungerleider and Mishkin (1982) in the macaque brain. Presumably, the conscious representation of visual objects, on the one hand, and the unconscious guidance of movements toward these objects, on the other hand, require their processing along the ventral and dorsal streams, respectively.

Support for this double dissociation between perception-for-identification and perception-for-action comes from neuropsychological observations in patients suffering from optic ataxia (Perenin and Vighetto 1988) and visual agnosia (Goodale et al. 1991), two clinical syndromes caused by lesions of the dorsal and the ventral stream, respectively.

Experimental evidence in normal subjects draws first and foremost on the frequently used paradigm of *subliminal action priming* with backward masking. In this paradigm, observers are presented in rapid succession with two stimuli, the first of which (S1) is masked (hence close to or presumably below the "visibility threshold") by a second highly suprathreshold one (S2). In this paradigm the dissociation between perception and action is demonstrated if a *completely* masked (i.e., zero sensitivity/d') S1-stimulus (a theoretically untenable clause; see Schmidt and Vorberg 2006) affects motor performance (e.g., Taylor and McCloskey 1990) or, similarly, if the effect of the masked S1-stimulus on motor performance is larger than expected given its assessed visibility (for details see, for example, Schmidt 2002). Among such studies, Taylor and McCloskey's (1990) is conceptually the most comparable to the present investigation inasmuch as it relates *simple* (rather than choice) reaction times (RT) to the S1 + S2 stimulus-pair and the sensitivity to S1 (as assessed in independent sessions with a forced choice paradigm). Taylor and McCloskey showed that although the masked stimulus was reported "invisible" by the observer, the mean simple RT to the masked + masking stimulus-pair was shorter than the mean RT to the masking stimulus alone.

Effects of this kind imply that the motor response is, at least to some extent, independent of the perceptual response. Little effort has been spent, however, on the investigation of the explicit characteristics of this independency. According to the Signal Detection Theory (SDT; e.g., Green and Swets 1966), a stimulus will be reported anytime the internal response it elicits exceeds a criterion c and ignored otherwise (for more details see Fig. 4). From this theoretical perspective, the question bears on whether, and if so, how the motor response depends on the perceptual criterion. To anticipate, the present results suggest that the perceptual decision (i.e., whether to report a stimulus as being present or absent) is made with reference to a perceptual criterion which is variable in that it depends on the context the processing episode takes place in, whereas the motor response to the stimulus depends on a "fixed" energy threshold that is independent of the processing context.

The present study assesses sensitivity with a yes/no (SDT; Green and Swets 1966) paradigm and relates these responses to the motor latencies within the same experimental session on a trial-by-trial basis. To our knowledge, Waszak and Gorea (2004) were the first to take advantage of this experimental format. These authors presented subjects with a masked stimulus (S1; presented with a variable probability) followed by a mask (S2) and asked them to perform a speeded response to the onset of any of the two (S1 and/or S2) stimuli. In contrast to other experiments, their subjects were also required to indicate in each trial whether they perceived S1. This enabled Waszak and Gorea (2004) to assess the effect of S1 (the liminal masked stimulus) on RT as a function of both S1's sensitivity (d') and the observer's internal state, i.e., "seen" (perceptual Hits and False Alarms) and "not seen" (Misses and Correct Rejections).

Waszak and Gorea (2004) reported two types of effect of S1 (masked stimulus) on the motor RT. When, over a range of d', S1's physical energy was relatively weak (as a consequence of a weak backward masking by the highly suprathreshold stimulus, S2), RTs to the S1 + S2 stimulus-pair decreased with increasing d' *only* for perceptual Hits, that is once the internal response exceeded the perceptual criterion. However, when the physical energy of S1 was increased while keeping its visibility/d' constant (by means of shortening the S1–S2 stimulus onset asynchrony, SOA, and hence increasing S2's masking efficiency), RTs to the S1 + S2 complex decreased with increasing d' of S1 for *both* perceptual Hits *and* Misses, i.e., independently of the internal response exceeding or not exceeding the perceptual criterion.

Waszak and Gorea (2004) concluded that, as long as the physical stimulus energy is relatively low, visual stimulation is exclusively processed along the explicit (i.e., perceptual) pathway that serves as a gate to the motor system. It is only when the physical stimulus energy is strong enough to hurdle a high-energy motor response threshold that the 'automatic pilot' comes into play. While this account alludes to the existence of two distinct processing pathways and implies that the masking effect occurs in only one of them (the perceptual stream), the possibility remains that the incoming sensory information is processed along a unique pathway with the perceptual and motor responses triggered at different moments in the processing stream and by distinct magnitudes of the evoked internal response.

The present study uses Waszak and Gorea's (2004) paradigm to address two issues: First (but not foremost), it is meant to replicate and consolidate Waszak and Gorea's (2004) findings under conditions dissociating S1's physical strength (at a constant d') from the S1–S2 SOA factor, viz. by means of presenting the two stimuli at far apart spatial locations (so that the masking of S1 by S2 be negligible or null); this will insure that the different motor behaviors they obtained with low and high S1 energies cannot be attributed to this factor. Second, the study should help to put forward a more elaborated interpretation of the results that extends the conclusions drawn by Waszak and Gorea (2004). To anticipate, the present results attune to the existence of a one-way processing stream where perceptual and motor decisions are made with reference to an adjustable *criterion* and to a *fixed energy threshold*, respectively.

Methods

Observers

Five males and nine females, corrected to normal vision if necessary, all naïve as to the purpose of the experiment, with a mean age of 22 years took part in the experiment. Each observer received a 50 € compensation for his/her participation. The experiment lasted for about 6 h. It complies with the standard procedures recommended by the ethics committee of our institution and with the Helsinki Declaration and has been run with full consent of the subjects.

Stimuli

The stimuli were displayed on a 768 × 1,024 pixels, 77 Hz Phillips 17T color monitor at a viewing distance of 100 cm. The mean luminance of the screen was set at 45 cd/m². The experiment was programmed and executed using MATLAB 6.5 and the Psychophysics Toolbox extensions (Brainard 1997; Pelli 1997). During the whole trial a fixation cross was presented in the middle of the screen. On each trial, two visual stimuli were presented with an SOA of 52 ms: S1, a close to threshold Gaussian luminance increment with a $\sigma = 0.26$, and S2, a bright, full-contrast, sharp edged annulus with inner and outer diameters of 0.45° and 0.85°, respectively. S1 was presented for 13 ms 3.7° below fixation on the vertical meridian. S2 was displayed for 39 ms either at the same location as S1 (*masked* condition), or to the left or right of S1 (*non-masked* condition; see Fig. 1). In the latter case, the distance between S1 and S2 was ±22.5° on a virtual circle centered on the fixation point. The luminance of S1 was set to yield one out of 13 contrasts (steps of 2% in-between 6 and 30% with respect to the mean screen luminance) for the masked condition, and one out of seven contrasts (steps of 2% in-between 4 and 16%) for the non-masked condition. These contrast ranges were chosen so as to encompass the whole range of measurable d'-s (from about 0.2 to about 3.4).

Procedure

The lower panel of Fig. 1 illustrates the sequence of events in one trial. Observers were presented with (a) a random blank interval within a 300–1,000 ms range; (b) S1 with an occurrence probability of 0.5; the RT measurement was always initiated at the onset of S1 (even if not presented); (c) S2 at an SOA of 52 ms with respect to S1. S2 was presented either at the "masked" location or, randomly, at one of the two "non-masked" locations (see above).

Observers were required to (1) press a key on the keyboard as soon as they detected *any* luminance change (that is as soon as they detected either S1 or S2) and (2) indicate, after the speeded response, whether they saw S1 or not (by pressing one of two keys on the keyboard); for this second response, observers could take as much time as needed. The inter-trial interval was 400 ms.

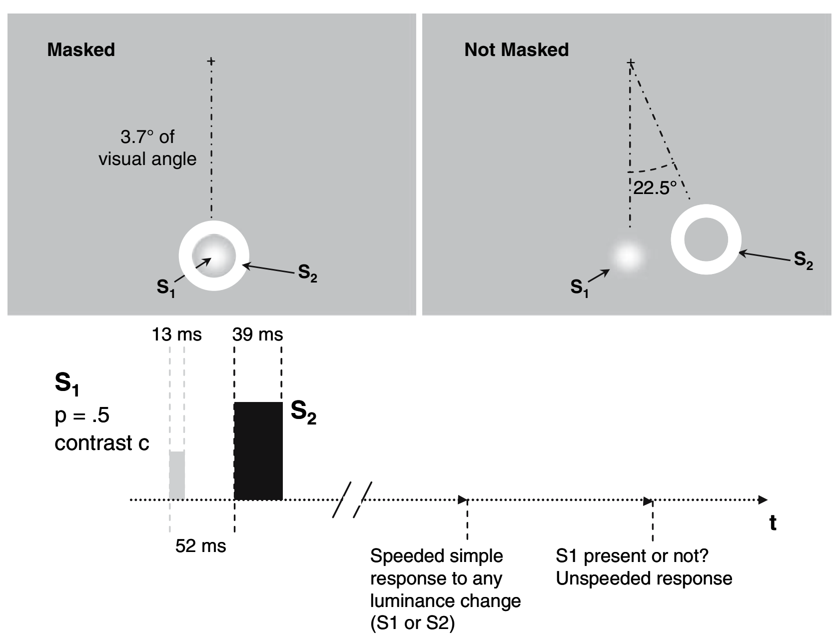

Fig. 1 Illustration of stimuli and procedure

Design

The experiment was run in two parts ("masked" and "non-masked"). There were fourteen different observers. Six observers performed the masked part and eight observers the non-masked part. Each part was run in blocks of 300 trials. One block was specified by the contrast of S1 (see above) and by the position of S2 (masked/non-masked conditions). In order to partially compensate for the fact that the number of perceptual Misses decreases with increasing d' (hence with S1-contrast), the number of (300 trials) blocks was allocated as follows: for the masked condition observers ran one single block for each contrast in the 6–18% range, two blocks per contrast in the 20–26% range and three blocks per contrast in the 28–30% range; for the non-masked condition observers ran one single block for contrasts 4–8%, two blocks for contrasts 10–14%, and three blocks for the 16% contrast. In order to make sure that differences in performances between masked and non-masked conditions were not contaminated by inter-observer differences (as these two conditions were run with different observers), observers run with the non-masked condition were also tested for three S1-contrasts (8% [one block], 12% [two blocks], 16% [three blocks]) under the masked condition. The order of each contrast-defined block was randomized across observers in each group.

RTs were analyzed for each experimental block type (i.e., masking condition and S1 contrast) and for each perceptual response category under SDT (Hits, False Alarms [FA], Misses and Correct Rejections [CR]). This allowed the study of the motor system's response to the close-to-threshold S1 stimulus as a function of its visibility (d'), its presence/absence and as a function of the observer's internal state (S1 reported as being present or absent).

Results

RT faster than 130 ms and slower than 900 ms were discarded. One subject showed very high d's. In the high-contrast conditions, this subject committed only very few errors (Misses and FA). Accordingly, for this subject there were not enough data to calculate a reliable mean for the category Misses of the contrasts of 12, 14, and 16% of the non-masked condition. The missing values were estimated by the group mean. Table 1 shows mean RTs separately for the two parts of the experiment and separately for the four categories under SDT. Figure 2 shows mean RT gains averaged across the observers as a function of S1-contrast for the non-masked (a) and masked (b) conditions. Negative gains refer to the RT *decrease* for perceptual Hits (grey squares and triangles) and Misses (black squares and triangles) relative to the RT for perceptual Correct Rejections, with the latter used as a RT baseline in the absence of S1. As noted in the Methods section, the non-masked and masked conditions were run by independent groups of eight and six observers, respectively. The average gains of the masked group are shown as grey (for Hits) and black triangles (for Misses) in panel b. The average gains of the non-masked group are shown as grey (for Hits) and black squares (for Misses) in panel a. However, the "non-masked" group has also been run for three S1-contrasts under the masked condition and these data are shown as grey (Hits) and black squares (Misses) in panel b. The two groups of observers show very similar results under the masked condition for both Hits and Misses so that their performances across non-masked and masked conditions can be confidently compared.

Figure 2 shows a rather clear pattern of results: in the non-masked condition RT is a decreasing function of contrast for *perceptual Hits only*. That is, only S1 stimuli exceeding the perceptual criterion bear on the motor response. By contrast, in the masked condition RT is a decreasing function of contrast for *perceptual Hits and Misses*. That is, S1 affects the motor response regardless of whether it exceeds the perceptual criterion or not. Figure 2b shows also that, in the masked condition, the RT gain for perceptual Hits is larger than for perceptual Misses.

Given the experimental format, two distinct three-way ANOVAs with S1-contrast, Masking condition (non-masked and masked) and Perceptual state (Hits and Misses) as factors were run on the mean RT gains: one that included Masking condition as a between-subjects factor and another one included Masking condition as a within-subjects factor. For the between-subjects analysis, the S1-contrast factor involved the six contrast levels shared by the two groups of observers (i.e., 6, 8, 10, 12, 14, 16%); for the within-subjects analysis, the S1-contrast factor included the three contrast levels (8, 12, 16%) run by these observers under both non-masked and masked conditions.

The between-subjects ANOVA included the between-subjects factor Masking condition (masked vs. non-masked) and the within-subjects factors S1-Contrast (6, 8, 10, 12, 14, 16) and Perceptual state (Hits vs. Misses). The ANOVA yielded a significant main effect of S1-Contrast [$F(5,60) = 17.75$, $P < 0.001$], indicating increasing RT gain (RT *decrease* relative to the RT for perceptual Correct Rejections used as a baseline in the absence of S1) with increasing contrast, and a significant main effect of Perceptual state [$F(1,12) = 81.02$, $P < 0.001$], indicating larger RT gain for perceptual Hits than for perceptual Misses. These main effects were qualified by a significant interaction of S1-Contrast × Perceptual state [$F(5,60) = 4.18$, $P < 0.01$] and, more importantly, by a significant interaction Perceptual state × Masking condition [$F(1,12) = 6.21$, $P < 0.05$]. The latter interaction is due to subjects showing significant

Table 1 Leftmost columns: mean RTs separately for the two parts of the experiment, for the contrasts tested in the two parts, and for the four categories under SDT (see text for details)

Rightmost columns: error probabilities (one-tailed *t* tests) for the contrasts Hits versus CR, Misses versus CR, and Hits versus Misses

Contrast	CR (ms)	FA (ms)	Hit (ms)	Miss (ms)	Hit vs. CR	Miss vs. CR	Hit vs. Miss
Part 1 masked							
6	278	279	274	277	<0.35	<0.4	<0.4
8	288	287	277	287	<0.01	<0.4	<0.01
10	293	285	273	285	<0.001	<0.01	<0.01
12	301	303	273	296	<0.001	<0.2	<0.01
14	285	273	255	270	<0.001	<0.02	<0.02
16	292	289	259	274	<0.0001	<0.001	<0.01
18	288	283	249	272	<0.0001	<0.01	<0.002
20	299	299	258	279	<0.0001	<0.0001	<0.001
22	289	284	249	271	<0.0001	<0.001	<0.001
24	279	274	237	256	<0.0001	<0.01	<0.02
26	297	293	254	273	<0.0001	<0.001	<0.01
28	290	291	249	268	<0.0001	<0.01	<0.01
30	287	276	243	270	<0.0001	<0.03	<0.01
Part 2 masked							
8	288	284	272	282	<0.02	<0.1	<0.02
12	278	278	248	260	<0.0001	<0.002	<0.01
16	279	282	243	262	<0.0001	<0.01	<0.001
Part 2 not masked							
4	284	280	280	286	<0.1	<0.2	<0.1
6	285	279	274	286	<0.01	<0.4	<0.02
8	280	278	268	280	<0.02	<0.5	<0.05
10	288	287	263	288	<0.0001	<0.5	<0.01
12	282	287	251	279	<0.0001	<0.3	<0.001
14	280	299	247	274	<0.0001	<0.3	<0.001
16	279	313	242	280	<0.0001	<0.4	<0.0001

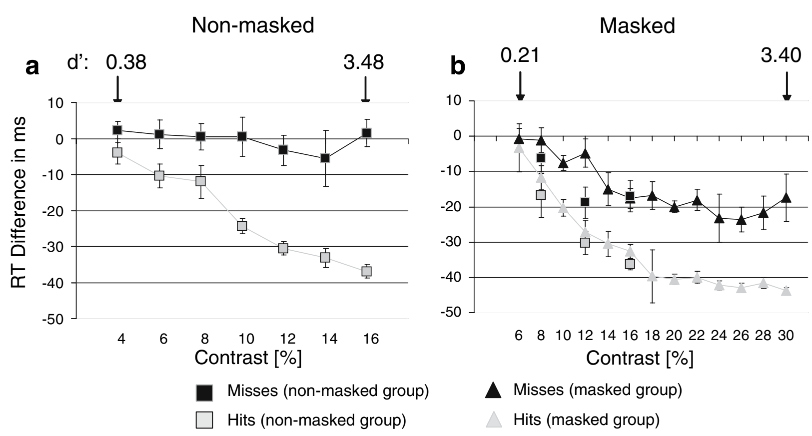

Fig. 2 Reaction time differences between perceptual Hits (*gray symbols*, see text for details) and Misses (*black symbols*, see text for details), respectively, and perceptual Correct Rejections as a function of contrast, separately for non-masked (*left panel*) and masked stimuli (*right panel*; *triangles*: masked group; *squares*: the three contrasts tested masked in the non-masked group). Both ranges of contrast yield about the same range of d'-s. *Error bars* denote the standard error of mean

RT gain for perceptual Hits ($P < 0.001$) and Misses ($P < 0.01$) in the masked condition and for perceptual Hits *only* ($P < 0.001$) in the non-masked condition (error probability for perceptual Misses in this condition >0.4). Moreover, in the masked condition, the RT gain is significantly larger for perceptual Hits than for perceptual Misses ($P < 0.001$). The interaction S1-contrast × Perceptual state × Masking condition failed to reach significance [$F(5,60) = 1.08$, $P > 0.2$]. In all ANOVAs, degrees of freedom were Huynh-Feldt corrected if appropriate.

The within-subjects ANOVA included the within-subject factors Masking condition (masked vs. non-masked), S1-Contrast (8, 12, vs. 16), and Perceptual state (Hits vs. Misses). The ANOVA yielded a significant main effect of S1-Contrast [$F(2,14) = 17.27$, $P < 0.001$], indicating increasing RT gain with increasing contrast, a significant main effect of Perceptual state [$F(1,7) = 63.94$, $P < 0.001$], indicating larger RT gain for perceptual Hits than for perceptual Misses, and a significant main effect of Masking condition [$F(1,7) = 9.67$, $P < 0.05$], indicating larger RT gain in the masked than in the unmasked condition. The main effects were qualified by a significant interaction of S1-Contrast × Perceptual state [$F(2,14) = 10.60$, $P < 0.01$] and, more importantly, a significant interaction Perceptual state × Masking condition [$F(1,7) = 8.90$, $P < 0.02$]. The latter interaction is due to subjects showing significant RT gain for perceptual Hits ($P < 0.001$) and Misses ($P < 0.01$) in the masked condition and for perceptual Hits *only* ($P < 0.001$) in the non-masked condition (error probability for perceptual Misses in this condition >0.44). Moreover, in the masked condition, the RT gain is significantly larger for perceptual Hits than for perceptual Misses ($P < 0.001$). The triple interaction S1-contrast × Perceptual state × Masking condition almost reached significance [$F(2,14) = 3.33$, $P = 0.06$].[1]

Table 1 shows mean RTs for all contrasts used in the present study separately for the two parts of the experiment and separately for the four categories under SDT. The rightmost columns of Table 1 show α error probabilities for the contrasts Hits versus Correct Rejections, Misses versus Correct Rejections, and Hits versus Misses. The table shows that in the masked conditions, for all but the lowest contrasts, RTs for perceptual Hits and for perceptual Misses are significantly faster than RTs for Correct Rejections. Moreover, for almost all contrasts, RTs for perceptual Hits are faster than RTs for perceptual Misses. In the not-masked condition, by contrast, RTs of perceptual Hits are faster than RTs of Correct rejections, but not RTs of perceptual Misses.

Figure 3a shows RT differences between S1-present and S1-absent trials—regardless of whether the observer reported it to be present or not—separately for non-masked (black squares) and masked stimuli (gray squares for the masked group; black triangles for the three contrasts tested masked in the non-masked group). The functions are shown over the contrast range shared by the two Masking conditions. The non-masked data (black squares) can be compared to the masked data in two ways: either between-subjects (black squares vs. gray squares), for the whole range of contrasts in-between 6 and 16% common to both groups of subjects, or within-subjects (black squares vs. black triangles), for the contrasts of 8, 12, and 16% that have been tested masked and non-masked in the same group of subjects. The figure shows that the impact of S1 on the motor system increases with increasing contrast. Importantly, there was no difference whatsoever between the two masking conditions. (The small difference between the two groups of subjects [gray and black squares] is far from being significant, see below.)

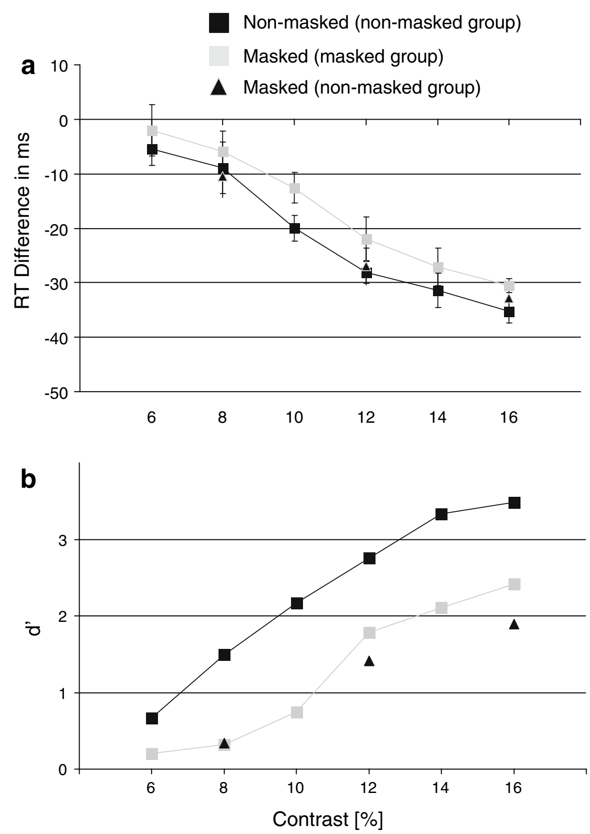

Fig. 3 Reaction time differences between S1-present trials and S1-absent trials (**a**) and S1 visibility (d'; **b**) as a function of contrast, separately for the non-masked group (*black squares*: non-masked condition; *black triangles*: the three contrasts tested masked in this group) and the masked group (*gray squares*). *Error bars* in **a** denote the standard error of mean

[1] Notice that our main argument outlined below is based on the finding that, in the masked condition, there is an RT gain for perceptual Hits and Misses, whereas in the not-masked condition there is an RT gain for perceptual Hits only. This translates into a Perceptual State × Masking interaction, which is significant in both ANOVAs (and the corresponding simple effects, too). That the triple interaction is not significant (or only touches the 0.05 level of significance) is due to the fact that the Perceptual State × Masking interaction does not change tremendously across the contrast used in the ANOVAs. However, this does by no means undermine our conclusions. Figure 2 and Table 1 present the data as if the triple interaction was significant. This is because we did not want to ignore a triple interaction with an alpha error of 0.06, the more so as the triple interaction is by no means surprising or counterintuitive. It indicates that the Perceptual State × Masking effect gets larger with increasing contrast. Given that RTs decrease with increasing contrast the triple interaction is rather trivial.

Again, two distinct ANOVAs were run on the RT differences between S1-present and S1-absent trials; one ANOVA included the Masking condition (masked vs. non-masked) as a *within-subjects* factor and another one including the Masking condition as a *between-subjects* factor. Both ANOVAs included the within-subject factor S1-contrast (8, 12, 16% and 6, 8, 10, 12, 14, 16%, respectively). Both ANOVAs yielded a significant main effect of S1-Contrast [within: $F(2,14) = 51.46$, $P < 0.001$; between: $F(5,60) = 61.77$, $P < 0.001$], indicating increasing RT gain with increasing contrast. However, in both analysis neither the main effect of Masking nor its interaction with S1-Contrast reached significance [within: Main effect of Masking: $F(1,7) = 0.18$, $P < 0.6$; interaction of Masking × S1-Contrast: $F(2,14) = 0.81$, $P < 0.4$; between: Main effect of Masking: $F(1,12) = 1.69$, $P < 0.25$; interaction of Masking × S1-Contrast: $F(5,60) = 0.29$, $P < 0.9$].

Figure 3b shows S1 visibility (d') for the same range of contrasts separately for non-masked (black squares) and masked stimuli (gray squares for the masked group; black triangles for the three contrasts tested masked in the non-masked group). The same ANOVAs as defined above were run on S1 visibility; one ANOVA including the Masking condition (masked vs. non-masked) as a within-subjects factor and another one including the Masking condition as a between-subjects factor. Both ANOVAs included the within-subject factor S1-contrast (8, 12, 16% and 6, 8, 10, 12, 14, 16%, respectively). Both ANOVAs yielded a significant main effect of S1-Contrast [within: $F(2,14) = 31.56$, $P < 0.001$; between: $F(5,60) = 51.84$, $P < 0.001$], indicating increasing visibility with increasing contrast, and a significant main effect of Masking condition [within: $F(1,7) = 85.51$, $P < 0.001$; between: $F(1,12) = 20.01$, $P < 0.001$], indicating larger d's in the non-masked conditions than in the masked conditions.

Discussion

The present experiments reveal two major facts: first, overall simple RTs, i.e., RTs pooled across the subject's perceptual report, in response to the S1–S2 stimulus pair are independent of S1 of a given contrast being masked or not (Fig. 3a). In other words, RTs depend on the physical contrast of the 'prime' (S1) and not on its visibility (d'). This is illustrated by comparing the RT functions shown in Fig. 3a with the S1 visibility functions shown in Fig. 3b. Although S1 of a given contrast was clearly less visible when masked than when not masked (panel b), it yielded equal effects on RT (panel a). This result parallels findings from masked action priming experiments exploring the influence of masked stimuli that are either congruent or incongruent with the mask on speeded *choice* reactions in response to the mask. These experiments show that manipulations modifying the visibility of a masked stimulus do not influence the motor effects of those stimuli (e.g., Vorberg et al. 2003; Ogmen et al. 2003).

However, the most important aspect of the present results bears on the difference in the pattern of results obtained in the masked and the non-masked condition when the data are classified according to observers' perceptual state (Fig. 2). Depending on whether a stimulus of a given contrast is masked or not, subjects show an RT gain for perceptual Hits *and* perceptual Misses or for perceptual Hits *only*, respectively. In other words, equally energetic stimuli unavailable for conscious report (Misses) may or may not influence the motor behavior depending on whether they are masked or not.

The present results replicate and extend those reported by Waszak and Gorea (2004). These authors evidenced the two RT patterns by means of varying the strength of the masking stimulus (S2) via the manipulation of the S1–S2 SOA, while correspondingly modulating S1's physical contrast so as to keep its sensitivity constant. The present study not only replicates their results over a larger d'-range, but uses a fixed SOA while including a non-masking condition. The present experimental format hence insures that Waszak and Gorea's critical result was genuinely due to the change in the contrast of S1 (at constant d') rather than to a putative SOA-related interference process.

More importantly, the data do not only tell us that stimuli unavailable for conscious report may influence motor behavior, thus being in accordance with the general idea of at least a partial independence between perception-for-action and perception-for-identification; the results also allow us to draw a more explicit picture of the relationship between perceptual and motor processes as assessed in the present experiment. They suggest that the consecutive motor and perceptual decisions made by observers within the same trial relative to the same visual event are taken with respect to two different internal references and at two different moments in the processing stream.

The perceptual decision is presumably referenced to the standard Signal Detection Theory (SDT; Green and Swets 1966) perceptual *criterion*. The perceptual criterion is variable in that it depends on the context of a given processing episode. It is the result of a subjective optimization process (i.e., maximizing the number of correct responses) whereby the observer develops some knowledge of the internal response distributions evoked by the stimulus and by its absence, while also evaluating factors such as stimulus' a priori probability and payoff. By contrast, inasmuch as observers' motor task is not to maximize correct responses but to minimize reaction times, they presumably set the motor threshold as low as possible irrespective of the processing context (e.g., masked vs. non-masked, occurrence probability, etc.). Hence, the motor decision to initiate a response is brought about with reference to a "fixed" energy *threshold* that is independent of factors that influence the perceptual decision.

The above-mentioned tentative interpretation can be summarized as follows: S1 elicits an internal response that rises over time until it reaches an asymptotic value. Following standard SDT this asymptotic value at the end of the processing event is a normally distributed random variable that determines the visibility (d') of S1 when compared to the noise distribution.

O*verall* RTs pooled across perceptual Hits and Misses are independent of masking (Fig. 3a) because the internal response evoked by the masked stimulus (S1) triggers a motor response whenever it exceeds a fixed motor threshold (T_M) that is referenced to the absolute internal response. At the time of the motor decision, the internal response evoked by S1 has not yet reached its asymptote value and, thus, is not yet affected by masking. As a consequence, the internal response depends only on S1's physical contrast. Hence, stimuli of the same contrast yield the same mean RT, whether they are masked or not.

In contrast to the pooled RTs, however, RTs very well depend on masking when analyzed separately for perceptual Hits and Misses: if masked, S1 affects RTs of perceptual Hits and Misses (with a larger effect for perceptual Hits); if not masked, S1 affects RTs of perceptual Hits only. Figure 4 makes use of the SDT to illustrate the asymptotic internal response of the observer at the end of the processing episode when the perceptual decision is taken. Within the SDT framework, S1 is reported present whenever its evoked internal response exceeds a perceptual criterion (C_P) that depends on the discriminability of the Signal and Noise distributions. Critically, the C_P under the non-masked and masked conditions may well be below and above the T_M, respectively. When S1 is not masked, the reference Noise is identical to the internal noise of the system and its mean is relatively low. In this case the perceptual criterion is lower than the motor threshold, so that an S1-evoked internal response sufficiently strong to exceed T_M would perforce exceed C_P. As a consequence, in all non-masked processing episodes in which S1 triggers a motor response (yielding faster RT than those triggered by S2 alone—i.e., S1 absent trials), it will also be reported as being present (perceptual Hits). Conversely, for all trials where S1 is reported absent (perceptual Misses), the S1-evoked internal response will perforce fail to exceed T_M, resulting in the pattern of results found with the non-masked

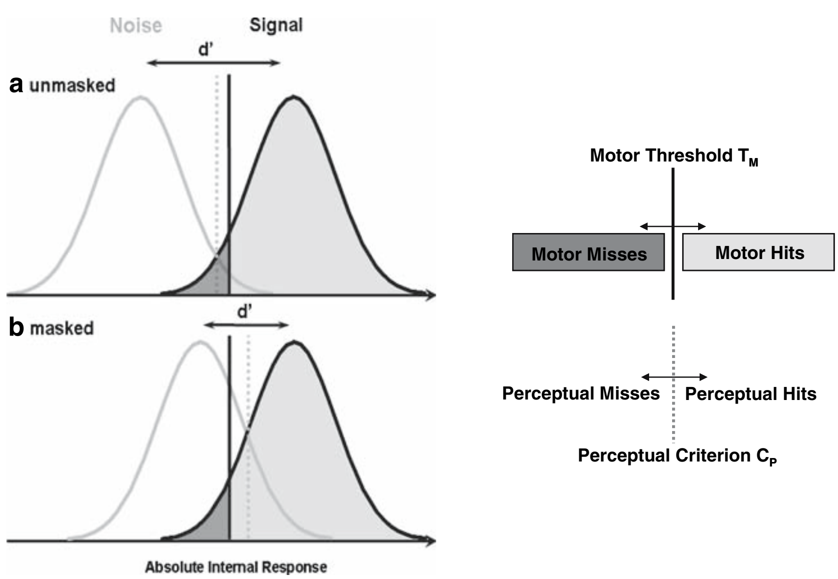

Fig. 4 Theoretical framework: observer's internal response in terms of the standard Signal Detection Theory (Green and Swets 1966; Macmillan and Creelman 1991). Gaussian functions describe the probability density of the internal response distributions (in arbitrary units; abscissa) for the *signal* (S1 present; *black curves*) added to the baseline strengths (S1 absent, *noise*, *gray curves*). The visibility of S1 (d') corresponds to the difference between the mean of the Noise and the Signal distribution (weighted by the standard deviation of the two distributions, which equals 1 in the illustration). The *dashed gray line* represents the perceptual criterion C_P. Anytime the internal response of S1 exceeds this criterion, S1 is reported as being "present" (perceptual Hit). Otherwise it is reported as being "absent" (perceptual Miss). The *black line* represents the motor threshold T_M. Anytime the internal response to S1 exceeds this threshold, S1 triggers a motor response (motor Hit). Otherwise S1 does not initiate any motor activity (motor Miss). Panel **a** shows the case in which S1 is not masked: C_P cuts the response continuum left of T_M. Panel **b** shows the case in which S1 is masked (and, thus, elicits a lower d'): C_P cuts the response continuum right of T_M. The contrast of S1 is the same in both conditions. Moreover, in both cases, subjects optimize % correct responses by locating C_P at $d'/2$ (where an optimal observer places C_P when signal and noise have equal occurrence probabilities) and, in both cases, T_M is fixed with respect to the absolute internal response

stimuli, viz. an RT effect for perceptual Hits only. In the masked condition the situation is different. The masking stimulus is liable to increase the internal noise level with reference to which the perceptual decision is taken and, as a consequence, C_P (equal to $d'/2$ for an optimal observer). On this hypothesis, C_P will be amply higher than T_M. An internal response sufficiently strong to exceed T_M will *not* necessarily exceed C_P. As a consequence, in the processing episodes where S1 triggers a motor response, it may or may not be reported present, resulting in the pattern of results found with masked stimuli, viz. an RT effect for perceptual Hits and Misses.

Notice that this framework transcends the unidimensionality that underlies classic Signal Detection Theory. SDT assumes that observers test for the noise/signal distributions of the asymptotic value at the end of the processing event. However, we suppose that when investigating the relationship between perceptual and motor decisions in response to the same visual event, we also need to take into account how the internal response grows over time to reach its normally distributed asymptote. We assume that it is before the internal response of S1 reaches its asymptote that it exceeds (or not) the fixed motor threshold and triggers (or not) a motor response. It is only thereafter that the internal response reaches its asymptote and that the processing context (mask/not masked in our study) determines whether the perceptual criterion C_P is low (and therefore below the motor threshold T_M) or relatively high (and therefore above motor threshold T_M). The internal responses as depicted in Fig. 4 merely reflect the asymptotic activity at the end of the processing episode.

One objection to the method of the present study is that the use of a dual-task setting might entail the danger of possible mutual influences of the two tasks. Notably, it might be possible that the perceptual report of the observer is influenced by the prior motor response. Observers might rely on their perceived response speed for making their rating about S1. We cannot exclude this possibility entirely. However, Klotz and Neumann (1999) who investigated motor responses to geometric stimuli preceded by congruent or incongruent masked primes did not find substantial differences in the pattern of results under conditions in which the RT and discrimination tasks were administered blocked or combined on each trial. Thus, there is, at least, no evidence that would suggest that we should expect a different outcome if we administered the two tasks in separate blocks. Moreover, the notion cannot account for the pattern of results presented above, since it cannot explain why, in the masked condition, fast responses to the S1–S2 stimulus couple sometimes translate into perceptual Hits and sometimes into perceptual Misses (yielding an RT effect for perceptual Hits and Misses), whereas in the not masked condition they are always translate into perceptual Hits only.

Another potential objection refers to the fact that the two masking conditions do not only differ in terms of masking but also in the number of positions of S2. Accordingly, the laterality and variation of S2 in the non-masked condition could be responsible for some of the effects rather than the unmasking, due to a different allocation of attention. However, this seems improbable given that the RT levels in the two conditions are virtually equal. For the three contrasts tested masked and not masked in part 2 of the experiment, RTs in S1-absent trials are 281 and 282 ms, respectively. The same holds true for S1-present trials (8% contrast: 277 vs. 271 ms; 12% contrast: 252 vs. 255 ms; 16% contrast: 247 vs. 244 ms). Any major difference in allocation of attention between the two masking conditions should result in a difference of the general RT level.

The data presented above fit nicely with the idea that the input from S1 and S2 arrive successively at motor areas, either one leading to the build-up of a response vector that gives rise to a motor response if it exceeds the motor threshold or that goes unnoticed for the motor system otherwise. This may take place during a fast feed-forward sweep of information processing that activates the successive hierarchical levels of the brain (see Lamme and Roelfsema 2000; see also Schmidt 2002). This fast feed-forward cascade connects the relevant areas in a hard-wired fashion, so that the motor response, given a fix motor threshold, depends merely on the contrast of S1.

The conscious perception of S1, by contrast, may rely on recurrent processing from higher to lower areas (Bullier 2001; Lamme and Roelfsema 2000; Pascual-Leone and Walsh 2001). Even if presented not masked, stimulus energy of S1 is so weak that information accumulated in the course of the recurrent loops is not always sufficient to exceed the perceptual criterion (but still more often than to exceed the high energy motor threshold in the course of the fast feedforward sweep). However, if presented masked, S1 may be destabilised because recurrent information from higher areas arrives in lower areas when the feedback information no longer matches the low-level activity, the latter having already been replaced by the mask (e.g., DiLollo et al. 2000). This would decrease the visibility of S1, without affecting the motor response, because by the time the recurrent processing has been completed, the fast feedforward sweep initiated by S1 has already begun its way to motor areas. As a consequence, perceptual criterion and motor threshold change their relative positions, resulting in the pattern of results shown in Fig. 2. If so, the perceptual and the motor decision would be made in different time segments of the processing stream. The motor decision would be brought about online in the course of the fast feedforward volley, whereas the perceptual decision would be made après-coup based on some internal response stabilized by recurrent processing.

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