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Induced dissociations: Opposite time courses of priming and masking induced by custom-made mask-contrast functions

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Abstract
We present a new experimental technique to induce dissociations between the visibility of a masked prime and its ability to induce a priming effect in response times. In three experiments, we systematically couple an independent variable known to influence the priming effect (prime-mask SOA) with a variable expected to influence prime visibility but not priming (mask contrast). This way, we create mask-contrast functions where mask contrast either increases with SOA, decreases, or remains constant at maximum or minimum levels. We show that different mask-contrast functions can lead to qualitatively different time courses of masking without affecting the time course of priming, allowing for double dissociations (e.g., increasing priming effects under decreasing prime visibility). For the first time, we demonstrate such double dissociations for response priming by color as well as shape stimuli. We also show that the technique requires stimuli that decouple the mask's ability to mask the prime from its ability to activate the response. We conclude that mask-contrast functions can accentuate or even induce dissociations between priming and masking, opening new possibilities for studying perception without awareness.

Keywords Response priming · Metacontrast · Double dissociation · Induced dissociations · Mask-contrast function · Perception without awareness

Looking at the research field of perception without awareness, the most controversial question is how to establish that a critical stimulus (e.g., the prime in a priming experiment) did not reach visual awareness. Starting with the earliest experiments by Peirce and Jastrow (1884), there has been a consensus in the field that in order to demonstrate perception without awareness, one has to show that observers were unaware of the prime, or more importantly, the specific prime features critical for the task. In this paper, we want to challenge this established view. Instead of asking whether perception is possible in the absence of awareness, we ask whether a continuous variation in the perceptual processing of a stimulus is in line or disagrees with a continuous variation in the awareness of that stimulus. We will introduce a new experimental paradigm where independent variables are systematically interloped in such a way that measures of perceptual processing and of visual awareness are provoked to vary in contradictory ways. Finally, we will show how this paradigm can demonstrate the unconscious processing of shape and color stimuli.

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Simple and double dissociations in perception without awareness

The dissociation paradigm is the traditional approach for demonstrating perception without awareness (Cheesman & Merikle, 1984; Erdelyi, 1986; Reingold, 2004). It relies on two types of measurements. The direct measure is some measure of visual awareness of the critical stimulus. It may consist in objective measures (e.g., discrimination or detection performance), subjective measures (e.g., visibility or confidence ratings), or both (e.g., ROC curves). The indirect measure then demonstrates that the critical stimulus has been processed at all (e.g., by generating a priming effect in response times). Under the dissociation paradigm, perception without awareness is established by demonstrating a nonzero effect of stimulus processing in the indirect measure, while the direct measure indicates absence of visual awareness (zero-awareness criterion; Reingold & Merikle, 1988; T. Schmidt & D. Vorberg, 2006).

The zero-awareness criterion, even though intuitively convincing, is highly problematic. It gives rise to two major issues. First, it involves the problem of convincingly corroborating the null hypothesis of zero performance in the direct measure.[1] Second, and more problematic, it requires strong assumptions about the measurement process. Reingold and Merikle (1988) have stressed that in order to interpret zero performance in the direct task as evidence of zero awareness, one has to assume that the direct measure is *exhaustive* with respect to any aspect of stimulus awareness relevant for the task. Otherwise, there could be some remaining awareness of the critical stimulus that was not captured by the direct measure and that may explain performance in the indirect task.

T. Schmidt and Vorberg (2006) analyze the exhaustiveness assumption in more detail (see Fig. 1 and the Mathematical Appendix). Assume a direct measure D and an indirect measure I, each of them a function of two types of information, labeled *conscious (c)* and *unconscious (u)*, such that $D = D(c,u)$ and $I = I(c,u)$. We start with the assumption that both D and I are weakly monotonic functions of both c and u: In the long run, if any of the inputs increases, the expected values of D and I may increase or remain the same, but will not decrease. Now assume that we measure zero performance in the direct measure and a solid nonzero effect in the indirect measure (simple dissociation; T. Schmidt & Vorberg, 2006). Even if the direct measure is exactly zero ($D = 0$, chance level), it does not imply that $c = 0$: because D is only weakly monotonic with respect to conscious information, it could be that the stimulus gave rise to some $c > 0$ that failed to lead to a corresponding shift in D. To actually infer $c = 0$ from $D = 0$, we need the additional assumption that D is *strictly monotonic* in c. In other words, we have to assume that any change in c, no matter how small, will lead to a concomitant change in D. This is a highly problematic assumption from a psychometric viewpoint: It implies that D has perfect reliability and validity and is infinitely sensitive to conscious information.[2]

Intriguingly, there is a data pattern that circumvents those problems entirely: a *double dissociation* (T. Schmidt & Vorberg, 2006; cf. Merikle & Joordens, 1997; Shanks & St. John, 1994). Double dissociations occur when some independent variable is introduced that affects both measures in opposite directions, such that the indirect measure *increases* while the direct measure *decreases* (or vice versa). Double dissociations have a number of desirable properties (for proofs, see the Mathematical Appendix). First, T. Schmidt and Vorberg (2006) show that double dissociations do not require any exhaustiveness assumption but only require both measures to be weakly monotonic for conscious information, while no monotonicity assumption at all has to be made for unconscious information. This places very few constraints on the possible interactions between conscious and unconscious information. Second, the problem of null hypothesis corroboration disappears because double dissociations do not require the direct measure to be zero, or to have any specific value at all. They can occur under different levels of awareness and only require that D and I develop in opposite directions. Indeed, the simple dissociation can be viewed as an uninformative special case of a double dissociation, requiring additional assumptions precisely because all values of the direct measure are the same (zero). Finally, double dissociations are usually of theoretical interest because they immediately show that performance on one measure cannot explain performance on the other. Specifically, T. Schmidt and Vorberg (2006) show that a double dissociation refutes all models which assume that both measures depend monotonically on only one source of information. They conclude that “the best way to demonstrate unconscious cognition is to use stimuli that are not unconscious” (p. 500).

Both simple and double dissociations have been demonstrated in response priming (Klotz & Neumann, 1999; Klotz & Wolff, 1995; Vorberg, Mattler, Heinecke, T. Schmidt, & Schwarzbach, 2003). In a typical response priming task, participants respond as quickly and accurately as possible to a visually presented target stimulus (e.g., a square or a diamond) by pressing one of two response keys. The target is preceded by a quickly presented prime stimulus (e.g., another square or diamond) that is mapped to either the same response as the target (consistent trial) or to the opposite response (inconsistent trial). Typically, consistent primes speed and inconsistent primes slow responses to the target, and this response priming effect increases with stimulus-onset asynchronies (SOAs) between prime and target of up to 100 ms (T. Schmidt, Niehaus, & Nagel, 2006; T. Schmidt & F. Schmidt, 2009; Vath & T. Schmidt, 2007; Vorberg et al., 2003). The prime can be presented unmasked as a flanker (Eriksen & Eriksen, 1974; Schwarz & Mecklinger, 1995), can be masked by the target itself, or there may be a third stimulus serving as a backward mask to the prime.

Of special interest here is the variant where the target itself serves as a metacontrast mask to the prime (Klotz & Wolff, 1995). Metacontrast occurs when prime visibility is reduced by a mask with adjacent contours (Alpern, 1953; Stigler, 1910, 1926) and can lead to qualitatively different time courses of masking. In Type A masking, discrimination performance for the masked stimulus is low at short SOAs and either remains

[1] The null-hypothesis corroboration problem does not disappear with the use of Bayes factors, because this technique requires decisions about the shape of the prior distribution of the null hypothesis as well as the set of admissible alternative hypotheses that are to be compared with the null. Depending on settings, the test can either be strict or lenient.

[2] There is an alternative set of assumptions to interpret a simple dissociation as evidence for unconscious perception. Instead of the assumption that the direct measure is exhaustive for conscious information, we can alternatively assume that the indirect measure is exclusive for unconscious information. Such an indirect measure would be weakly monotonic with respect to u and not respond to any changes in c (T. Schmidt & Vorberg, 2006). T Schmidt (2007) argues that the plausibility of such a measure is an empirical question, whereas the assumption of an exhaustive measure is inadequate on measurement-theoretical grounds alone.

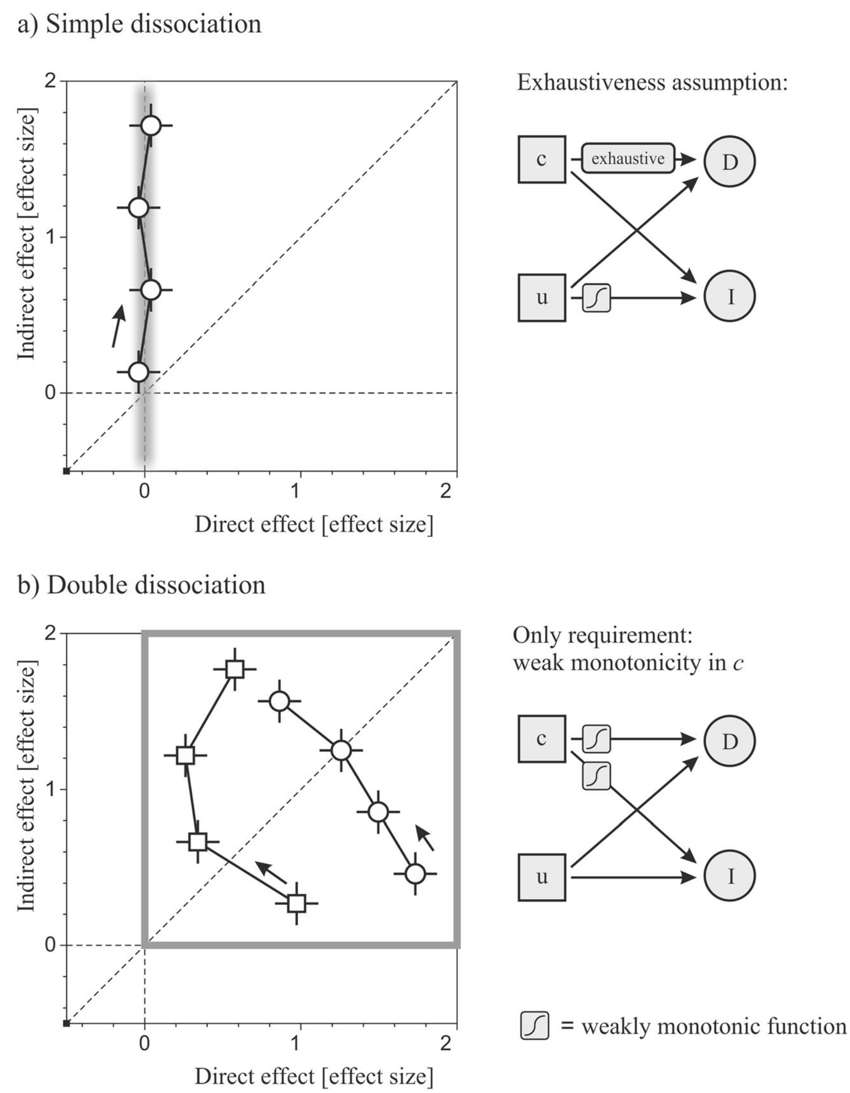

Fig. 1 **a** Simple dissociations consist in nonzero indirect effects (*I*) when direct effects (*D*) are at chance level. Data patterns are only valid when statistically close to the $D = 0$ line. Simple dissociations require the assumptions that *D* is exhaustive for conscious information and that *I* is a weakly monotonic function of unconscious information. **b** Two examples of double dissociations. Circles: Indirect effects are increasing while direct effects are decreasing over the range of an independent variable. Squares: Indirect effects are increasing while direct effects form a U-shaped visibility function. Arrows mark the ordering of the levels of an independent variable from smallest to largest. Data patterns are valid in the entire *D*–*I* space. Double dissociations only require the assumption that *D* and *I* are weakly monotonic functions of conscious information

low or gradually increases with SOA. Type A masking is typically observed when the mask has substantially more energy than the prime. In Type B masking, discrimination performance is relatively high at short and long SOAs and lower at intermediate SOAs, forming a U-shaped masking function. Type B masking is typically observed when prime and mask have similar energy (Breitmeyer & Öğmen, 2006; Kahneman, 1968). Vorberg et al., (2003) used arrow stimuli where the target arrow served as a metacontrast mask to the preceding prime arrow (in the remainder of this paper, we refer to this specific type of mask/target simply as the *mask*, while retaining the term *target* when talking about the general paradigm). They varied the prime-mask SOA as well as the relative durations of primes and masks to produce strongly different masking functions: prime discrimination performance could be at chance for all SOAs, could be nearly perfect, or it could either increase or decrease with SOA (Type A and Type B masking, respectively). Yet in all those conditions response priming was of similar magnitude and always increased with SOA. The study thus demonstrated simple dissociations (increasing priming with visibility constant at chance level) as well as double dissociations (increasing priming under decreasing visibility). Double dissociations between response priming and metacontrast masking have been demonstrated in many other experiments (e.g., Albrecht, Klapötke, & Mattler, 2010; Mattler, 2003; Peremen & Lamy, 2014).

Horses to unicorns: Bending masking functions into shape

While naturally occurring double dissociations are arguably the strongest type of dissociation that can be found in empirical data, they share some problems. First, they are difficult to find. In the area of visual masking, U-shaped or decreasing masking functions seem mostly limited to metacontrast masking of simple geometric shapes. Second, the magnitude and time course of masking is strongly person dependent (Albrecht et al., 2010; Albrecht & Mattler, 2010, 2012, 2016), making it difficult to find stimulus parameters that create a specific type of masking function for a majority of observers. It has been much more popular to demonstrate simple dissociations, despite all the well-known shortcomings, while the superior double dissociation patterns have not received much attention. Indeed, if simple dissociations are the timeworn, tired warhorses of unconscious perception, double dissociations are the unicorns: very precious, but also very rare. Here, we explore a new method for creating double dissociations artificially by altering the shape of the masking function, using custom-made mask-contrast functions. This way, we can create an optimal experimental environment to *design* double dissociations.

Consider a simple response priming experiment (a two-choice response to a mask preceded by a prime) where the prime-mask SOA is varied and strongly masked primes are compared with weakly masked primes. For each of the masking conditions, such an experiment yields a priming function, *P(s)*, and a masking function, *M(s)* (i.e., indirect and direct measures as a function of SOA). Assume that masking is controlled by altering the luminance contrast of the mask, using maximum contrast, c_{max}, or minimum contrast, c_{min} (see Fig. 2a). Instead of viewing mask contrast and SOA as independent factors, we can express mask contrast as a function of SOA, generating a mask-contrast function—*MCF(s)*. In this customary design, where strongly and weakly masked primes are compared, there would be two mask-contrast functions which are both constant across SOA, $MCF_{max}(s) = c_{max}$ and $MCF_{min}(s) = c_{min}$. If we find conditions where the masking function is convincingly close to zero while the priming function is convincingly larger than zero, we have induced a simple dissociation: $M(s) \approx 0$, $P(s) > 0$.

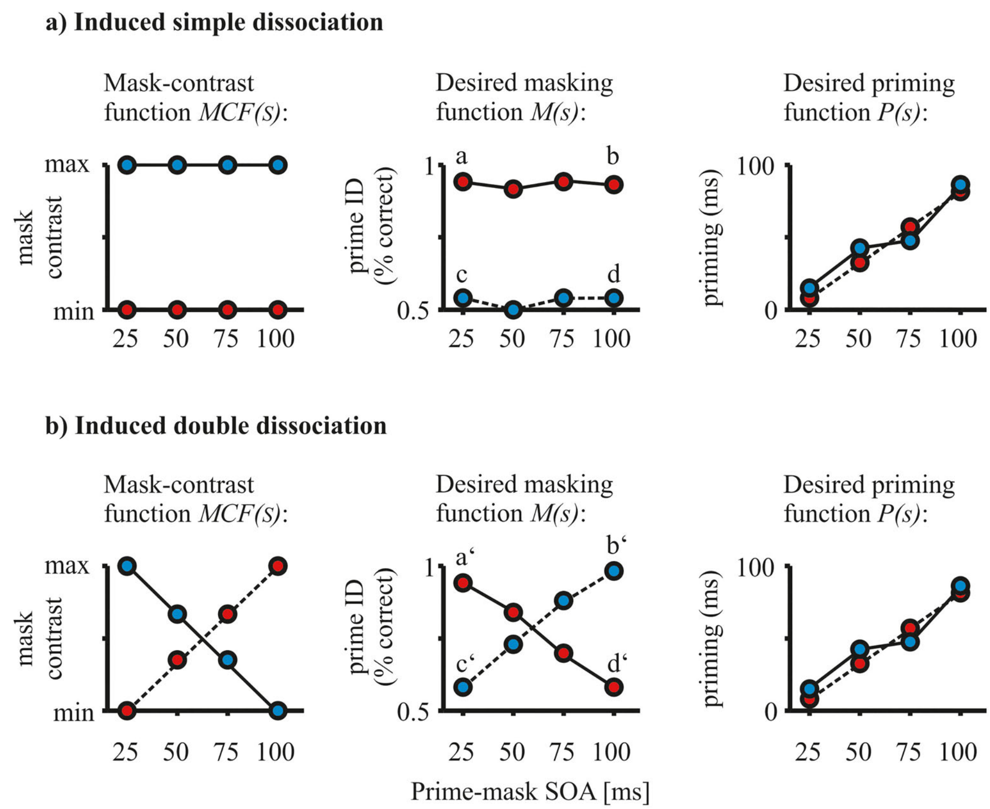

Fig. 2 **a** Induced simple dissociation. Masks at maximum contrast are expected to lead to near-chance performance in prime discrimination, whereas masks at minimum contrast should lead to high performance in prime discrimination. Ideally, priming effects would remain unaffected by masking. **b** Induced double dissociation. Mask-contrast functions of decreasing mask contrast should lead to increasing performance in prime discrimination, whereas increasing mask-contrast functions are expected to lead to decreasing prime discrimination. Ideally, priming functions should continue to increase under both masking regimes. Note that within measurement error, data points marked a–a', b–b', and so forth should correspond because they depend on physically identical stimulus conditions *(principle of connected endpoints)*. (Color figure online)

However, there is no reason at all why mask-contrast functions should have to be constant. Consider two new MCFs (see Fig. 2b), one where mask contrast decreases with SOA from c_{max} to c_{min} and one where it increases from c_{min} to c_{max}. This manipulation should bend the masking functions into new shapes. If mask contrast decreases with SOA, we can expect strong masking at the shortest SOA and weak masking at the longest SOA. Conversely, if mask contrast increases with SOA, we should find relatively less masking at short SOAs and relatively more masking at long SOAs. The two masking functions resulting from increasing and decreasing MCFs should be bounded from above and below by the MCFs constant at c_{max} and c_{min}, respectively. Specifically, let $MCF_{max}(s)$, $MCF_{min}(s)$, $MCF_{inc}(s)$, and $MCF_{dec}(s)$ denote MCFs with maximum, minimum, increasing, or decreasing mask contrast, and let $M_{max}(s)$, $M_{min}(s)$, $M_{inc}(s)$, and $M_{dec}(s)$ denote the resulting masking functions (we name them after the experimental mask-contrast conditions, not after their own shape). Order the SOAs from 1 to n. Then, within measurement error, $M_{dec}(s)$ should run from $M_{max}(1)$ to $M_{min}(n)$, and $M_{inc}(s)$ should run from $M_{min}(1)$ to $M_{max}(n)$. We will refer to this as the *principle of connected endpoints*. It is illustrated in Fig. 2, middle panels: If M_{max} runs from a to b and M_{min} runs from c to d, M_{inc} should run from $a' \approx a$ to $d' \approx d$, and M_{dec} should run from $c' \approx c$ to $b' \approx b$. The principle of connected endpoints is immensely useful for constructing masking functions of a desired shape.

As in simple dissociations, we would hope that the manipulation of mask contrast bends the masking functions into a desired shape but has less impact on the priming functions. The goal is to generate conditions where priming effects keep increasing with SOA not only when prime discrimination increases but also when it decreases. If that is the case, we have successfully generated an *induced double dissociation*. Note that a double dissociation does not require the priming function to be perfectly unchanged by the MCF; it is merely requires $P(s)$ to increase while $M(s)$ decreases, or vice versa.

The current study

We performed a single set of three experiments, reported here in chronological order. In all experiments, we compared different mask-contrast functions as a function of prime-mask SOA to induce double dissociations between priming and masking functions.

Experiment 1

Our first experiment was designed to explore the possibilities of response priming under custom-made masking functions. We employed simple geometrical shapes (squares and diamonds) as primes and masks, and the mask's inner contours were designed to mask the prime by metacontrast (see Fig. 3). The prime-mask SOA was varied in four steps, and the contrast of the entire mask stimulus was systematically coupled with SOA, producing increasing and decreasing mask-contrast functions. We also employed high and low MCFs for purposes of validation and for comparison with earlier data. To assess the impact of our MCFs on priming and masking functions, subjects performed two tasks with the exact same stimuli and procedure: They either had to discriminate mask shape under time pressure (priming task) or to discriminate prime shape without time pressure (prime identification task). The crucial question was whether the different MCFs would affect the masking functions while leaving the time course of priming intact. For establishing a double dissociation, priming effects should increase with SOA even under conditions of decreasing prime discrimination.

Method

Participants Six students from the University of Kaiserslautern (three men; five right-handed; age range 22–33 years) took part in eight 1-hour sessions. Their vision was normal or corrected to normal. All participants were naïve to the purpose of the study and received either course credit or 7€ per hour of participation. Each of them gave informed consent and was treated according to the ethical guidelines of the American Psychological Association. After the final session, they were debriefed and received an explanation of the experiment.

Apparatus The participants were seated in a dimly lit room in front of a color cathode-ray monitor (1,280 × 1,024 pixels, retrace rate 75 Hz) at a viewing distance of approximately 60 cm.

Stimuli and procedure We used stimuli similar to those by Mattler (2003). All stimuli appeared against a white background of 48.2 cd/m^2 (see Fig. 3). Primes were black squares or diamonds (0.04 cd/m^2) with an edge length of 1 cm (0.96° of visual angle) that appeared at fixation (about foveal metacontrast; see Ventura, 1980). Masks were squares or diamonds with an edge length of about 1.6 cm (1.53°) appearing at the same position as the primes. Masks had a central cutout corresponding to the superposition of a square and a diamond prime, so that prime and mask shared adjacent contours and both prime shapes would be masked by metacontrast (Breitmeyer & Öğmen, 2006; Di Lollo, Enns, & Rensink, 2000). The fixation point was presented in black at the center of the screen.

There were two session types. In Session Type 1, masks were either of high contrast to the white background (high MCF, 0.04 cd/m^2) or of low contrast (low MCF, 43.47 cd/

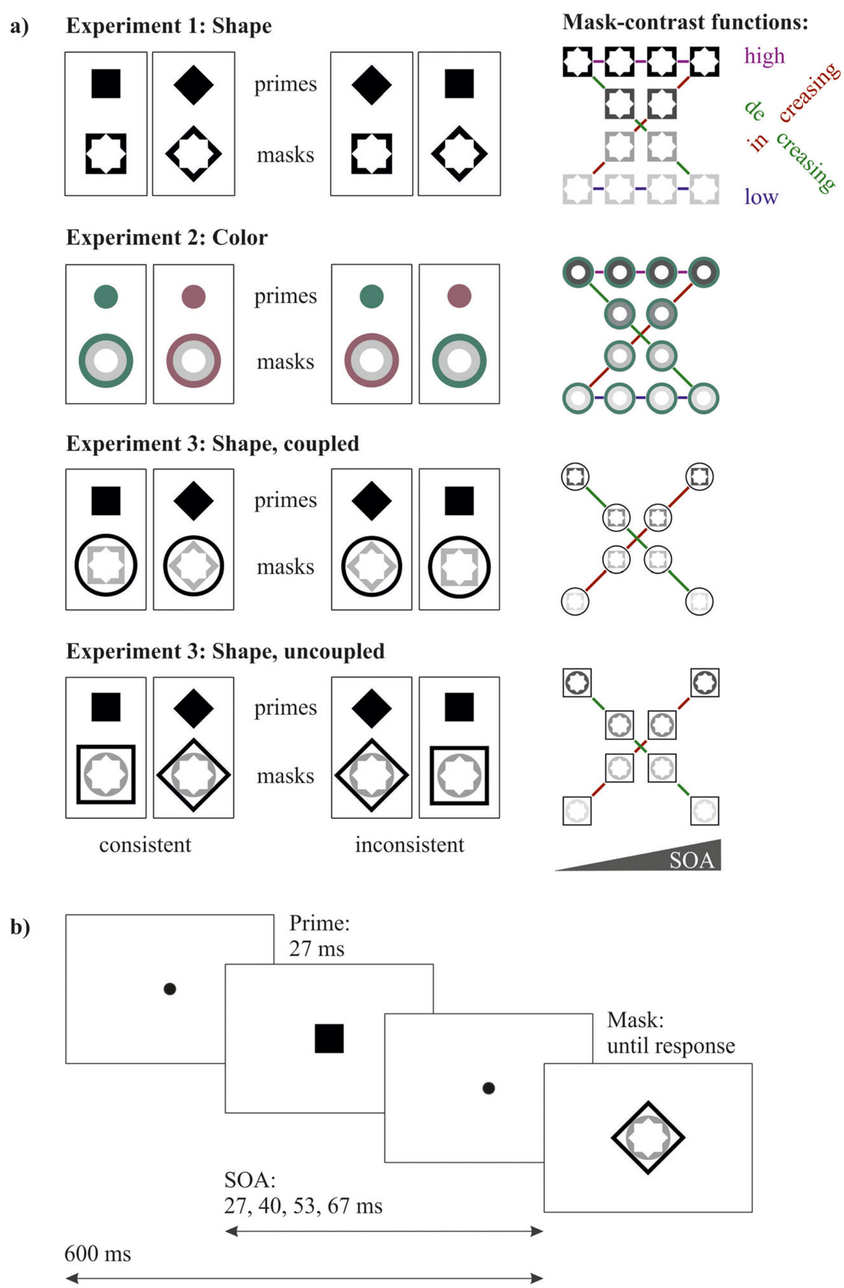

Fig. 3 **a** Prime stimuli, mask stimuli, and mask-contrast functions employed in all experiments. Mask-contrast functions are color-coded throughout the paper. **b** Time course of a trial, illustrated for an inconsistent trial in Experiment 3. (Color figure online)

m^2) at all SOAs. In Session Type 2, four different luminances were used (0.04, 3.65, 16.97, or 43.47 cd/m^2) such that mask contrast either increased or decreased with SOA (increasing and decreasing MCF, respectively).

The experiment consisted of a priming and a prime identification task performed in different sessions, each session comprising 31 blocks with 32 trials. The first block was always a practice block. Each trial started with a central fixation point, followed by a prime presented for 27 ms that was either the same shape as the mask (consistent trial) or the other shape (inconsistent trial). Finally, the mask appeared after a prime-mask SOA of 27 ms, 40 ms, 53 ms, or 67 ms, and remained on screen until response. Time from fixation to mask onset was constant at 600 ms.

Participants were instructed to keep their gaze on the fixation point and press the "F" button upon seeing a diamond, or the "J" button upon seeing a square, using the index fingers. This assignment was counterbalanced across participants. In the priming task, they were asked to respond to the shape of the mask as quickly and correctly as possible. They received visual feedback if the response was incorrect or too slow (response time [RT] > 1,000 ms). In the prime identification task, participants responded to the shape of the prime without time pressure and without trial-to-trial feedback. After each block, participants received summary feedback (in the priming task, on mean reaction time, mean accuracy, and number of errors; in the prime identification task, on mean accuracy only). Participants could take a break after each block.

Each participant took part in eight sessions. Each session contained either low or high MCFs (Type 1) or increasing and decreasing MCFs (Type 2), resulting in two sessions of the priming task (Type 1), followed by two sessions of prime ID (Type 1), priming (Type 2), and prime ID (Type 2). Sessions were usually carried out on different days, rarely in two sessions per day (with a break of at least 2 hours). All combinations of prime shape, prime-mask consistency, and SOA were presented equiprobably and pseudorandomly in each block.

Data treatment and statistical methods Dependent variables were response time and error rate in the priming task, and response accuracy in the prime identification task. Practice blocks were not analyzed. Reaction times were summarized by trimmed means; error trials were excluded from response-time analysis. In the priming task, response times shorter than 100 ms or longer than 999 ms were eliminated as outliers (0.16% in Session Type 1, 0.11% in Session Type 2). Repeated-measures analysis of variance (ANOVA) was performed with factors of mask-contrast function (*MCF*), prime-mask SOA (*S*), and prime-mask consistency (*C*, in analyses of priming effects only). Error rate and response accuracy were arcsine-transformed to meet ANOVA requirements (Winer, Brown, & Michels, 1991). For clarity, all results are reported with Huynh–Feldt-corrected *p* values and the original degrees of freedom, and effects are specified by subscripts to the *F* values (e.g., $F_{C\times S}$ for the interaction of consistency and SOA).

Throughout the paper, we report all ANOVA effects significant at $p \leq .05$, so that unreported effects are always nonsignificant, with the understanding that *p* values between .01 and .05 should be regarded with caution. We will mention *p* values between .05 and .10 if important to the argument.

In multifactor repeated-measures designs, statistical power is difficult to predict because too many terms are unknown. Instead, we control measurement precision at the level of individual participants in single conditions. We calculate precision as $s/\sqrt{r}$ (Eisenhart, 1969), where *s* is a single participant's standard deviation in a given cell of the design and *r* is the number of repeated measures per cell and subject. With r = 120 and 240 in the priming and prime identification task, respectively, we expect a precision of about 5.5 ms in response times (assuming individual *SD*s around 60 ms), at most 4.6 percentage points in error rates, and at most 3.2 percentage points in prime identification accuracy (assuming the theoretical maximum *SD* of .5). Precision thus exceeds our previous recommendations for response priming studies (r = 60; F. Schmidt, Haberkamp, & T. Schmidt, 2011; Smith & Little, 2018).

Results

Session Type 1: Prime identification under low versus high mask contrast We expected that prime discrimination performance would be high under low mask contrast and low under high mask contrast.

Averaged across observers, performance under high-contrast masking was lower than under low-contrast masking, and performance slightly increased with SOA (see Fig. 4). Repeated-measures ANOVA of SOA *(S)* and mask-contrast

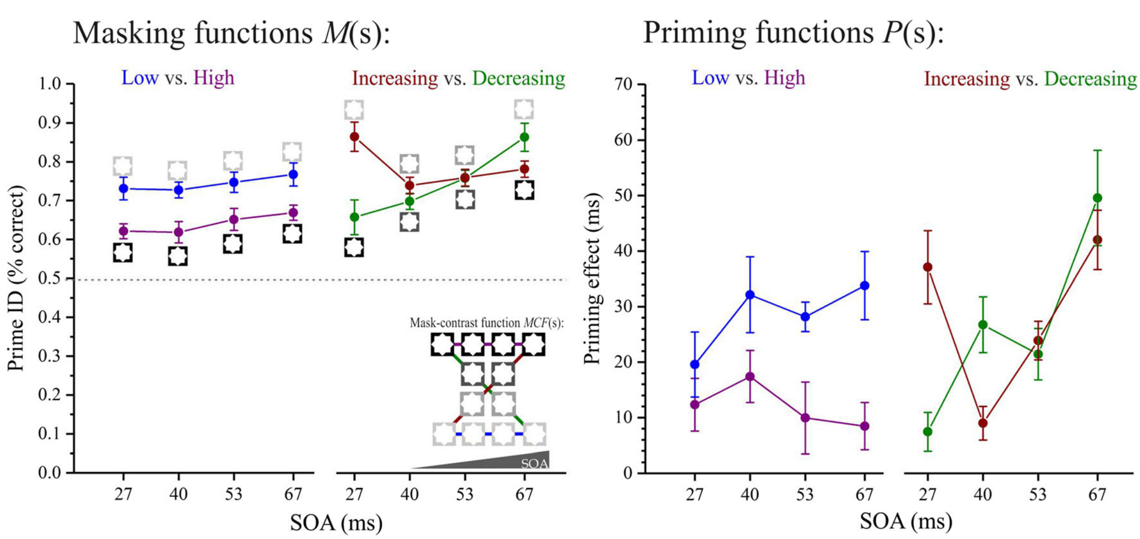

Fig. 4 Experiment 1. Left panel: Results of the prime identification task for both session types (left: Session Type 1; right: Session Type 2). Right panel: Priming effects ($RT_{incon} - RT_{con}$) for both session types. Standard errors of the mean are calculated across subjects and corrected for intersubject variance (Cousineau, 2005). Inlays illustrate the respective masking conditions. Only square targets are shown. (Color figure online)

function *(MCF)* only suggested main effect of mask-contrast function, $F_{MCF}(1, 5) = 6.47$, $p = .052$, and SOA, $F_S(3, 15) = 4.14$, $p = .042$, but no interaction. Note that the lackluster p values are not due to low measurement precision but to large differences between individuals (see below). Simple tests indicated that the SOA effect was not significant in either masking function.

Session Type 2: Prime identification under increasing versus decreasing mask contrast We expected that prime discrimination performance would increase for decreasing mask contrast. Under conditions of increasing mask contrast, we aimed to generate a decreasing masking function.

Performance under decreasing mask contrast was low at the shortest SOA and then increased with SOA. As intended, performance under increasing mask contrast started much higher for the shortest SOA but ended lower at the longest SOA, so that the functions crossed at the 53-ms SOA. Overall, the masking function was V-shaped (see Fig. 4, left panel). Averaged across observers, ANOVA only suggested a main effect of SOA, $F_S(3, 15) = 3.70$, $p = .036$, and a significant interaction, $F_{MCF\times S}(3, 15) = 5.95$, $p = .029$. Simple tests showed a significant SOA effect for decreasing MCF, $p = .008$, but not for increasing MCF. Note that the principle of connected endpoints is violated here: Performance in physically identical stimulus conditions was better by about 10 percentage points in Session Type 2 than in Session Type 1, $t(5) = -2.76$, $p = .040$, suggesting that the blocking of masking functions into separate sessions had a systematic impact on performance.

Priming effects Based on our previous work, we had clear predictions for priming under three of the four mask-contrast functions. For the high and low MCFs, we expected priming effects to increase with SOA. Because response priming effects increase with prime contrast and decrease with target contrast (F. Schmidt et al., 2011; T. Schmidt & F. Schmidt, 2018), we predicted larger priming effects for low-contrast than for high-contrast masks. For the same reason, priming effects should strongly increase with SOA under conditions of decreasing mask contrast. For the conditions of increasing mask contrast, we aimed to find a monotonically increasing priming effect that would be in opposition to the decreasing masking function. Priming effects in error rates should follow the same general pattern as priming effects in response times. For each session type, we performed a repeated-measures ANOVA with factors of consistency (C), SOA (S), and mask-contrast function (MCF).

Session Type 1: Low versus high mask contrast Responses were faster for consistent than for inconsistent trials, $F_C(1, 5) = 52.02$, $p = .001$ (see Fig. 5). This response priming effect (see Fig. 4, right panel) was larger for weak than for strong masks, $F_{C\times MCF}(1, 5) = 30.66$, $p = .003$. Responses were also slower for weak than for strong masks, $F_{MCF}(1, 5) = 55.14$, $p = .001$, a difference diminishing with SOA, $F_{MCF\times S}(3, 15) = 3.56$, $p = .040$. All other effects were nonsignificant. An analogous analysis of the error rates revealed no significant priming effects. Overall, more errors occurred for weak than for strong masks, $F_{MCF}(1, 5) = 7.17$, $p = .044$. There was a somewhat puzzling interaction of mask type and consistency indicating that priming effects were of positive sign for weak masks but were reversed for strong masks, $F_{C\times MCF}(1, 5) = 16.81$, $p = .009$. However, simple tests performed separately for the two mask types revealed no significant effects in either masking condition.

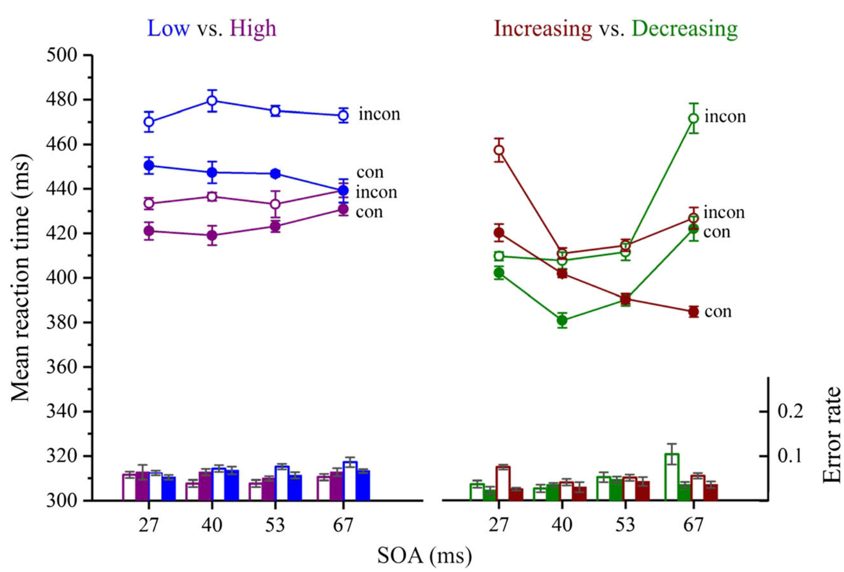

Fig. 5 Experiment 1. Mean reaction times and error rates for all mask-contrast functions, separately for both session types (left: Session Type 1; right: Session Type 2) and for consistent (*con*) and inconsistent (*incon*) trials. Standard errors of the mean are calculated across subjects and corrected for intersubject variance. (Color figure online)

Session Type 2: Increasing versus decreasing mask contrast Overall, response times formed a U-shaped function of SOA, $F_S(3, 15) = 30.43$, $p < .001$ (see Fig. 5). Responses were faster for consistent than for inconsistent trials, $F_C(1, 5) = 88.19$, $p < .001$, and this priming effect (see Fig. 4, right panel) increased with SOA, $F_{C\times S}(3, 15) = 17.75$, $p < .001$. Response times increased with SOA under conditions of decreasing mask contrast, but decreased with SOA under increasing mask contrast, $F_{MCF\times S}(3, 15) = 38.82$, $p = .001$. All other effects were nonsignificant apart from a significant triple interaction, $F_{MCF\times C\times S}(3, 15) = 30.89$, $p < .001$, showing different time courses of the priming effect in the two masking conditions. Roughly, under decreasing mask contrast, priming effects were small at the shortest SOA and then grew larger. Under increasing mask contrast, however, priming effects were large at the shortest SOA, broke down at the next-largest SOA, and only then continued to increase. Note that the smallest priming effect occurred at the same SOA (40 ms) where prime identification accuracy was also lowest, so that no double dissociation was established.

An analogous ANOVA of the error rates showed that more errors occurred in inconsistent than in consistent trials, $F_C(1, 5) = 15.39$, $p = .011$, and that error rates varied with SOA, $F_S(3, 15) = 12.73$, $p < .001$. Priming effects were larger at the shortest and longest SOA than at intermediate SOAs, $F_{C\times S}(3, 15) = 4.30$, $p = .024$, mainly due to the conditions with increasing mask contrast.

Individual differences in masking and priming Previous research has shown that participants can differ strongly in their time course of visual masking. Therefore, one has to be cautious in averaging across observers (Albrecht & Mattler, 2010). Indeed, participants differed greatly in the degree as well as the time course of masking (see Fig. 6). Four out of six observers responded to our manipulation of mask contrast. Of the two observers who failed to do so, one performed almost perfectly throughout all masking conditions (ceiling effect, Participant 5) and one was at chance throughout all conditions (floor effect, Participant 6). In contrast, participants were quite homogenous regarding the pattern of response priming effects, despite marked differences in overall response speed. Note, however, that there is no indication of a double dissociation between priming and masking even at the individual level. First, under low or high MCFs, none of our participants shows Type B masking. Second, participants tend to show larger priming effects in precisely those conditions where they also perform better at prime discrimination. Third, under increasing mask contrast, all six observers show a dip in priming effects at the second-shortest SOA, which is exactly the condition where prime discrimination is most impaired.

Discussion

Experiment 1 is no success for our method. On the one hand, we were able to strongly influence the level and time course of prime discrimination performance in the majority of observers by controlling mask contrast as a function of SOA. This manipulation is successful in inducing decreasing or U-shaped masking functions in some observers who would otherwise show only Type A masking. Also, we find that response priming effects are homogenous across observers despite large differences in masking functions: Priming effects are basically the same no matter whether prime discrimination is at chance (Participant 6) or nearly perfect (Participant 5), and no matter whether masking functions do or do not cross (Participants 1 & 3 vs. 2 & 4). On the other hand, the double dissociation we hoped for does not occur, either at the group or at the individual level: In the crucial condition of increasing mask contrast, priming effects decrease in exactly those conditions where prime discrimination performance is also lowest. So, even though there is plenty of evidence in this data set that the ability to identify the prime is no predictor of the priming effect, we failed to create a double dissociation between priming and masking.

Why the failure? There are indications that Experiment 1 confounded two aspects of the mask: its ability to reduce prime visibility and its ability to activate a response. Generally, priming effects decrease with increasing target contrast because stronger targets are more effective in counteracting response activation from the prime (Haberkamp, F. Schmidt, & T. Schmidt, 2013; F. Schmidt et al., 2011; T. Schmidt & F. Schmidt, 2018). In line with this, we observe a relative reduction in priming in those conditions where the mask has high contrast (because mask and target are the same stimulus). We therefore suspected that Experiment 1 failed to produce a double dissociation because the backward-masking aspect of the imperative stimulus was coupled to its response-activation aspect. In Experiment 2, we decoupled those features, allowing them to act independently on the masking and priming functions.

Experiment 2

For this experiment, we switched to a domain where double dissociations between masking and response activation have not been observed before: response priming by color under metacontrast masking. If a colored prime is followed by a metacontrast mask of a different color, strong masking can occur provided that the colors are sufficiently desaturated. Previous research has shown strong response priming when participants respond to the color of a mask preceded by a prime of consistent or inconsistent color, even when the prime's color cannot be discriminated (Breitmeyer, Ro, Oğmen, & Todd, 2007; Breitmeyer, Ro, & Singhal, 2004; T. Schmidt, 2000, 2002). However, only Type A masking is typically observed under metacontrast by heterochromatic color stimuli (Breitmeyer & Oğmen,

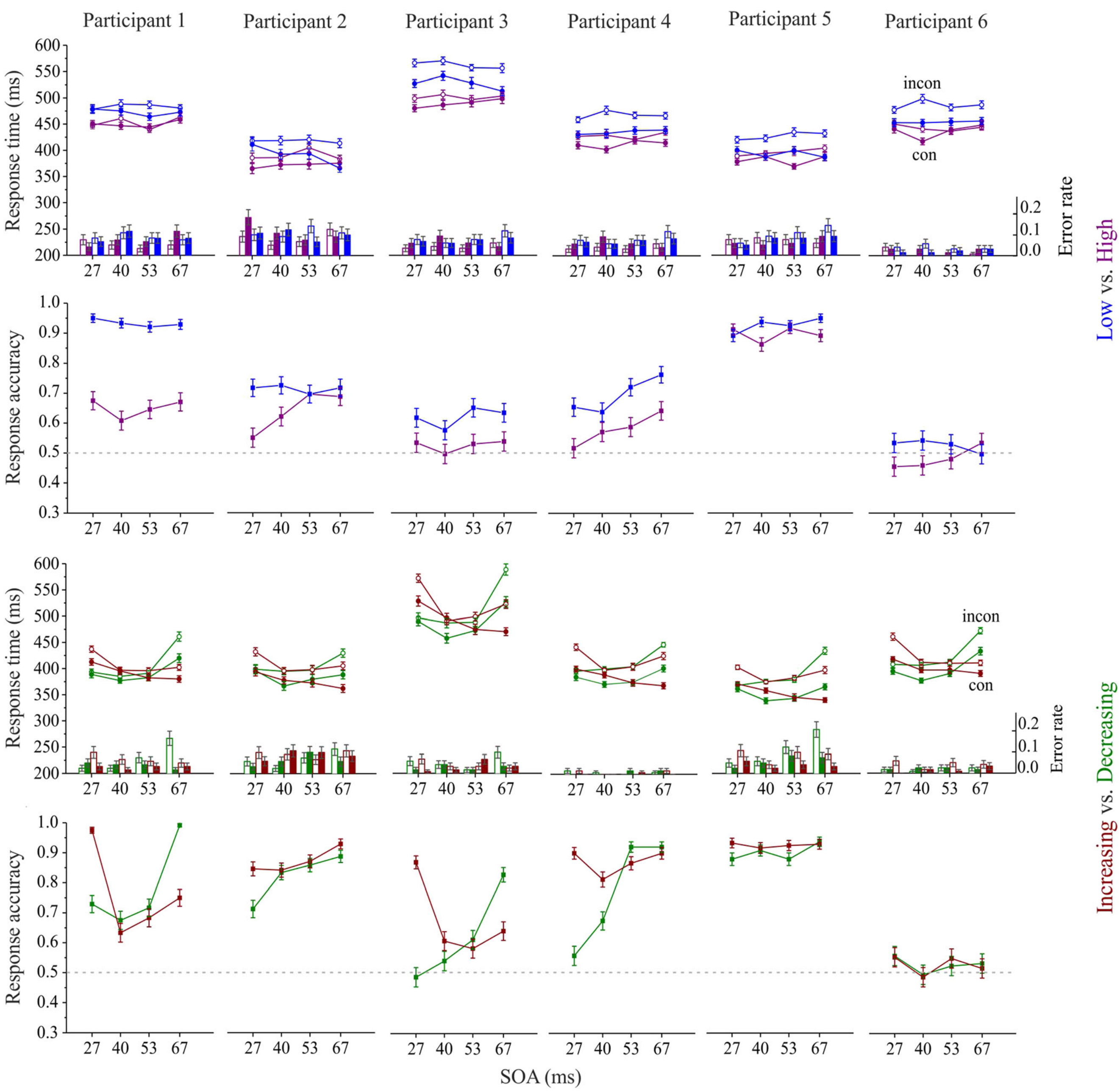

Fig. 6 Results for each individual participant in Experiment 1. Standard errors of the mean are calculated across trials. (Color figure online)

2006), and therefore no double dissociation has ever been reported for response priming by color. We wanted to see whether double dissociations can be induced by employing different mask-contrast functions.

In Experiment 1, the mask's ability to activate responses was confounded with its ability to mask the prime. For Experiment 2, we decoupled those properties by separating the mask into two parts. Participants responded to the color (red or green) of a ring-shaped mask preceded by a disk-shaped prime either consistent or inconsistent in color. Only the outer part of the mask was colored and thus able to activate a response, while the inner part was presented in grayscale and designed to mask the prime by metacontrast (see Fig. 3). Only the luminance contrast of the inner part was manipulated to control the degree of masking, independent from response activation from the colored outer part. As before, we compared increasing and decreasing mask-contrast functions, but once again included low and high MCFs to validate the principle of connected endpoints in an improved design where all masking conditions were randomly intermixed instead of blocked. With this setup, we expected priming effects in response times and error rates to increase with SOA under all MCFs, irrespective of the time course of masking.

Method

Participants Six students from the University of Kaiserslautern (three male; five right-handed; mean age 26.3 years) took part in eight 1-hour sessions. Their vision was normal or corrected to normal. All but two participants were naïve to the purpose of the study and received 7€ per hour of participation. Each of them gave informed consent and was treated according to the ethical guidelines of the American Psychological Association. After the final session, they were debriefed and received an explanation of the experiment.

Apparatus, stimuli, and procedure The apparatus and procedure were identical to Experiment 1 except for new stimuli. Prime stimuli were red or green disks (diameter of 0.86°) which exactly fitted the inner cutout of the masks. Mask stimuli were annuli, consisting of a colored outer ring (outer diameter 1.92°) and a gray inner ring (outer diameter 1.54°, inner diameter the size of the prime) with a luminance of either 4.69, 12.6, 25.03, or 23.47 cd/m^2. Red and green stimuli were desaturated in color to allow for metacontrast masking (T. Schmidt, 2000) and had CIE coordinates of x = 0.33 and 0.25, y = 0.26 and 0.31, respectively. They were similar in luminance (red: 5.28 cd/m^2; green: 7.70 cd/m^2).

The priming and the prime identification task were performed in alternating sessions, each session comprising 31 blocks with 32 trials. Participants were instructed to keep their gaze on the fixation point and press the “F” button for red stimuli or the “J” button for green stimuli, using the index fingers. This assignment was counterbalanced across participants. In the priming task, they were asked to respond to the color of the mask (i.e., its outer ring) as quickly and correctly as possible. In the prime identification task, they responded to the color of the prime without time pressure. Feedback was given as in Experiment 1.

Data treatment and statistical methods Trimming of response times and data analysis proceeded as in Experiment 1 and eliminated 0.07% of trials in the priming task. Because the trial structure is identical to that of Experiment 1, we again expected a measurement precision of 5.5 ms in response times, at most 4.6 percentage points in error rates, and at most 3.2 percentage points in prime identification accuracy.

Results

Prime discrimination performance As in Experiment 1, we expected that prime discrimination performance would be high under low mask contrast, low under high mask contrast, and increasing for decreasing mask contrast. Under conditions of increasing mask contrast, our goal was to generate a decreasing or U-shaped masking function.

Low versus high mask contrast As expected, prime discrimination performance was better under low than under high mask contrast, $F_{MCF}(1, 5) = 15.99$, $p = .010$ (see Fig. 7, left panel). Mask function interacted with SOA, such that performance increased with SOA at high mask contrast but decreased at low mask contrast, $F_{MCF\times S}(3, 15) = 12.87$, $p = .005$. Simple tests showed that both the increase and the surprising decrease were significant, $p = .002$ and .027. There was no significant main effect of SOA.

Increasing versus decreasing mask contrast Performance increased with SOA under decreasing mask contrast (see Fig. 7, left panel). Under increasing mask contrast, performance

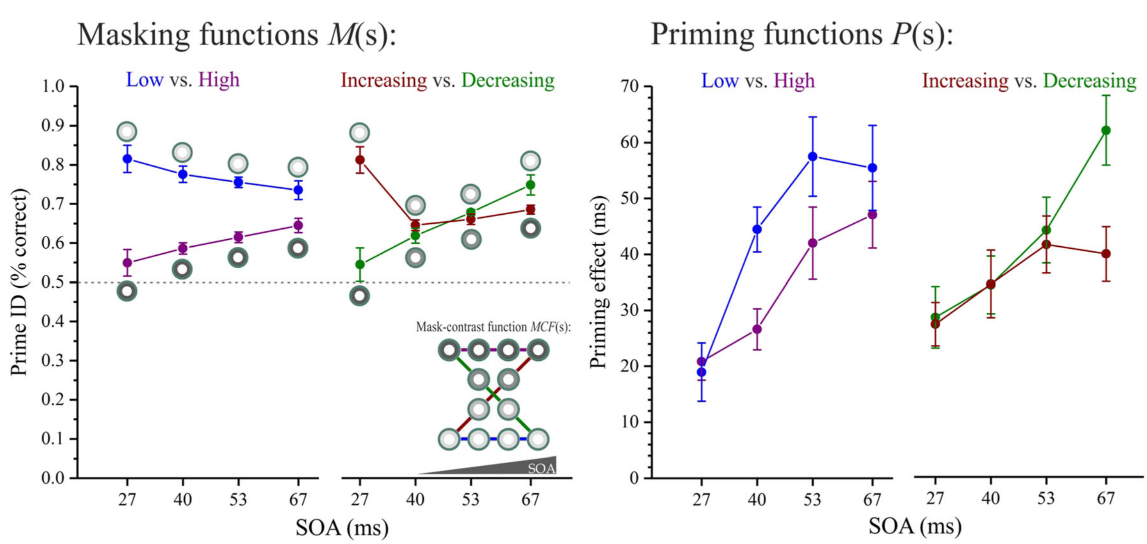

Fig. 7 Experiment 2. Left panel: Results of the prime identification task for all masking functions. Overall response accuracy is averaged across consistency. Right panel: Priming effects for all masking functions. Inlays illustrate the respective masking condition. Only green masks are shown. (Color figure online)

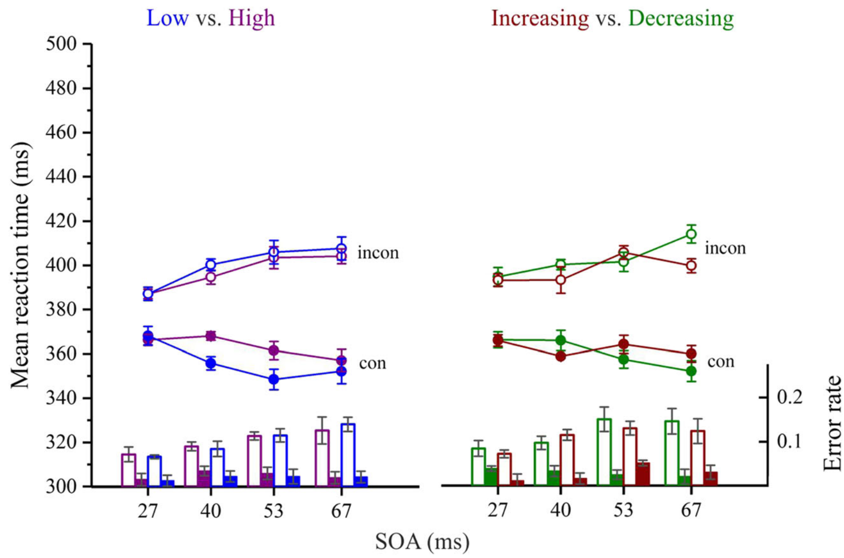

Fig. 8 Experiment 2. Mean reaction times and error rates for all mask-contrast functions. (Color figure online)

strongly decreased between the shortest two SOAs and then remained constant. The different time courses led to a significant interaction of mask function and SOA, $F_{MCF\times S}(3, 15) = 10.93$, $p = .017$. Overall, performance was better under increasing mask contrast, $F_{MCF}(1, 5) = 12.99$, $p = .015$, and increased with SOA, $F_S(3, 15) = 5.46$, $p = .010$. Simple tests showed significant SOA effects for both decreasing and increasing MCFs, $p = .020$ and .010, respectively. Note that the principle of connected endpoints is well met, so that performance levels are similar in physically identical conditions, $t(15) = -1.63$, $p = .164$.

Priming effects We expected priming effects to increase with SOA for all mask-contrast functions because the mask's ability to activate responses was now decoupled from its ability to mask the prime.

Low versus high mask contrast Responses to the mask were faster for consistent than for inconsistent trials, $F_C(1, 5) = 49.02$, $p = .001$, and these priming effects increased with SOA, $F_{C\times S}(3, 15) = 16.57$, $p < .001$ (see Fig. 8). Priming effects (see Fig. 7, right panel) were larger by about 10 ms for weak than for strong masks, $F_{MCF\times C}(1, 5) = 9.67$, $p = .027$. All other effects were nonsignificant, indicating that the time course of priming was similar under both masking functions. An analogous analysis showed that error rates were higher in inconsistent trials, $F_C(1, 5) = 29.41$, $p = .003$, and increased with longer SOA, $F_S(3, 15) = 8.20$, $p = .002$.

Increasing versus decreasing mask contrast In contrast to Experiment 1, both conditions now showed priming effects that increased with SOA (see Fig. 8). Overall, response times were significantly faster for consistent than for inconsistent trials, $F_C(1, 5) = 51.16$, $p = .001$, and this priming effect (see Fig. 7, right panel) increased with SOA, $F_{C\times S}(3, 15) = 13.33$, $p < .001$. Priming effects were larger under decreasing than under increasing mask contrast $F_{C\times MCF}(1, 5) = 16.02$, $p = .010$, but there was no three-way interaction, and simple tests showed that priming effects increased with SOA for both mask-contrast functions, $p = .042$ and .009, respectively. An analogous analysis showed that error rates were higher in inconsistent trials, $F_C(1, 5) = 21.26$, $p = .006$, and increased with SOA, $F_S(3, 15) = 11.15$, $p = .002$. Priming effects increased faster with SOA under decreasing mask contrast, $F_{MCF\times C\times S}(3, 15) = 6.15$, $p < .006$.

Individual differences in masking and priming As in Experiment 1, participants showed marked differences in prime discrimination performance (see Fig. 9). All participants performed better under low than under high mask contrasts. Participant 1 performed at chance level throughout, Participant 4 was close to chance performance. Surprisingly, the remaining participants showed increasing performance with SOA for high-contrast masks, but *decreasing* performance (Type B masking) for low-contrast masks. Under decreasing mask contrast, performance strongly increased with SOA from very low to very high values, conforming to the principle of connected endpoints. Under increasing mask contrast, there was a sharp dip in performance between the shortest two SOAs, after which performance remained constant. This variation in masking functions was in marked contrast to the priming effects, which increased with SOA in all participants. This was the case irrespective of whether prime discrimination performance was high or at chance, and no matter whether it increased or decreased with SOA.

Discussion

Experiment 2 successfully demonstrates a double dissociation (Vorberg et al., 2003): Priming effects increase with SOA no

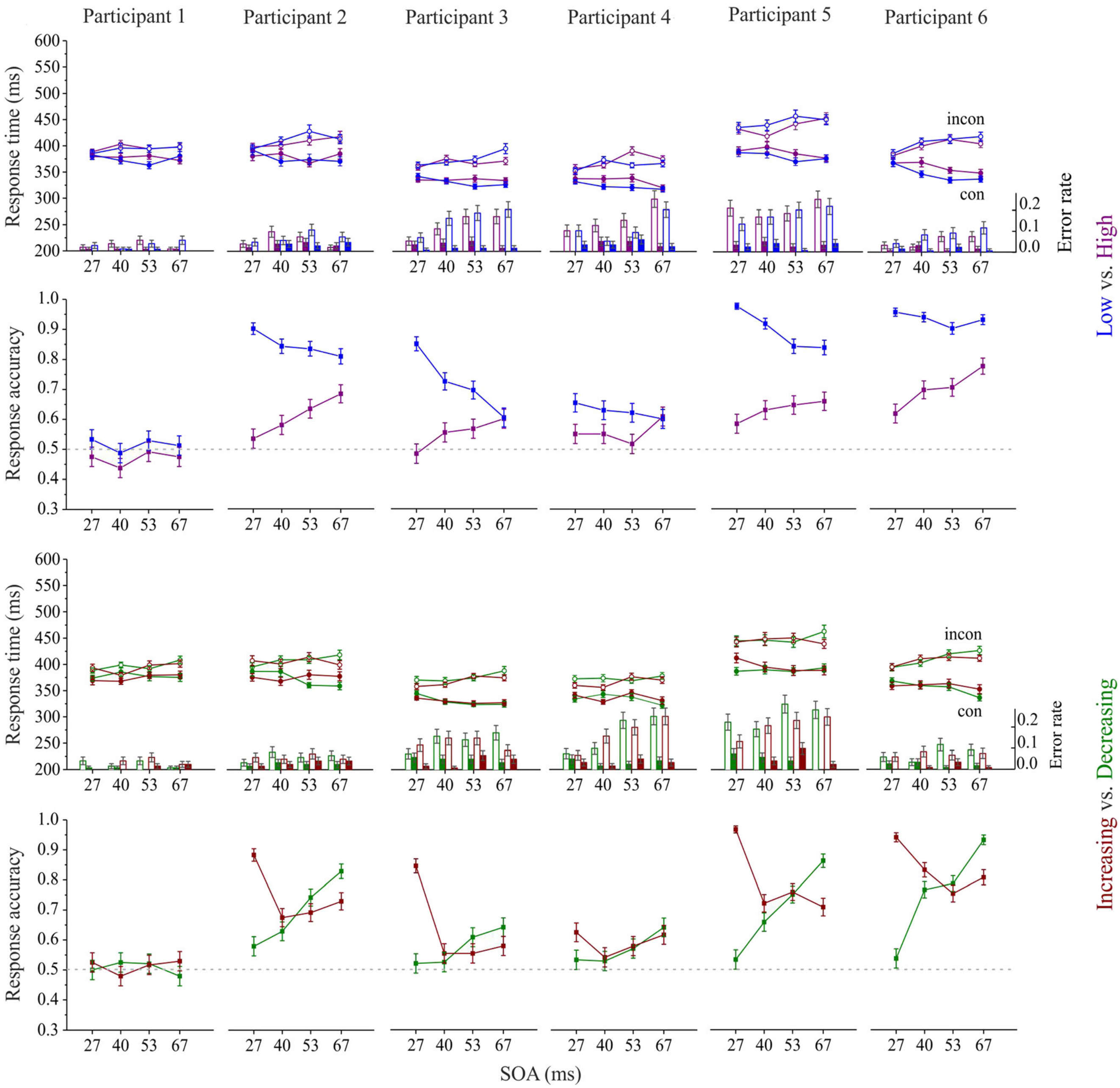

Fig. 9 Results of each individual participant in Experiment 2. (Color figure online)

matter whether prime discrimination increases or decreases. Double dissociations are observed in a majority of participants. The key for this seems to be the use of uncoupled mask features (i.e., the separate manipulation of the mask's ability to reduce the visibility of the prime and its ability to activate the response). If those stimulus aspects are not decoupled, masking and priming are confounded, spoiling the chance of finding qualitatively different time courses even if the processes would be dissociable in principle.

Our data show that custom-made MCFs can modulate masking functions while leaving priming functions intact, and are able to accentuate dissociations between them. They are also able to provoke surprising new dissociation patterns: Under increasing versus decreasing MCFs, priming functions remain unchanged while the masking functions cross. This is actually evidence of an additional dissociation pattern: Priming effects are similar under increasing versus decreasing MCFs no matter which one leads to higher prime discrimination at a given SOA. A second surprise was that many participants showed spontaneous Type B masking under low-contrast masks, something ordinarily not observed in metacontrast masking of color stimuli. It is probably made possible by our special design of the stimuli: Whereas in previous studies color primes were surrounded by masks of either the same or different color, in our stimuli the masking is achieved primarily by the gray inner part of the stimulus. This setup reduces the color contrast between prime and mask (e.g., to red:gray instead of red:green) without reducing the luminance contrast of either stimulus. Luminance contrast is necessary for Type B metacontrast masking while mere color contrast is insufficient (Bowen, Pokorny, & Cacciato, 1977), and metacontrast decreases with increasing color dissimilarity between mask and masked stimulus (McKeefry, Abdelaal, Barrett, & McGraw, 2005). Therefore, masking color primes by gray masks may allow Type B masking on the basis of luminance contrast. To our knowledge, this is the first time that increasing response priming effects by color are demonstrated under conditions of decreasing prime discrimination performance.

By randomly intermixing all stimulus conditions, the behavior of the masking functions becomes predictable because they now all conform to the principle of connected endpoints: They are forced to take crossed paths from strong masking at the shortest SOA to weak masking at the longest SOA (decreasing MCF), or vice versa (increasing MCF). Our data therefore suggest that the shape of the masking function can largely be controlled by managing the degree of masking at the endpoints of the functions. The degree of control is limited, however, by the strong individual differences in the time course of masking (Albrecht et al., 2010).

Experiment 3

In Experiment 1, we employed shape stimuli and found that priming effects and prime discrimination performance had comparable time courses under the different mask-contrast regimes. We suspected that this failure to observe a double dissociation was due to the design of our mask stimulus, which confounded the mask's ability to activate a response with its ability to reduce the visibility of the prime. In Experiment 2, we decoupled these two aspects of the mask by separating it into two parts: an inner masking part and an outer response-activating part (in red or green). With these stimuli, we were able to observe double dissociations in the color domain.

It remains to be shown conclusively that the use of uncoupled mask features is really the key to the problem. In Experiment 3, we return to shape stimuli and systematically compare coupled and uncoupled mask features. Masks now consist of an inner part (responsible for metacontrast masking of the prime and varying in contrast) and an outer response-activating part. In *uncoupled masks*, the inner masking part is neutral in shape, and response activation is driven entirely by the shape of the outer part. This design should allow us to use mask-contrast functions to manipulate masking functions without affecting the priming functions in response times or error rates. In *coupled masks,* the outer part is neutral in shape, and response activation is driven entirely by the shape of the inner part. With this design, both response activation and masking should depend on the inner part alone, and priming and masking effects should be associated.

Method

Participants Twelve students from the University of Kaiserslautern (six men; mean age 23.4 years; one left-handed) took part in eight 1-hour sessions. All of them were naïve to the concept of the experiment and did not participate in Experiments 1 or 2. All participants had normal or corrected-to-normal vision and received 7€ per hour as payment.

Apparatus, stimuli, and procedure The apparatus and procedure were identical to Experiments 1 and 2, except for new stimuli and for the sequence of blocks. Primes were small black squares and diamonds (0.04 cd/m^2) with an edge length of 0.8 cm (0.76° of visual angle), appearing at fixation. Mask stimuli were about 2.2 cm in size (2.1° of visual angle).

There were two configurations of mask stimuli, employed in different sessions (see Fig. 3). Coupled masks were squares or diamonds surrounded by a circle (i.e., a neutral shape). Uncoupled masks were circles surrounded by either a square or a diamond. While the inner part varied in luminance (4.69, 12.60, 25.03, or 43.47 cd/m^2) according to two mask-contrast functions (increasing or decreasing with SOA), the outer part was always presented at maximum contrast (black). As in Experiment 1, the inner part of the mask had a central cutout (both prime shapes superimposed) designed to mask both square and diamond primes by metacontrast.

Participants either responded to the shape of the mask (square or diamond, priming task) or to the shape of the prime (prime identification task). Two consecutive sessions always consisted of one session of the priming task followed by one session of the prime identification task. Pairs of sessions alternated between coupled and uncoupled mask conditions (or vice versa)—that is, the first two sessions employed coupled masks, the next two uncoupled masks, and so on.

Data treatment and statistical methods Trimming of response times and data analysis proceeded as in Experiments 1 and 2. In the priming task, the trimming procedure eliminated 0.12% and 0.14% of outlier trials for coupled and uncoupled masks, respectively. With only 60 and 120 trials per participant and ANOVA cell in priming and prime identification, respectively, we expected standard errors per cell and subject of about 7.7 ms in response times, at most 6.5 percentage points in error rates, and at most 4.6 percentage points in prime identification accuracy. We compensated this loss in precision by doubling the number of participants.

Results

As before, we expected that prime discrimination performance would be increasing for decreasing mask contrast, and aimed to generate a decreasing or U-shaped masking function for increasing mask contrast, while priming effects should increase under both masking regimes. Crucially, this double dissociation should only occur for uncoupled masks, while priming and masking functions should be associated for coupled masks. Data were analyzed separately for the two mask types.

Prime discrimination performance The pattern of prime discrimination performance was similar for coupled and uncoupled masks (see Fig. 10, left panel). Performance increased with SOA under decreasing mask contrast. Under increasing mask contrast, performance decreased between the shortest two SOAs and then remained constant. The different time courses led to a significant interaction of mask function and SOA for coupled as well as uncoupled masks, $F_{MCF\times S}(3, 33) = 5.52$ and 6.89, $p = .031$ and .014, respectively. For coupled masks, performance was significantly better under increasing mask contrast, $F_{MCF}(1, 11) = 14.68, p = .003$, a main effect not significant for uncoupled masks. For uncoupled masks, performance increased significantly with SOA, $F_S(3, 33) = 3.51$, $p = .035$. This main effect was not significant for coupled masks. Simple tests indicated that the SOA effect was significant in each of the four masking functions, all $ps \leq .044$.

Priming effects For coupled masks, responses were faster in consistent than in inconsistent trials, $F_C(1, 11) = 11.21$, $p = .007$ (see Fig. 11). This priming effects (see Fig. 10, right panel) increased under conditions of increasing mask contrast (with the same dip at the 40-ms SOA that was observed in Experiment 1) and decreased under conditions of decreasing mask contrast, $F_{MCF\times C\times S}(3, 33) = 10.99, p < .001$. In contrast to Experiment 1, but in tight agreement with the time course of masking, this decrease continues until the priming effect virtually disappears. Averaged across SOA, the priming effect was slightly larger under increasing mask contrast, $F_{MCF\times C}(1, 11) = 18.73$, $p = .001$. Overall response times increased with SOA for decreasing mask contrast but increased with decreasing mask contrast, forming an X-shaped pattern, $F_{MCF\times S}(3, 33) = 283.65, p < .001$. Overall, response time was a U-shaped function of SOA, $F_S(3, 33) = 145.05$, $p < .001$. The error rates follow a similar pattern, with more errors in inconsistent than consistent trials, $F_C(1, 11) = 7.68, p = .018$, and at the shortest and longest SOA, $F_S(3, 33) = 14.67$, $p < .001$. These priming effects were larger under increasing mask contrast, $F_{MCF\times C}(1, 11) = 10.39, p = .008$, and differed across SOAs, $F_{C\times S}(3, 33) = 6.07$, $p = .002$. ANOVAs performed separately for each mask-contrast function confirmed significant priming effects in response times for increasing as well as decreasing mask-contrast functions, $F_C(1, 11) = 16.55$ and 6.32, $p = .002$ and .029, significant main effects of SOA, $F_S(3, 33) = 243.99$ and 211.86, both $ps < .001$, and significant interactions of SOA and consistency, $F_{C\times S}(3, 33) = 8.04$ and 5.09, $p < .001$ and $p = .016$, respectively.

For uncoupled masks, responses were faster for consistent than for inconsistent trials, $F_C(1, 11) = 102.70, p < .001$ (see Fig. 11), and this priming effect increased with SOA, $F_{C\times S}(3, 33) = 26.98$, $p < .001$ (see Fig. 10, right panel). Overall, response times increased with SOA, $F_S(3, 36) = 15.32, p < .001$. Although priming functions under increasing and decreasing mask contrast look quite similar, there is a significant three-

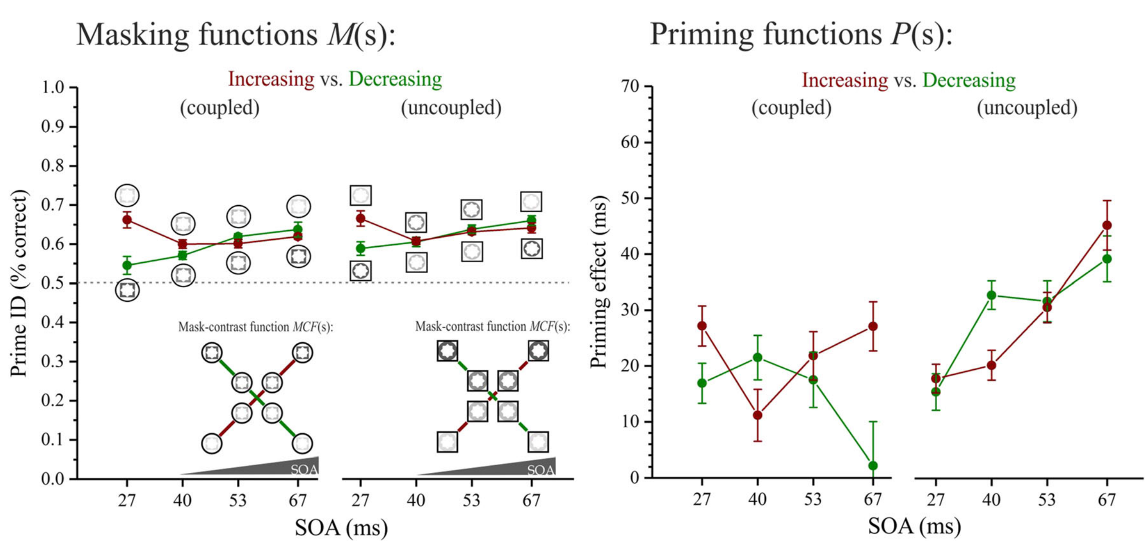

Fig. 10 Experiment 3. Left panel: Results of the prime identification task for all masking functions. Overall response accuracy is averaged across consistency. Inlays illustrate the respective masking condition. Only square masks are shown in the coupled condition; only circle masks are shown in the uncoupled condition. Right panel: Priming effects for all masking functions. (Color figure online)

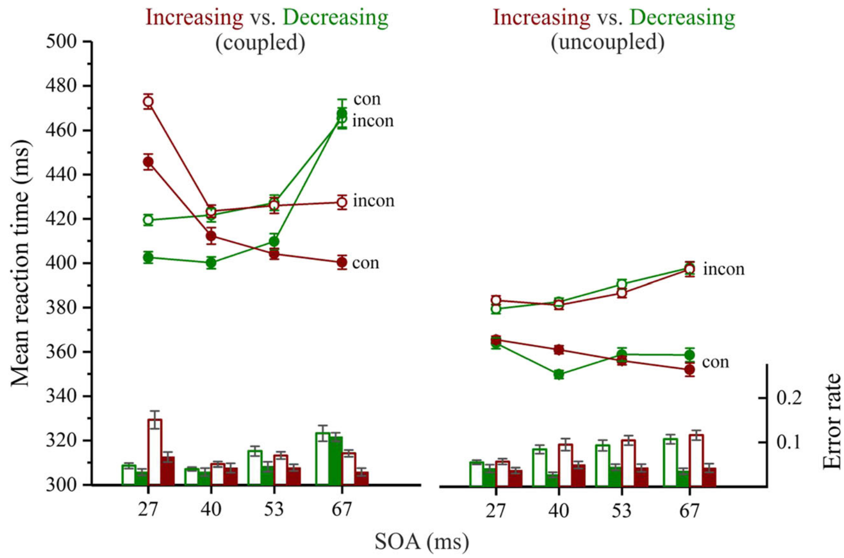

Fig. 11 Experiment 3. Mean reaction times and error rates for all mask-contrast functions and for coupled and uncoupled stimuli. (Color figure online)

way interaction, $F_{MCF\times C\times S}(3, 33) = 3.80$, $p = .019$, and an interaction of mask-contrast function with SOA, $F_{MCF\times S}(3, 33) = 5.69$, $p = .003$. The error rates follow a similar pattern, with more errors in inconsistent than in consistent trials, $F_C(1, 11) = 29.11$, $p < .001$, and errors increasing with SOA in inconsistent trials only, $F_{C\times S}(3, 33) = 10.12$, $p < .001$, $F_S(3, 33) = 10.52$, $p < .001$. Error rates were slightly higher under increasing mask contrast, $F_{MCF}(1, 11) = 5.26$, $p = .043$. ANOVAs performed separately for each mask-contrast function confirmed the finding of significant priming effects in response times for increasing as well as decreasing mask-contrast functions, $F_C(1, 11) = 111.04$ and 74.58, both *p*s < .001, significant main effects of SOA, $F_S(3, 33) = 3.64$ and 13.26, $p = .022$ and < .001, and significant interactions of SOA and consistency, $F_{C\times S}(3, 33) = 13.77$ and 18.44, both *p*s < .001, respectively. Overall, responses were about 50 ms faster for uncoupled than for coupled masks, $t(11) = 10.67$, $p < .001$, reflecting the generally higher contrast of the imperative stimulus.

Individual differences in masking and priming Again, participants showed remarkable homogeneity in their priming effects (see Fig. 12). For uncoupled masks, most participants showed the characteristic response-time pattern where priming effects increase with SOA. For coupled masks, most of them showed the crossover pattern characteristic for Experiment 1, with elevated response times when the imperative stimulus was low in contrast, and a dip in priming effects at the 40-ms SOA. Again, participants were much more variable in their masking functions. Most participants performed close to chance level throughout. The remaining participants showed increasing accuracy for decreasing mask contrast, and U-shaped masking functions for increasing mask contrast.

Discussion

Experiment 3 clearly shows that in order to use induced dissociations, it is necessary to decouple the ability of the imperative stimulus to mask the prime from its ability to activate the response. When those two aspects of the mask were confounded, we obtained a data pattern where priming and masking were closely associated, as in Experiment 1. In contrast, when those two aspects were decoupled, we obtained the data pattern of Experiment 2, where priming effects increased despite decreasing performance in prime discrimination (double dissociation). In addition, we find that priming effects are similar under increasing versus decreasing MCFs no matter which one leads to higher prime discrimination performance at a given SOA.

All these principles can be demonstrated on the basis of individual participants. However, the analysis of single subjects also reveals limitations of our method. Participants differ strongly in the overall shape of their masking functions, and many of them operate close to chance level when trying to discriminate the prime. They generate floor effects that spoil any chance of a double dissociation, but of course still give rise to a simple dissociation: large priming effects in the absence of prime discrimination. Those participants that did respond to the change of the mask-contrast function showed double dissociation patterns where priming effects increased no matter whether prime discrimination increased or decreased (Vorberg et al., 2003).

Why is masking so strong in so many participants even under conditions where the metacontrast mask is at minimal contrast? It is possible that the composite stimuli we used as masks generate not only metacontrast from the inner part of the stimulus but also object substitution masking from the

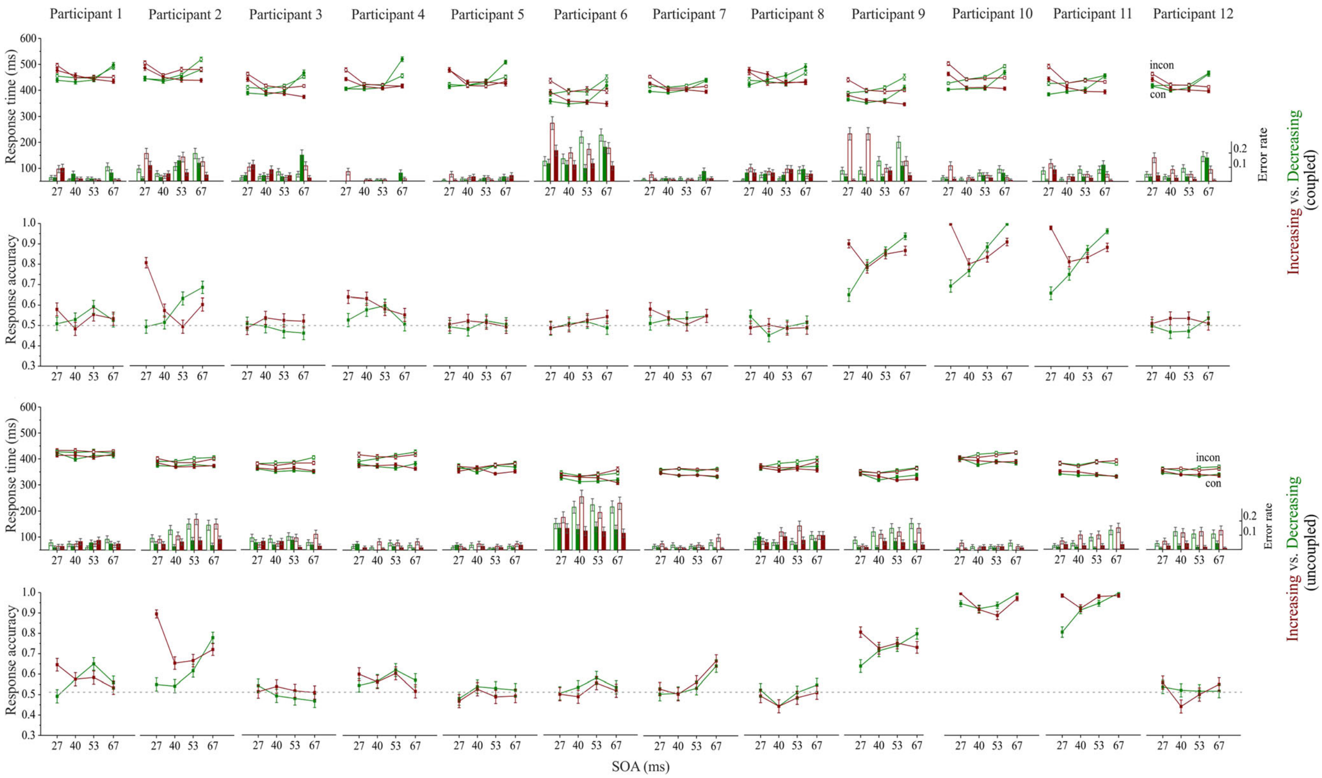

Fig. 12 Results of each participant in Experiment 3. (Color figure online)

outer part, a form of masking where the to-be-masked stimulus is replaced with surrounding stimuli that are not immediately adjacent to its contours (DiLollo, Enns, & Rensink, 2000; Enns & DiLollo, 1997, 2000). Our mask-contrast functions only control the amount of metacontrast but would still allow for substitution masking.

General discussion

Our study introduces the technique of *induced dissociations* between indirect measures of stimulus processing (e.g., response priming effects) and direct measures of visual awareness (e.g., prime discrimination performance) in response priming by both shape and color. By systematically coupling mask contrast to the prime-mask SOA, we create different mask-contrast functions to provoke qualitatively different time courses of prime discrimination performance while the time courses of priming effects remain unchanged (induced dissociations).

The technique of induced dissociations enables us to demonstrate a range of dissociation patterns. *Simple dissociations* include the observation of priming effects when prime discrimination is near chance, as well as the observation that priming functions remain similar under increasing versus decreasing MCFs no matter which one of them leads to higher prime discrimination at a given SOA. Most importantly, we observe *double dissociations*, increasing priming effects in spite of decreasing prime discrimination. Double dissociations are important because they circumvent the classical problem of demonstrating the absence of awareness. Convincingly establishing priming under zero awareness (simple dissociation) requires strong assumptions about the measurement of awareness, in particular the assumption that the direct measure is exhaustive—a strictly monotonic function of awareness that is certain to detect any increase in awareness, no matter how small (Reingold & Merikle, 1988). In contrast, double dissociations only require assumptions of weak monotonicity, do not require zero awareness of the critical stimulus, and are of immediate theoretical interest because they summarily refute all models which assume that both direct and indirect measures depend monotonically on only one source of information (T. Schmidt & Vorberg, 2006).

All those effects are readily established at the level of individual participants. However, while priming effects are homogenous across participants, the variations in the amount and time course of metacontrast masking are huge—so huge, in fact, that they could never be remedied by adjusting prime or mask contrast for individual observers, because there are floor as well as ceiling effects under minimum as well as maximum mask contrast. Albrecht et al. (2010) and Albrecht and Mattler (2010, 2012, 2016) have shown that metacontrast masking functions are idiosyncratic and stable over time. Our findings suggest that they are malleable only to some degree, even though our method is able to strongly accentuate the functions. This raises the question whether masking functions from individual observers should ever be averaged, at least not as uncritically as is customary in the masked-priming literature.

The technique of induced dissociations requires stimuli that separate the ability to mask the prime from the ability to activate a response. If those two aspects of the imperative stimulus remain confounded (*coupled masks*), priming effects will be compromised in exactly those conditions where prime visibility is also low, and no dissociation between the two measures can be expected.[3] But when composite stimuli are used in which the part that induces masking (e.g., luminance contrast of a metacontrast ring mask) is varied independently from the part that activates the response (e.g., an additional shape or color part), masking can be varied without affecting the time course of response priming (*uncoupled masks*). This allows us to obtain smooth and regular priming functions that increase with SOA in basically all observers, no matter whether prime visibility is high, low, increasing, or decreasing with SOA (cf. Vorberg et al., 2003).

Why do coupled masks influence response priming in the first place? Response priming is best described as a conflict between responses elicited in turn by the prime and target. Accumulator models of response priming assume that after the prime has begun to activate its associated response, the target will activate either the same response (consistent trial) or the opposite response (inconsistent trial), which requires counteracting the previous influence of the prime. T. Schmidt and F. Schmidt (2018; cf. Schubert et al., 2013; Vorberg et al., 2003) present an accumulator model for the case that primes and targets have different rates of response activation depending on prime and target strength. This model predicts (1) that response times decrease with target strength, and (2) that priming effects increase with prime strength but decrease with target strength (because a stronger target is quicker in counteracting the prime). In coupled masks, high mask contrast would thus lead to strong masking as well as reduced priming, whereas low mask contrast would lead to weak masking and increased priming. The model also explains why response times are generally faster under uncoupled than under coupled conditions: uncoupled masks have a response-activating part that is always at maximum contrast, whereas coupled masks vary between minimum and maximum values.

One strength of our method is that it does not rely on post hoc classification of trials into "aware" and "unaware" classes. Post hoc classification has become a popular approach to unconscious perception (e.g., Avneon & Lamy, 2018; Ro, 2008; Sergent, Baillet, & Dehaene, 2005; van den Bussche et al., 2013), but the correlational nature of this method generates a number of problems. As an example, van den Bussche et al. (2013) employed a priming version of the Stroop paradigm and used subjective prime visibility ratings to categorize individual trials as "conscious," "uncertain," or "unconscious." On each trial, participants first performed a speeded response to the target masked by forward and backward masks, and then rated their confidence in identifying the prime word. Because the two primes always appeared under physically identical conditions, awareness was not controlled experimentally, and all results were derived by sorting the participants' judgments into categories post hoc. After a somewhat worrisome scheme that excluded 19 of the 56 participants, priming effects were found in all three rating categories, but were most prominent for trials rated as "conscious." The authors conclude that the magnitudes of priming effects "are highly dependent on prime visibility" (Desender & van den Bussche, 2012, p. 1572; see also Avneon & Lamy, 2018; van den Bussche, Hughes, Humbeeck, & Reynvoet, 2010; van den Bussche et al., 2013). We believe that this method is unsatisfactory for a number of reasons. First, it replaces the experimental control of prime visibility with a correlational approach. Second, it suffers from regression to the mean: If correlations between visibility ratings and priming effects are not downright perfect, sampling error will cause priming effects to be too similar to each other, overestimating the amount of priming in the "unconscious" selection (Shanks, 2017). Third, all sources of variation that are common to both measures (early ones such as signal fluctuations in the early visual system, late ones such as attention or decision noise) would create a correlation between priming and visibility, so no conclusion can be made that awareness causes priming (let alone the stronger conclusion that awareness is *necessary* for priming). Our technique of induced dissociations with uncoupled masks/targets shows that prime visibility can be experimentally controlled without confounding it with prime or target strength. Moreover, the repeated demonstration of double dissociations between priming and masking immediately refutes the idea that awareness of the prime is necessary for response priming.[4]

The technique of induced dissociation comes at an interpretational cost. It requires conjoining two independent variables (here, mask contrast and SOA) in one *supervariable*. This means that the two independent variables are deliberately confounded and cannot be interpreted separately. For that reason, a decrease in visibility that is only brought about by a

[3] In the present experiments, the 40-ms SOA shows the strongest masking effects. This is in line with Breitmeyer and Öğmen's (2006) conclusion that the optimal SOA for metacontrast is between 10 and 40 ms (cf. Macknik & Livingstone, 1998; van Aalderen-Smeets, Oostenveld, & Schwarzbach, 2006).

[4] However, this might be difficult to demonstrate with pattern masks, which seem to interfere with prime processing (Wernicke & Mattler, 2019). Most successful demonstrations of double dissociations employ metacontrast masks.

manipulation of mask contrast but would not occur otherwise should *not* be called Type B masking. That term should be reserved for MCFs that are constant across SOA and can be freely interpreted without reference to an additional variable. But even so, a double dissociation is always informative, no matter whether it arises from a cunning manipulation of supervariables or more “naturally” from a single variable like contrast or SOA.

Induced double dissociations can be applied to objective as well as subjective measures, like discrimination tasks, same–different and oddity tasks, visibility and confidence ratings, ratings on the Perceptual Awareness Scale (Ramsøy & Overgaard, 2004), or ratings on customized scales. Even though all these methods are designed to measure some aspect of awareness of a critical stimulus, they all likely differ in criterion content (Kahneman, 1968) and will generally not lead to interchangeable results (Breitmeyer & Öğmen, 2006; Sackur, 2013; Sandberg, Timmermans, Overgaard, & Cleeremans, 2010), claims that one or the other were some kind of “gold standard” notwithstanding. Visual awareness is a multifaceted construct, and observers can be aware of some stimulus features without being aware of others (Albrecht & Mattler, 2016; Koster et al., 2016a, b). We therefore caution against the view that visual awareness is some sort of unitary experience that can be captured in a single measure of “consciousness” (Irvine, 2017).

Even though induced double dissociations are introduced here only in the context of masked response priming, it should be obvious that the technique is of general utility. The trick is always to treat one independent variable as a function of another independent variable, and then to pit several such functions against each other to provoke dissociations between dependent variables. For instance, in masked semantic priming, mask contrast could be made a function of prime characteristics known to influence the priming effect, such as word frequency or semantic relatedness. In techniques based on binocular rivalry, such as continuous flash suppression, many characteristics of the mask and the to-be-masked stimulus can be varied independently and parametrically (such as temporal frequency, spatial frequency, color or luminance contrast), including changes over the time-course of a trial. In experimental medicine, induced double dissociations may be employed to dissociate the effects of two drugs on two physiological functions by making one dosage an increasing or decreasing function of the other dosage. There is a world of possibilities for exotic experimental design.

Methodological considerations

1. Mask-contrast functions have to be assigned beforehand; they cannot be assembled post hoc. Otherwise, the procedure would capitalize on chance fluctuations, would be correlative instead of experimental, and likely not lead to replicable results.
2. Mask-contrast functions should be intermixed across trials so that the local context of visibility is the same for all functions. It also ensures that we can exploit the principle of connected endpoints: If we control visibility under maximum and minimum mask contrast at the endpoints of the SOA range only, then the rest of the masking functions have to run from endpoint to endpoint. Staircase algorithms can be employed to establish the endpoints (Lu & Dosher, 2014) but may not converge at the desired values for all participants.
3. For a double dissociation, it is sufficient to show that both measures vary in opposite directions. Therefore, the slope of the priming effects is allowed to vary under different MCFs as long as they all keep increasing with SOA.
4. We only presented mask-contrast functions that vary monotonically with SOA. Mask-contrast functions may also be nonmonotonic (U-shaped, inversely U-shaped, or periodic). They can be generalized to designs with more than two measures and more than two independent variables. They can be generalized to domains other than masked priming (there must be a few).
5. There are huge, qualitative differences between individual masking functions. It is advisable to measure both masking and priming with high precision in each individual participant. In contrast, measuring a large number of participants with low precision and then averaging the results can be highly misleading. Measuring masking functions with high precision requires a high number r of observations per subject and condition. For dependent variables scaled as proportions, which have a standard deviation of maximally .5, individual-subject standard errors will be roughly ≤ 7, 5, and 4 percentage points for r of 50, 100, and 150 repetitions, respectively.
6. Even though it sometimes appears possible to sort observers into homogenous groups (e.g., Seydell-Greenwald & T. Schmidt, 2012), such a post hoc classification is always subject to regression to the mean (Shanks, 2017; also see T. Schmidt, 2015) and may not lead to replicable results.
7. Prime visibility should never be reduced by simply degrading the prime because this would result in reduced priming as well (F. Schmidt et al., 2011; T. Schmidt & F. Schmidt, 2018). Forward masks interfere with response priming in both pattern and metacontrast masking (Becker & Mattler, 2019). Generally, pattern masks interfere with response priming more strongly than metacontrast masks (Wernicke & Mattler, 2019).
8. An equivalent to our method is to realize all $m \times m$ combinations of independent variables and then to use contrasts to compare the mask-contrast functions embedded in this matrix. These contrasts need to be specified a priori.

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Compliance with ethical standards

Open practices statement All data, materials and analyses are available from the authors upon request. All independent and dependent variables are identified. Preregistration was not employed.

Mathematical appendix: Simple and double dissociations

The following proofs are modified from T. Schmidt and Vorberg (2006), where additional details are provided. Original proofs are by Dirk Vorberg.

Definitions and assumptions Let a and b index the magnitudes of two types of sensory information, A and B, with $a, b \geq 0$. Let M be a measure that may respond to either type of information, $M \equiv M(a,b)$. M is *weakly monotonic* for Type A information if for all $a' \geq a$ and all b, $M(a',b) \geq M(a,b)$, and *strictly monotonic* for Type A information if for all $a' > a$ and all b, $M(a',b) > M(a,b)$. M is *exclusive* for Type A information if it is sensitive to this type of information only, $M(a,b) = M(a,0)$ for all a and b. M is *exhaustive* for Type A information if it is strictly monotonic in a. Exhaustiveness implies that a measure is able to respond to any change in the relevant information, no matter how small. We define *effects* on a measure by the difference from a no-information baseline, $M^* = M(a,b) - M(0,0)$.

Without loss of generality, let c and u index the magnitudes of one source of conscious information, C, and another source of unconscious information, U, with $c, u \geq 0$. Let D and I be the *direct* and *indirect measures*, where D is intended to measure conscious information. Because we do not assume either of these measures to be process-pure, we start from the assumption that either measure may be influenced by either type of information, $D \equiv D(c,u)$ and $I \equiv I(c,u)$. Note that these functions are specified on the level of expected values (i.e., the behavior of measures in the long run irrespective of trial-by-trial fluctuations). Unless stated otherwise, we assume either measure to be weakly monotonic in either argument.

Simple dissociation An observed dissociation $I^* > 0$ and $D^* = 0$ implies $u > 0$ if the direct measure is exhaustive for conscious information.

Proof: If D is exhaustive for c, $D^* = D(c,u) - D(0,u) = 0$ implies $c = 0$. Then,

$I^* > 0 \Leftrightarrow I(c,u) = I(0,u) > 0$ implies $u > 0$.

This derivation requires weak monotonicity of the indirect measure for unconscious information.

Double dissociation Let D^*_i and I^*_i denote the direct and the indirect effects observed under experimental conditions i, $i \in \{1, 2\}$. The joint observation of $D^*_1 < D^*_2$ and $I^*_1 > I^*_2$ implies $u > 0$ in at least one of the conditions.

Proof We prove that $u_1 \neq u_2$ by showing that the assumption $u_1 = u_2 = u$ leads to a contradiction. By the assumption, observing $D^*_1 < D^*_2$ implies $D(c_1,u) < D(c_2,u)$, which implies $c_1 < c_2$. At the same time, observing $I^*_1 > I^*_2$ implies $I(c_1,u) > I(c_2,u)$, which implies $c_1 > c_2$. The contradiction implies that u_1 and u_2 cannot be equal, $|u_1 - u_2| > 0$. Moreover, as $u_1, u_2 \geq 0$ by assumption, $u_1 \neq u_2$ implies $max(u_1,u_2) > 0$, which completes the proof.

Remarkably, the proof requires weak monotonicity of D and I in the c argument only, while the measures may depend on u in an arbitrary way. Therefore, we can allow C and U to interact in an arbitrary fashion, as in reciprocal inhibition (T. Schmidt & Vorberg, 2006). Note that the proof requires strict inequalities if the exhaustiveness assumption is to be avoided. Mere invariance in one of the measures is thus insufficient to produce a double dissociation.

Importantly, the mechanics of the proof are agnostic as to how the arguments of the functions are labeled. A double dissociation refutes *any* model stating that both direct and indirect measures are driven weakly monotonically by only a single source of information, whatever that may be.

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