# Action priming suppression by forward masks

Nicolas Becker
Georg-Elias-Müller Institute for Psychology, University of Göttingen, Germany

Uwe Mattler
Georg-Elias-Müller Institute for Psychology, University of Göttingen, Germany

**Visual stimuli may produce strong and reliable effects on subsequent actions irrespective of their visibility. This dissociation between action priming and conscious perception of the stimuli suggests two ways of processing of visual stimuli. One way of processing leads to the emergence of conscious visual perception, and another way leads to action priming effects. Here we examined the influence of forward masks that precede the prime on processing for action. In three experiments, we found that forward masks can suppress and even abolish priming effects. Suppression was larger with strong rather than weak forward masks and with short rather than long prime durations. Similar suppression effects occurred with surrounding paracontrast masks and with overlapping pattern masks. Our findings emphasize that processing for action depends crucially on preceding stimuli suggesting that action priming may depend on the initial part of the response to the prime. Results indicate that the use of forward masks to reduce prime visibility may also reduce action priming and potentially other priming effects.**

## Introduction

When a visual stimulus is rapidly followed by another instance of this stimulus, speed and accuracy of responses to the second stimulus can be increased, a phenomenon called priming (Tulving & Schacter, 1990). Priming effects have been observed in conditions where participants cannot report the critical features of the prime either due to neurological disorders (Milner & Goodale, 1995; Weiskrantz, 1997) or due to masking procedures that made the prime invisible (e.g., Francken, van Gaal, & de Lange, 2011; Kouider & Dehaene, 2007; Mattler & Palmer, 2012; Vorberg, Mattler, Heineke, Schmidt, & Schwarzbach, 2003). These findings concur with the distinction of an action system that is able to trigger reactions independently of a perceptual system that is related to conscious perception.[1]

### Independent action and perception systems

An important contribution to this view comes from masking studies which revealed that processing for action remains unaffected by backward masks that follow the prime despite the detrimental effects of these masks on processing for perception (e.g., Francken et al., 2011; Kouider & Dehaene, 2007; Mattler & Palmer, 2012; Vorberg et al., 2003). Behavioral findings in action priming paradigms suggest that processing for action begins with the onset of the prime because priming effects increase monotonically with increasing stimulus onset asynchrony (SOA) between prime and target, and priming effects are not determined by the duration of the prime (Vorberg et al., 2003). In addition, the trajectories of participants' hand movements are time locked to the onset of the prime (Schmidt, Niehaus, & Nagel, 2006; Vath & Schmidt, 2007). Whereas backward masks were apparently unable to interfere with early action processing, they had strong effects on prime perception in these studies, arguing for independent action and perception systems. These findings accord well with evidence from single cell recordings, which indicate that backward masking specifically reduces the late component of the neuronal response to the prime (Lamme, Zipser, & Spekreijse, 2002; Macknik & Livingstone, 1998). In addition, studies suggest that an initial feedforward sweep of the neuronal response to a stimulus rapidly passes through the processing hierarchy of the visual brain (Lamme & Roelfsema, 2000; Thorpe & Fabre-Thorpe, 2001). Therefore, it has been suggested that feedforward sweeps might constitute the basis of action priming effects (Lamme & Roelfsema, 2000; Schmidt et al., 2006; Vath & Schmidt, 2007). These results suggest that the action system may be related to an early part of the neuronal response to a stimulus, whereas the perception system may be related to processing in a relatively later time window.

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## Effects of forward masks on the action system

An important common feature of these studies is that they use backward masks to reduce the visibility of their stimuli. In the literature, however, additional forward masks are often used, which are presented prior to the masked stimulus (Kouider & Dehaene, 2007; Wernicke, 2014). Whereas the previous studies suggest that backward masks do not interfere with processing in the action system, the findings are less clear for forward masks. Here, we want to clarify the role of forward masks for processing in the action system.

Studies on forward masking focused primarily on processing for perception showing that forward masking reduces the visibility of the masked stimuli (Breitmeyer & Öğmen, 2006; Schiller, 1966; Turvey, 1973). The literature on forward masking effects on processing for action, however, is equivocal. On the one hand, two experiments reported a suppressive effect of forward masks on processing for action. When participants responded to the color of a ring that was preceded by a prime consisting of a colored disk, action priming was reduced by a forward mask consisting of a (paracontrast) ring that was neutrally colored with respect to the two possible prime and target colors (Breitmeyer, Öğmen, & Chen, 2004). Deplancke, Madelain, and Coello (2016) reported that the priming effect of a distractor stimulus in a pointing task was reduced when the distractor was preceded by a forward mask. On the other hand, forward masking did not affect action priming when participants responded to the form rather than the color of a stimulus in the study of Breitmeyer et al. (2004). Although the results for priming by form are not clear, the results of priming by color (Breitmeyer et al., 2004) and priming by a spatial distractor (Deplancke et al., 2016) provide evidence for interfering effects of forward masks on the action system. This differs from the results with backward masks, which did not show interfering effects on the action system.

In addition to these behavioral findings, neurophysiological studies provided evidence that forward masks may interfere with the initial part of neuronal responses to visual stimuli in macaque V1 and V4 which is not modulated by backward masks (Kondo & Komatsu, 2004; Macknik & Livingstone, 1998; for responses of LGN in cats, see Schiller, 1968). To the extent that the initial part of the neuronal response to the prime is important for action priming (Lamme & Roelfsema, 2000; Schmidt et al., 2006), we hypothesized that forward masks which precede the prime could interfere with processing for action (see also Breitmeyer et al., 2004).

To shed more light on processing for action and the role of the initial response triggered by primes, we analyzed the suppressive effects of forward masks in a robust action priming paradigm (Mattler & Palmer, 2012; Vorberg et al., 2003). In this paradigm, participants respond to left or right pointing arrow stimuli with a speeded choice response. The target arrows also serve as metacontrast masks for smaller arrow primes that precede the surrounding targets. To examine the effects of forward masking, we presented a masking stimulus that preceded the prime and measured its effects on action priming with respect to the mask's intensity, spatial layout, and the duration of the prime in three experiments.

## Hypotheses

The first hypothesis of this study was that forward masks reduce priming effects. Second, we expected that the suppression of priming effects is larger with strong as compared to weak forward masks. The third hypothesis is related to an accumulator model that has been proposed by Vorberg and colleagues (2003) to account for priming effects in the processing for action system. According to this model, primes provide evidence for a response, which accumulates in a buffer with a certain rate until the target stimulus follows. If the target is congruent with the prime, the evidence provided by the target adds to the accumulated evidence provided by the prime until the response criterion is reached. When the SOA between prime and target is prolonged, the prime has more time to provide evidence and the target therefore needs less time until the response criterion is reached. On incongruent trials, in contrast, the prime provides evidence for the alternative response. Therefore, the target has to contribute the entire evidence that is necessary to reach the response criterion. Furthermore, the target has to compensate for a disadvantage, which results from the evidence provided by the incongruent prime. This disadvantage arises because the model assumes that the response criterion consists in a certain difference of accumulated evidence between the two alternative accumulators. In consequence, the response criterion is reached later when the SOA between the prime and the target is prolonged. The priming effect corresponds to the difference in RTs on incongruent minus congruent trials. This priming effect increases monotonically with increasing SOA between prime and target. When the priming effect is plotted as a function of SOA, the priming function with a positive slope is obtained. According to this model, the slope of the priming function is determined by the rate with which the prime provides evidence for its response alternative relative to the rate with which the target provides evidence for its alternative (e.g., Mattler & Palmer, 2012; Vorberg et al., 2003). Primes that provide evidence with a low rate produce priming functions with a reduced slope. Therefore, if the suppressive effect of forward masks is realized by a reduction of the rate of evidence that the prime provides, we hypothesized that the slope of the priming function should be reduced. Empirically, this would be indicated by a significant interaction between Congruency × SOA × Forward Mask. Finally, we expected to replicate the finding that backward masks do not affect priming effects (Hypothesis 4).

# General methods

## Participants

In each experiment, we used a new sample of participants. In Experiments 1 and 2 the sample size was 14. We deemed this sample size sufficient based on previous studies, which found reliable effects with similar stimuli and similar paradigms in samples of 12 or 6 participants (Mattler & Palmer, 2012; Vorberg et al., 2003, respectively). In Experiment 3, the sample size was reduced to 10 due to the strong effects obtained in the previous two experiments. Participants were students from the University of Göttingen aged between 19 and 32 years old (Experiment 1: $M = 21.7$ years, $SD = 2.2$ years; Experiment 2: $M = 24$ years, $SD = 4.3$ years; Experiment 3: $M = 22.2$ years, $SD = 1.8$ years). All participants had normal or corrected-to-normal vision, reported no neurological disorders, and received course credit or monetary compensation (€7 per hour). Each participant accomplished a choice reaction time task (RT-task) on two 1-hr sessions in Experiments 1 and 3, or three sessions in Experiment 2. In the final session of each experiment, participants performed a prime discrimination task. Sessions were run on separate days.

## Tasks

We examined participants' performance in a choice RT-task and a separate prime discrimination task. (a) In the choice RT-task, participants were instructed to respond as fast and accurately as possible to the orientation of the target arrow (left vs. right) with their left and right index fingers by pressing the left and right Ctrl-button on a computer keyboard, respectively.

(b) In the prime discrimination session, participants were informed about the occurrence of the prime. Participants were asked to indicate the orientation of the prime arrow (left vs. right) using the same buttons that were used in the choice RT-task before. No time pressure was placed on participants in the prime discrimination task, and they received error feedback when they responded faster than 500 ms. These provisions were done to exclude any potential influence of primes on motor responses that might occur unconsciously and thereby lead to an overestimation of prime visibility. The delay of 500 ms has been chosen because previous research suggests that unconscious priming effects decay within 500 ms (Mattler, 2005).

## Apparatus

Stimuli were displayed on a Viewsonic 1900 Perfect Flat monitor with a vertical refresh rate of 75 Hz in Experiments 1 and 3. In Experiment 2, we increased the vertical refresh rate to 100 Hz to achieve different prime durations. Experiments were run on a Windows PC with the software "Presentation" (Version 19.0, www.neurobs.com). Participants placed their heads on a chin rest ensuring a viewing distance of 1 m.

## Stimuli

Stimuli are depicted in Figure 1 (Experiments 1 and 2) and Figure 4 (Experiment 3). Small black arrows pointing to the left or right served as primes (1.74° × 0.58° of visual angle), and larger arrows as target (5.79° × 1.94°). The prime could be preceded by a forward mask (3.90° × 1.94°). In the choice-RT task, participants received auditory feedback (450 Hz tone) if their response was wrong, or combined auditory and visual feedback ("too slow" in German), if their response exceeded 900 ms. In the prime discrimination task, participants received auditory error feedback when they were wrong or faster than 500 ms.

## Data analysis

Trimmed mean reaction times (RTs) per subject and condition were based on correct trials of the participant, excluding posterror trials. In addition, outliers were excluded in two steps: First, responses with RTs < 100 ms and RTs > 900 ms (response deadline) were omitted. Second, the fastest and the two slowest trials of each condition were considered outliers and discarded for each subject. In the prime discrimination task, no trials except the warm-up trials were excluded. A signal detection analysis was applied to prime discrimination performance to obtain $d'$ values as measures of sensitivity (Macmillan & Creelman, 1991; Vorberg et al., 2003). RTs, arc-sine transformed error rates, and $d'$ values were analyzed using within-subject ANOVAs. All reported $p$ values are based on Greenhouse-Geisser corrected degrees of freedom, whereas, for the sake of readability, the stated degrees

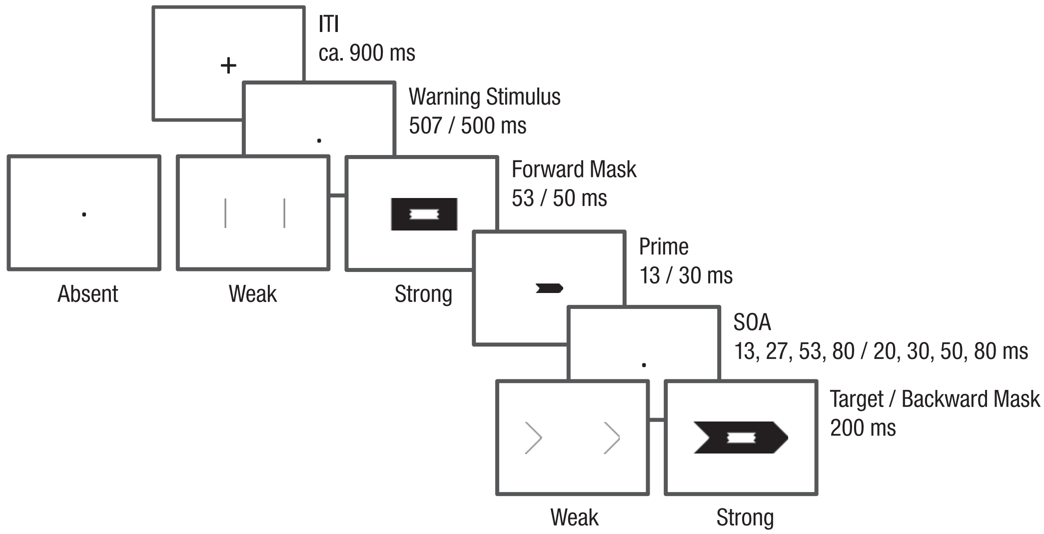


Figure 1. Sequence of events in Experiment 1/Experiment 2. Stimulus times were adapted to the monitor refresh rate of 75 and 100 Hz in the two experiments, respectively. The prime was presented for 13 ms in Experiment 1 and for 30 ms in Experiment 2.

of freedom are uncorrected. We report the Greenhouse-Geisser ε to quantify the degree of sphericity violation. To facilitate communication we focus this report on main effects and interactions with Congruency on RT and Choice Error Rates and supply complete ANOVA tables in the supplementary material. To estimate the slope of the priming functions, mixed linear regressions of priming effects on RTs with SOA as numerical predictor and random intercepts for participants were performed for each masking condition. We used MATLAB R2013b (MathWorks, Natick, MA) to calculate means for each experimental condition and each subject and RStudio (Version 1.0.143) for the inferential statistics.

# Experiment 1

In the initial experiment we examined priming effects of simple arrow stimuli when forward masks were either present or absent. In addition we varied the strength of the masks to examine the role of masking strength on priming effects.

## Method

### *Stimuli*

Prime duration was 13 ms (see Figure 1). When forward masks were present, they were of the same strength as the backward masks. Strong metacontrast masks were black arrows with a central opening in the shape of two superimposed prime arrows; weak backward masks were two parallel arrows with the same outer dimensions as the strong mask. Forward masks consisted of two straight lines (weak forward masks) or a filled rectangle with the same central opening as the target stimuli (strong forward masks). Both forward masks were neutral/noninformative regarding the shape of the prime or target.

### *Procedure*

Each trial started with a 507 ms warning dot in the center of the screen. When forward masks were presented, the warning dot was followed by a 53 ms forward mask. On trials without forward masks, the dot continued for another 53 ms. Following the prime after a variable SOA between 13–80 ms, the target appeared for 200 ms. After the response, a fixation cross was shown, which lasted between 800 and 1853 ms following a quasiexponential distribution (intertrial interval, ITI).

### *Design*

Each session included 13 blocks of 64 trials each, plus one demo-block of 8 trials. The demo-block and the first block of each session were considered warm-up and discarded from further analysis. In each experimental block, all possible conditions resulting from a factorial combination of two prime-target Congruency (congruent vs. incongruent), two Masking Strengths (weak vs. strong), two Forward Mask (absent vs. present), and four SOAs (13, 27, 53, and 80 ms) were repeated once for each target orientation. Within each block, all conditions were presented in randomized order. Excluding practice trials, participants thus completed 48 trials per experimental condition in both the choice-RT and the prime discrimination task.

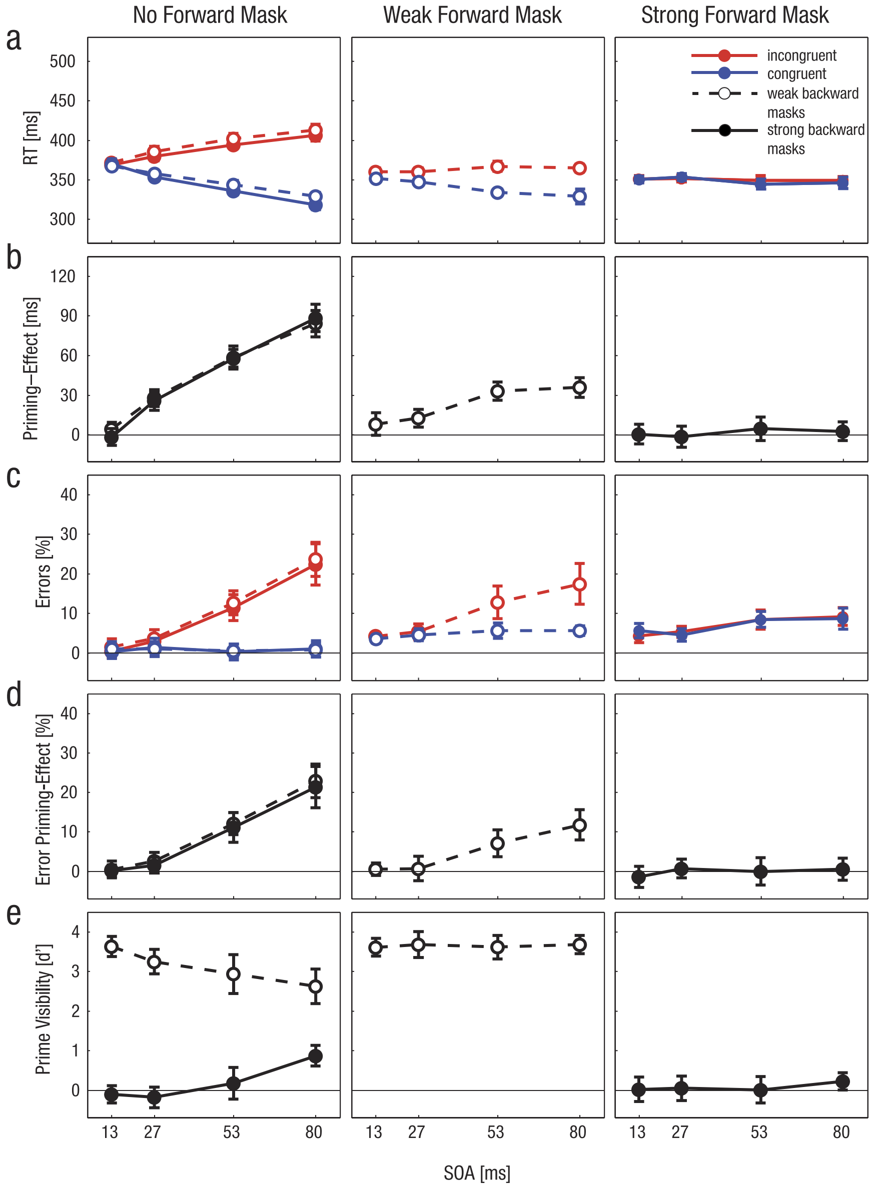


Figure 2. (a) Mean reaction time (RT) and (c) choice errors in Experiment 1, with (b) the resulting priming effects for reaction times and (d) errors and the corresponding (e) prime discrimination performance. Open symbols represent weak backward masks, whereas closed symbols represent strong backward masks (in Experiment 1, the strength of forward and backward masks was always the same). Red and blue lines represent congruent and incongruent conditions, respectively. Error bars represent within-subject confidence intervals (Morey, 2008).

## Results

Figure 2 shows the results of Experiment 1. The complete ANOVA results are reported in Supplementary Tables S1.1–S.1.5.

### *Reaction times*

Comprising errors, posterrors, and outliers as reported above, 18.6% of the total trials in the RT task were discarded. RTs were shorter on congruent (346 ms) than on incongruent trials (374 ms), as indicated by the significant main effect of Congruency, $F(1, 13) = 323.35$, $p < 0.001$, $\eta_p^2 = 0.96$. Supporting our first hypothesis, the presence of forward masks reduced priming effects as indicated by the significant interaction Congruency × Forward Mask, $F(1, 13) = 105.02$, $p < 0.001$, $\eta_p^2 = 0.89$. Without forward masks, priming effects were 43 ms, which were reduced to 12 ms by the presence of forward masks.

Supporting our second hypothesis, this suppressive effect of forward masks was larger when the masks were strong. This is indicated by the significant three-way interaction of Congruency × Forward Mask ×

Masking Strength, $F(1, 13) = 16.15$, $p = 0.001$, $\eta_p^2 = 0.55$. A separate ANOVA on trials with forward masks (see Supplementary Table S1.2) revealed that priming effects were moderated by Masking Strength as indicated by the significant interaction Congruency × Masking Strength, $F(1, 13) = 32.36$, $p < 0.001$, $\eta_p^2 = 0.71$. Priming effects amounted to 23 ms, $t(13) = 9.19$, $p < 0.0005$, Cohen's $d = 0.56$, with weak and 2 ms with strong forward masks, which did not reach significance in the posthoc *t* test, $t(13) = 0.88$, $p = 0.397$. In contrast, in a separate ANOVA on trials without forward masks, where only weak and strong backward masks where shown (see Supplementary Table S1.3), the interaction Congruency × Masking Strength was not significant, $F(1, 13) = 0.19$, $p = 0.667$ and priming effects amounted to 44 ms and 43 ms with weak and strong backward masks, respectively. This finding supports our fourth hypothesis that backward masking does not influence priming effects.

Visual inspection of Figure 2b shows that priming effects increased with SOA as indicated by the significant interaction Congruency × SOA, $F(3, 39) = 88.04$, $p < 0.001$, $\varepsilon = 0.74$, $\eta_p^2 = 0.87$. Figure 2b also shows that the slope of this time course of priming effects was reduced by the presence of forward masks as indicated by the significant interaction of Congruency × SOA × Forward Mask, $F(3, 39) = 70.14$, $p < 0.001$, $\varepsilon = 0.72$, $\eta_p^2 = 0.84$. This finding is supporting our third hypothesis. Moreover, the strength of the masks reduced the slope only when forward masks were present, as indicated by the significant interaction of Congruency × SOA × Forward Mask × Masking Strength, $F(3, 39) = 8.53$, $p = 0.001$, $\varepsilon = 0.72$, $\eta_p^2 = 0.40$. A separate ANOVA on trials with forward masks revealed that the slope of the priming effects were moderated by Masking Strength as indicated by the significant interaction Congruency × SOA × Masking Strength, $F(3, 39) = 7.13$, $p < 0.01$, $\varepsilon = 0.70$, $\eta_p^2 = 0.35$, with slopes of 0.45 and 0.06 for weak and strong masks, respectively.

In contrast, in a separate ANOVA on trials without forward masks—where only weak and strong backward masks were shown—the interaction Congruency × SOA × Masking Strength was not significant, $F(3, 39) = 1.22$, $p = 0.315$, indicating no difference between slopes of priming functions when backward masks were weak or strong (with slopes of 1.17 and 1.31 for weak and strong backward masks, respectively). In sum, the presence of forward masks reduced priming effects and the slopes of the priming functions, and this suppressive effect was larger when masks were strong rather than weak.

### Choice error rates

Errors were fewer on congruent (3.3%) than on incongruent trials (9.1%), as indicated by the significant main effect of Congruency, $F(1, 13) = 122.41$, $p < 0.001$, $\eta_p^2 = 0.90$. Supporting our first hypothesis, the presence of forward masks reduced priming effects on choice error rates as indicated by the significant interaction Congruency × Forward Mask, $F(1, 13) = 69.56$, $p < 0.001$, $\eta_p^2 = 0.84$. Without forward masks, priming effects were 9.1%, which were reduced to 2.5% by the presence of forward masks.

Supporting our second hypothesis, this suppressive effect of forward masks on priming effects was larger when the masks were strong. Although the three-way interaction Congruency × Forward Mask × Masking Strength, $F(1, 13) = 4.42$, $p = 0.055$, just failed to reach significance, we conducted to separate ANOVAS. A separate ANOVA on trials with forward masks revealed that priming effects were moderated by Masking Strength as indicated by the significant interaction Congruency × Masking Strength, $F(1, 13) = 10.46$, $p = 0.007$, $\eta_p^2 = 0.45$. Priming effects were 5.1%, $t(13) = 6.87$, $p < 0.0005$, Cohen's $d = 0.52$, with weak and 0% with strong forward masks, $t(13) = 0.07$, $p = 0.944$. In contrast, in a separate ANOVA on trials without forward masks—where only weak and strong backward masks were shown—the interaction Congruency × Masking Strength did not reach significance, $F(1, 13) = 1.55$, $p = 0.234$, and priming effects amounted to 9.5% and 8.6% with weak and strong backward masks, respectively, supporting our fourth hypothesis.

Visual inspection of Figure 2d shows that priming effects on choice error rates increased with increasing SOA as indicated by the significant interaction Congruency × SOA, $F(3, 39) = 59.32$, $p < 0.001$, $\varepsilon = 0.67$, $\eta_p^2 = 0.82$. Figure 2d also shows that the slope of this time course of priming effects was reduced by the presence of forward masks as indicated by the significant interaction of Congruency × SOA × Forward Mask, $F(3, 39) = 21.84$, $p < 0.001$, $\varepsilon = 0.89$, $\eta_p^2 = 0.63$, supporting our third hypothesis. Although Figure 2d suggests different slopes of the priming effects on choice error rates similar to those on RTs, the interaction of Congruency × SOA × Forward Mask × Masking Strength did not reach significance, $F(3, 39) = 2.00$, $p = 0.143$. In sum, the presence of forward masks reduced priming effects and this suppressive effect was larger when masks were strong rather than weak.

### Prime discrimination

For the analysis of the data from the visibility task, 0.2% of the trials were excluded because participants responded too soon. Prime visibility in terms of $d'$ (Figure 2e) decreased with stronger masks as indicated by the significant main effect of Masking Strength, $F(1, 13) = 241.01$, $p < 0.001$, $\eta_p^2 = 0.95$, with $d' = 3.38$ and $d' = 0.13$ for weak and strong masks, respectively. Prime visibility was further modulated by the presence of the forward mask, as indicated by the significant interaction Masking Strength × Forward Mask ($F(1, 13) = 18.38$ $p < 0.001$, $\eta_p^2 = 0.59$) and also by SOA as indicated by the significant interaction Masking Strength × SOA, $F(3, 39) = 19.00$, $p < 0.001$, $\eta_p^2 = 0.59$. However, as Figure 2e indicates, the presence of the forward mask modulated the interaction of Masking Strength and SOA, which was absent when the forward mask was present. This is indicated by the significant interaction Masking Strength × Forward Mask × SOA, $F(3, 39) = 19.73$, $p < 0.001$, $\eta_p^2 = 0.60$, and subsequent analyses, which revealed that the interaction Masking Strength × SOA was significant only *without*, $F(3, 39) = 25.71$, $p < 0.001$, $\eta_p^2 = 0.66$, but not *with* forward masks, $F(3, 39) = 0.57$, $p = 0.635$.

In sum, with and without forward masks, the strength of the backward masks determined prime visibility, and SOA modulated this effect only in conditions without forward masks. Findings resemble reports of larger metacontrast masking effects than forward/paracontrast masking effects (e.g., Kolers & Rosner, 1960) and accord with the view that forward masking can improve backward masking effects although the effect is rather small in the case at hand.

## Summary: Experiment 1

Experiment 1 provided evidence for our first hypothesis that forward masks, which precede the prime, reduce action priming effects. Our second hypothesis was also supported. With strong forward masks, the priming effect was abolished. However, even weak forward masks reduced priming effects substantially. This impact of weak forward masks on priming effects is remarkable because the masks consisted of a pair of vertical lines that were shown relatively far from the prime. Consistent with our third hypothesis, forward masks reduced the slope of the priming function. Supporting hypothesis 4, Experiment 1 replicated previous findings with this type of paradigm (e.g., Mattler & Palmer, 2012; Vorberg et al., 2003), indicating that action priming effects do not depend on prime visibility because in conditions with no forward mask, strong and weak backward masks modulated prime visibility without any influence on priming effects. Although forward masks suppressed priming effects, they did not have a comparable effect on prime visibility. Compared to trials without forward masks, weak forward masks improved prime visibility, but they suppressed priming effects. This finding suggests that forward masks influence processing for action in a direct way, which leads to suppressed priming effects rather independent of forward masking effects on prime visibility.

# Experiment 2

Experiment 1 demonstrated that strong forward masks can completely suppress action priming effects of a briefly presented prime with 13 ms duration. To examine whether this suppressive effect is limited to cases with short prime durations, we increased the prime duration to 30 ms in Experiment 2. In addition, we varied the strength of forward and backward masks orthogonally to separate the strength effects of the two types of masks.

## Method

### Stimuli and procedure

Due to the new monitor vertical refresh rate of 100 Hz, the temporal sequence of events differed from that of Experiment 1. Most important, the duration of the prime was increased to 30 ms. The forward mask was shown for 50 ms immediately before the prime (mask-prime-ISI 0 ms) and prime-target SOAs varied in four steps between 20 and 80 ms. The warning period lasted for 500 ms (see Figure 1).

### Design

Excluding warm-up blocks, each of the three RT sessions included eight blocks, and the prime discrimination session, 10 blocks of 96 trials each. In each experimental block, all possible conditions resulting from a factorial combination of two prime-target Congruency (congruent vs. incongruent), three Forward Masking Strength (none vs. weak vs. strong), two Backward Masking Strength (weak vs. strong) and four SOAs (20, 30, 50, and 80 ms) were repeated once for each target orientation. Excluding practice trials, participants thus completed 48 trials per experimental condition in the choice-RT task, and 40 trials per condition in the prime discrimination task.

## Results

The results of Experiment 2 are displayed in Figure 3. The complete ANOVA results are reported in Supplementary Table S2.1–S.2.5.

### Reaction times

Data treatment proceeded as in Experiment 1, excluding 21.6% of the total trials in the RT task. RTs were shorter on congruent (322 ms) than on incongruent trials (359 ms), as indicated by the significant main effect of Congruency, $F(1, 13) = 131.05$, $p < 0.001$, $\eta_p^2 = 0.91$. Supporting our first hypothesis,

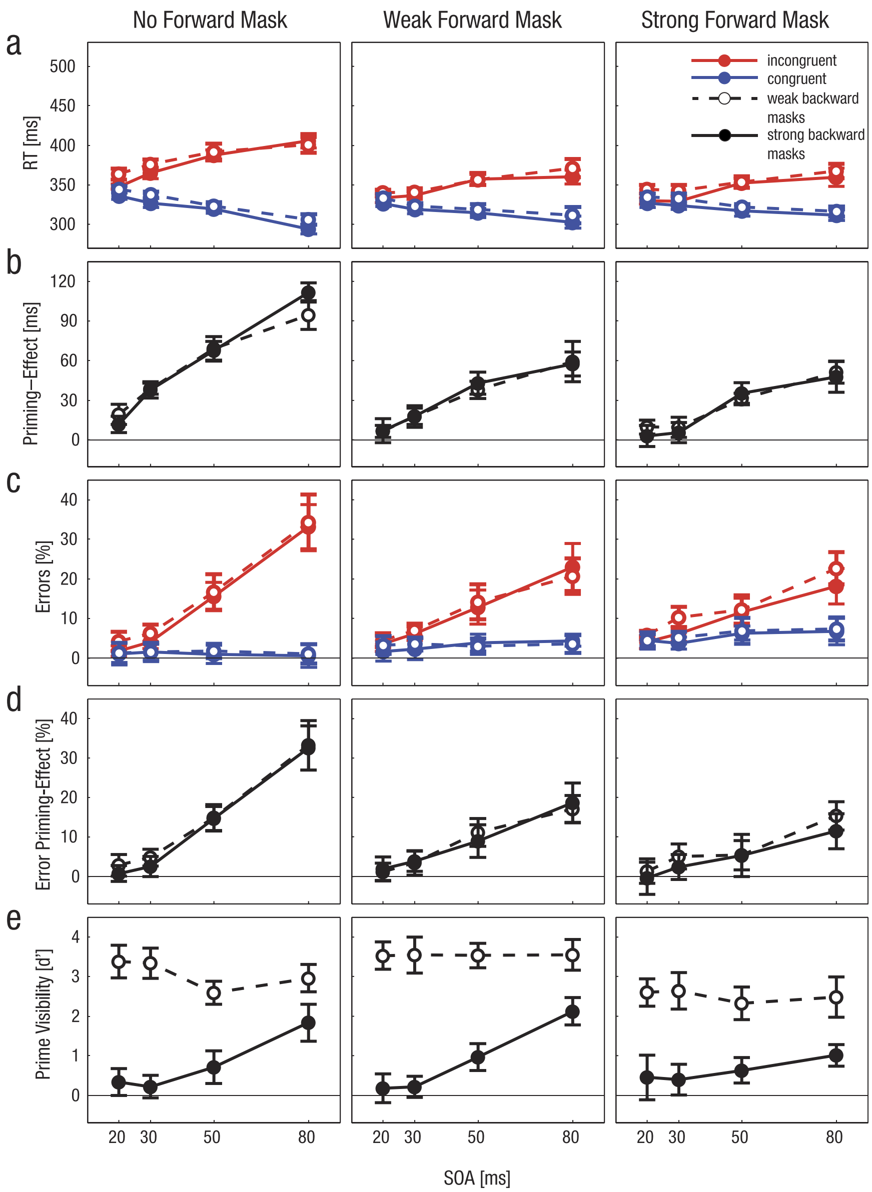


Figure 3. Priming effects and prime discrimination performance in Experiment 2. See legend of Figure 2.

forward masks suppressed priming effects as indicated by the significant interaction Congruency × Forward Masking Strength, $F(2, 26) = 106.31$, $p < 0.001$, $\varepsilon = 0.96$, $\eta_p^2 = 0.89$. Without forward masks, priming effects amounted to 56 ms, which were reduced to 31 ms by the presence of weak, and to 24 ms by strong forward masks. The latter difference was significant, as indicated by a subsequent ANOVA, which was performed with the factor Forward Masking Strength (2) consisting of the two levels weak vs. strong forward masks (without the "no forward mask" condition; see Supplementary Table S2.2): The interaction Congruency × Forward Masking Strength (2) was significant, $F(1, 13) = 10.09$, $p = 0.007$, $\eta_p^2 = 0.44$, supporting the second hypothesis.

Visual inspection of Figure 3b shows that priming effects increased with SOA as indicated by the significant interaction Congruency × SOA, $F(3, 39) = 132.12$, $p < 0.001$, $\varepsilon = 0.48$, $\eta_p^2 = 0.91$. In addition, Figure 3b also shows that the slope of the priming function was reduced by the presence and strength of forward masks as indicated by the significant interaction of Congruency × SOA × Forward Masking Strength, $F(6, 78) = 10.91$, $p < 0.001$, $\varepsilon = 0.57$, $\eta_p^2 = 0.46$, with slopes of 1.42, 0.86, and 0.77 for absent, weak, and strong forward masks, respectively. The subsequent ANOVA with the two levels factor Forward Masking Strength (2) revealed that the slope of the priming function did not differ between conditions with strong and weak forward masks, indicated by the nonsignificant interaction Congruency

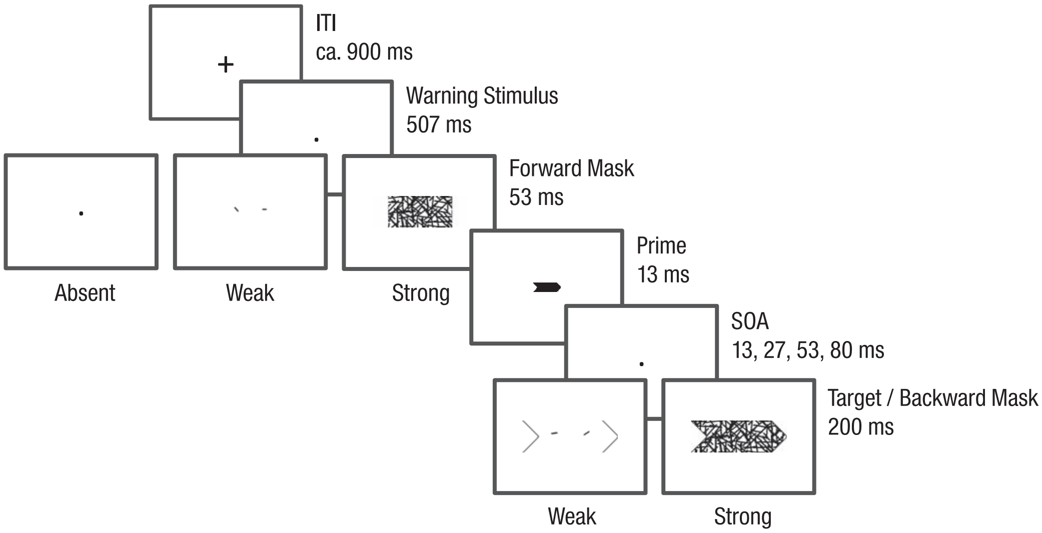


Figure 4. Sequence of events in Experiment 3. Stimulus times were identical to Experiment 1. Pattern masks were based on a set of each 100 weak and strong random line patterns.

× SOA × Forward Masking Strength (2), $F(3, 39) = 0.88$, $p = 0.435$, $\varepsilon = 0.72$. The latter finding provides a challenge for the third hypothesis.

Supporting Hypothesis 4, priming effects were not influenced by the strength of the backward masks because the interaction Congruency × Backward Masking Strength was not significant, $F(1, 13) = 0.00$, $p = 0.993$. No other interaction that included the factor Congruency was significant. The absence of any interaction between the strength of forward and backward masks suggests that the suppressive effect of forward masks was not modulated by an interaction between the two masks.

#### *Choice error rates*

Errors were fewer on congruent (3.3%) than on incongruent trials (12.4%), as indicated by the significant main effect of Congruency, $F(1, 13) = 92.24$, $p < 0.001$, $\eta_p^2 = 0.88$. Supporting Hypothesis 1, priming effects on choice error rates were suppressed by forward masks as indicated by the significant interaction Congruency × Forward Masking Strength, $F(2, 26) = 36.43$, $p < 0.001$, $\varepsilon = 0.83$, $\eta_p^2 = 0.74$. Without forward mask, priming effects amounted to 13.3%, which were reduced to 8.3% by weak, and to 5.7% by strong forward masks. The latter difference was significant, as indicated by the subsequent ANOVA with the factor Forward Masking Strength (2) consisting of the two levels weak vs. strong forward masks (without the "no forward mask" condition; see Supplementary Table S2.4) which revealed a significant interaction Congruency × Forward Masking Strength (2), $F(1, 13) = 16.83$, $p = 0.001$, $\eta_p^2 = 0.56$. This finding supports Hypothesis 2.

Figure 3d shows that priming effects on choice error rates increased with increasing SOA, as indicated by the significant interaction Congruency × SOA, $F(3, 39) = 74.93$, $p < 0.001$, $\varepsilon = 0.77$, $\eta_p^2 = 0.85$. In addition, Figure 3d also shows that the slope of the priming function was reduced by forward masks, as indicated by the significant three-way interaction Congruency × SOA × Forward Masking Strength, $F(6, 78) = 12.16$, $p < 0.001$, $\varepsilon = 0.54$, $\eta_p^2 = 0.48$. The subsequent ANOVA with the two levels factor Forward Masking Strength (2) revealed, however, that the slope of the priming function did not differ significantly between conditions with strong and weak forward masks, since the interaction Congruency × SOA × Forward Masking Strength (2) did not reach significance, $F(3, 39) = 2.51$, $p = 0.086$, $\varepsilon = 0.83$. Again, the latter finding challenges our third hypothesis.

Finally, supporting Hypothesis 4, priming effects were not influenced by the strength of the backward masks since the interaction Congruency × Backward Masking Strength was not significant, $F(1, 13) = 0.84$, $p = 0.377$.

#### *Prime discrimination*

Due to premature responses, 0.5% of the trials were excluded from analysis. Prime visibility in terms of $d'$ (Figure 3e) decreased with stronger backward masks as indicated by the significant main effect of Backward Masking Strength, $F(1, 13) = 118.97$, $p < 0.001$, $\eta_p^2 = 0.90$, with mean $d' = 3.04$ and 0.76 for weak and strong backward masks, respectively. Forward masks also affected prime visibility, as is indicated by a significant main effect of Forward Masking Strength, $F(2, 26) = 7.10$, $p = 0.015$, $\varepsilon = 0.59$, $\eta_p^2 = 0.35$, with $d'$ values of 1.92, 2.20, and 1.57 for absent, weak, and strong forward masks, respectively. It is important to note that prime visibility was not reduced by the presence of weak forward masks as compared to conditions without forward masks, but rather increased with weak forward masks. All other effects of this analysis were also significant (see Supplementary ANOVA Table S2.5), suggesting that prime visibility was influenced by the specific combination of SOA, strength of the backward mask, and the strength of the forward mask. Since these complex interactions are not in the focus of the present study, we do not delve into these complexities here.

## Summary: Experiment 2

Results replicate those of Experiment 1 showing that forward masks can suppress action priming effects in contrast to backward masks (Hypothesis 1), which showed no influence on action priming effects. Priming effects were sensitive even to weak forward masks although the prime duration was increased from 13 to 30 ms in Experiment 2. Strong forward masks suppressed priming effects to a greater degree than weak forward masks (Hypothesis 2) but they did not completely abolish priming effects as they did in Experiment 1 where the prime duration was 13 ms. This result indicates that the suppressive effect of forward masks depends on both, the strength of the mask and the duration of the prime. Interestingly, suppression of priming effects with strong forward masks was larger than with weak forward masks, but the slope of the priming function did not differ significantly between these two conditions, which challenges our third hypothesis. Despite their suppressive effect on action priming, however, weak forward masks did not reduce prime visibility when compared to trials without forward masks. Therefore, the suppressive effect of forward masks is not directly due to forward masking effects on prime visibility. In support of Hypothesis 4, backward masks did not modulate priming effects.

# Experiment 3

To examine whether our findings generalize to other masking paradigms, we replaced the para- and metacontrast masks with pattern masks in Experiment 3. Whereas para- and metacontrast masks do not spatially overlap with the prime, pattern masks do overlap with the primes. We reasoned that a replication of the suppressive effects of forward masks with pattern masks would provide evidence for the view that the suppression mechanism does not depend on the specific features of the masks. In addition, we wanted to relate our findings to common priming paradigms in the literature that typically use pattern masks as forward masks (for reviews, see Kouider & Dehaene, 2007; Wernicke, 2014). Finally, we wanted to substantiate the role of the prime duration and therefore reduced the prime duration to 13 ms as in Experiment 1.

## Method

### *Stimuli*

In Experiment 3, overlapping pattern masks replaced the metacontrast masks (see Figure 4). First, random line patterns were created that served as basis to create 100 different weak and strong pattern masks each. The strong pattern masks were made by placing 400 randomly oriented lines of varying length centered on the $20 \times 20$ intersections of a virtual grid with a small random spatial jitter. In a next step, these random line patterns were cropped to the shape of the forward mask or the shape of the arrow targets given by the stimuli of the previous experiments. The left and right contours of the target arrows were reinforced by a 3-pixel line so that all targets could be clearly recognized as an arrow despite any random fluctuations of the mask elements.

For the weak pattern masks, only two random lines were inserted into the masks that were placed approximately at the location of the left and right contours of the prime to ascertain contour overlap between prime and mask. In the case of weak target arrows, the two random lines were inserted into the double-arrows that served as weak masks in the previous experiments.

### *Procedure*

The stimulus times were identical to those of Experiment 1, and stimuli were presented with a 75 Hz monitor vertical refresh rate. As in Experiment 1, the prime duration was 13 ms (see Figure 4).

### *Design*

Excluding warm-up blocks, each RT session and the prime recognition session included 10 blocks of 96 trials each. In each experimental block, all possible conditions resulting from a factorial combination of two prime-target Congruency (congruent vs. incongruent), three Forward Masking Strength (weak vs. strong vs. none), two Backward Masking Strength (weak vs. strong), and four SOAs (13, 27, 53, and 80 ms) were repeated once for each target orientation. Excluding practice trials, participants thus completed 40 trials per experimental condition in the choice-RT and the prime recognition task.

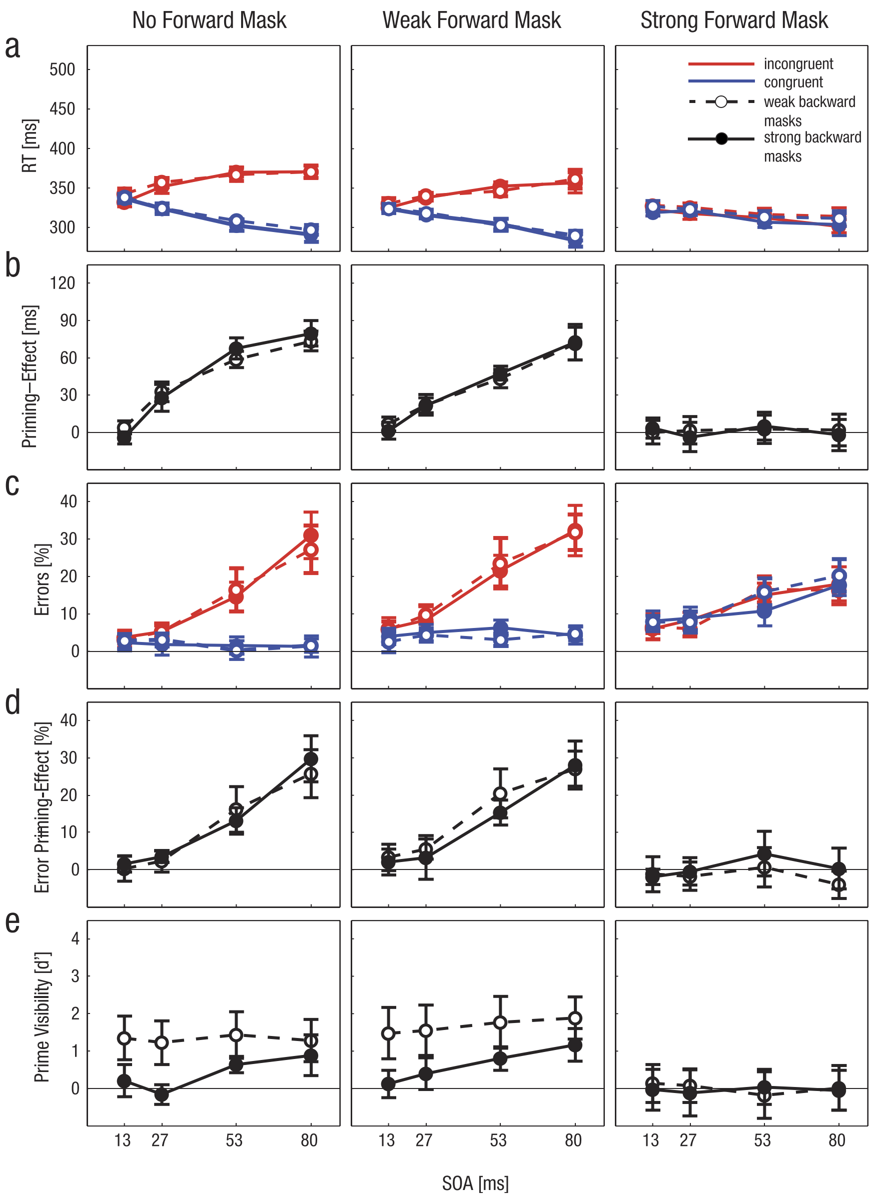


Figure 5. Priming effects and prime discrimination performance in Experiment 3 using pattern masks. See legend of Figure 2.

## Results

The results of Experiment 3 are shown in Figure 5. The complete ANOVA results are reported in Supplementary Tables S3.1–S.3.5.

### *Reaction Times*

Data treatment proceeded as in Experiment 1, excluding 26.9% of the total trials in the RT task. Reaction times were shorter on congruent (312 ms) than on incongruent trials (339 ms), as indicated by the significant main effect of Congruency, $F(1, 9) = 207.33$, $p < 0.001$, $\eta_p^2 = 0.96$. In support of Hypothesis 1, forward masks suppressed priming effects as indicated by the significant interaction Congruency × Forward Masking Strength, $F(2, 18) = 128.79$, $p < 0.001$, $\varepsilon = 0.77$, $\eta_p^2 = 0.93$. Without forward masks, priming effects amounted to 43 ms, which were reduced to 36 ms by the presence of weak, and to 1 ms by strong forward masks. To test whether priming effects were significantly reduced by weak as compared to absent forward masks, we performed a subsequent ANOVA with the factor Forward Masking Strength (2) consisting of the two levels absent vs. weak forward masks (without the "strong forward mask" condition; see Supplementary Table S3.2). The interaction Congruency × Forward Masking Strength (2) was significant, $F(1, 9) = 11.00$, $p = 0.009$, $\eta_p^2 = 0.55$, confirming that weak forward masks reduced priming effects, supporting hypothesis 2.

Visual inspection of Figure 5b shows that priming effects increased with SOA as indicated by the significant interaction Congruency × SOA, $F(3, 27) = 82.70$, $p < 0.001$, $\varepsilon = 0.48$, $\eta_p^2 = 0.90$. In addition, Figure 5b shows that the slope of the increasing priming effects was reduced by the strong forward masks as indicated by the significant interaction of Congruency × SOA × Forward Masking Strength, $F(6, 54) = 29.21$, $p < 0.001$, $\varepsilon = 0.68$, $\eta_p^2 = 0.76$, with slopes of 1.50, 1.32, and 0.00 for absent, weak, and strong forward masks, respectively. The subsequent ANOVA with the two levels factor Forward Masking Strength (2) yielded no evidence for different slopes of the priming functions in conditions without and weak forward masks, because the interaction Congruency × SOA × Forward Masking Strength (2) did not reach significance, $F(3, 27) = 3.04$, $p = 0.066$, $\varepsilon = 0.73$, $\eta_p^2 = 0.25$. Thus, the presence of weak forward masks significantly reduced priming effects compared to conditions without forward masks, but there was no evidence for a significant reduction of the slope of priming functions by weak forward masks, which challenges Hypothesis 3.

Supporting Hypothesis 4, there was no evidence for an influence of the strength of the backward masks on priming effects because neither the interaction Congruency × Backward Masking Strength, nor any other interaction between Congruency and Backward Masking Strength reached significance ($ps > 0.20$ in all cases). The absence of any interaction between the strength of forward and backward masks suggests that the suppressive effect of forward masks was not modulated by an interaction between the two masks.

### Choice error rates

Choice errors were fewer on congruent (6.1%) than on incongruent trials (14.1%), as indicated by the significant main effect of Congruency, $F(1, 9) = 103.79$, $p < 0.001$, $\eta_p^2 = 0.92$. Supporting Hypothesis 1, priming effects on choice error rates were suppressed by forward masks as indicated by the significant interaction Congruency × Forward Masking Strength, $F(2, 18) = 73.77$, $p < 0.001$, $\varepsilon = 0.94$, $\eta_p^2 = 0.89$. Priming effects amounted to 11.5% without forward masks, 13.1% with weak, and –0.5% with strong forward masks. To test whether priming effects differed between trials with weak as compared to absent forward masks, we performed a subsequent ANOVA with the factor Forward Masking Strength (2) consisting of the two levels absent vs. weak forward masks (without the "strong forward mask" condition; see Supplementary Table S3.4). The interaction Congruency × Forward Masking Strength (2) was not significant, $F(1, 9) = 0.63$, $p = 0.447$.

Figure 5d shows that priming effects on choice error rates increased with increasing SOA, as indicated by the significant interaction Congruency × SOA, $F(3, 27) = 55.03$, $p < 0.001$, $\varepsilon = 0.63$, $\eta_p^2 = 0.86$. In addition, Figure 3d also shows that the slope of the priming function was reduced by forward masks, as indicated by the significant three-way interaction Congruency × SOA × Forward Masking Strength, $F(6, 54) = 14.28$, $p < 0.001$, $\varepsilon = 0.54$, $\eta_p^2 = 0.61$. The subsequent ANOVA with the two levels factor Forward Masking Strength (2) revealed that the slope of the priming function did not differ significantly between conditions with no forward mask and weak forward masks, because the interaction Congruency × SOA × Forward Masking Strength (2) did not reach significance, $F(3, 27) = 1.21$, $p = 0.317$, $\varepsilon = 0.54$, challenging Hypothesis 3.

Finally, consistent with Hypothesis 4, priming effects were not influenced by the strength of the backward masks because the interaction Congruency × Backward Masking Strength was not significant, $F(1, 9) = 0.01$, $p = 0.943$.

### Prime discrimination

Due to premature responses, 7.2% of the trials were excluded from analysis. Prime visibility in terms of $d'$ (Figure 5e) decreased with stronger backward masks as indicated by the significant main effect of Backward Masking Strength, $F(1, 9) = 10.61$, $p = 0.010$, $\eta_p^2 = 0.54$, with mean $d' = 1.00$ and 0.32 for weak and strong backward masks, respectively. Forward masks also affected prime visibility, as is indicated by a significant main effect of Forward Masking Strength, $F(2, 18) = 7.37$, $p = 0.021$, $\eta_p^2 = 0.45$, with $d'$ values of 0.86, 1.15, and –0.02 for absent, weak, and strong forward masks, respectively. It is important to note that prime visibility was not reduced by the presence of weak forward masks as compared to conditions without forward masks, but rather visibility increased with weak forward masks. Figure 5e shows that the effect of the backward mask was eliminated when strong forward masks were used. This is indicated by the significant interaction Forward Masking Strength × Backward Masking Strength, $F(2, 18) = 6.09$, $p = 0.018$, $\varepsilon = 0.76$, $\eta_p^2 = 0.40$, which might be due to a floor effect in visibility with strong forward masks. Similarly, Figure 5e suggests that the increase of prime visibility with SOA is absent when strong forward masks are used. These effects are confirmed by the significant main effect of SOA, $F(3, 27) = 6.01$, $p = 0.021$, $\varepsilon = 0.53$, $\eta_p^2 = 0.40$, and the significant interaction Forward Masking Strength × SOA, $F(6, 54) = 3.61$, $p = 0.018$, $\varepsilon = 0.61$, $\eta_p^2 = 0.29$. In sum, findings suggest once more that prime visibility was influenced by the specific combination of SOA, strength of the backward mask, and the strength of the forward mask.

## Summary: Experiment 3

Experiment 3 shows that the suppressive effect of forward masks is not restricted to paracontrast masks but can also be found with pattern masks that overlap with the prime. Supporting Hypothesis 1 and 2, pattern forward masks suppressed priming effects and suppression increased with the strength of the forward masks. Weak forward masks significantly reduced priming effects, but strong pattern forward masks eliminated priming effects. The latter finding replicates the effect of strong forward masks in Experiment 1, suggesting that strong forward masks can abolish effects of primes that have a short stimulus duration. In contrast to Hypothesis 3, the suppressive effect of weak forward masks did not entail a significant reduction of the slope of the priming function when compared to trials without forward masks. Despite their suppressive effect on priming effects, weak forward masks did not reduce prime visibility. In contrast, the strength of the backward pattern masks affected prime visibility but had no systematic effect on priming effects, supporting Hypothesis 4. Overall, the impact of forward and backward masks on priming effects and prime visibility, respectively, were remarkably similar for both types of mask (pattern vs. paracontrast/metacontrast), despite considerable differences with regard to their spatial layout.

# Discussion

We examined processing for action and found that action priming effects can be substantially reduced and even eliminated by preceding stimuli. With a well-studied priming paradigm, our findings extend previous reports that indicated a detrimental effect of forward masks on priming by color (Breitmeyer et al., 2004) and priming by a spatial distractor (Deplancke et al., 2016). Beyond this, our study provides the first evidence for suppressive effects of forward masks on priming by form. This effect of forward masks is unlikely due to the effects of forward masks on prime visibility or any interaction between forward and backward masks, because weak forward masks significantly suppressed priming effects in each of the three experiments without a suppressive effect on prime visibility in any of the experiments. Our findings contribute new evidence for the distinction between processing for perception and processing for action (e.g., Milner & Goodale, 1995; Vorberg et al., 2003) because forward masks influenced action priming more and in a qualitatively different way than prime perception.

There are a number of novel contributions of our research to the understanding of processing for action. First, the suppressive effect of forward masks affected primes with short durations (Experiments 1 and 3) more severely than primes with longer durations (Experiment 2). This finding accords with the view that the action system is not only sensitive to the onset of the prime (e.g., Lamme & Roelfsema, 2000; Schmidt et al., 2006) but also to the prime's stimulus energy (Mattler & Palmer, 2012; Vorberg et al., 2003).

Second, strong forward masks reduced priming effects more strongly than weak forward masks. Surprisingly, however, even weak forward masks sufficed to reduce priming effects across experiments. The spatial layout of the masks, however, seems to be of less importance because there were only small differences between the suppressive effects of para- and metacontrast masks and pattern masks. Therefore, we speculate that the stimulus energy of the mask determines the strength of the suppressive effect of forward masks.

Third, challenging our third hypothesis, the view that the suppressive effect of forward masks is realized by an effect on the rate of evidence accumulation, which entails a reduction of the slope of the priming functions, was not consistently supported. Instead, the suppression of priming effects can occur without a significant effect on the slope of priming functions. This was the case in Experiment 2, where the suppression was larger with strong as compared to weak forward masks, but the slope of the priming functions was not different (see Figure 3b). Similarly, in Experiment 3, the suppression of priming effects by weak forward masks compared to priming without forward masks did not entail different slopes of the priming functions (see Figure 5b). These cases contrast with other cases where the slope of the priming functions was indeed reduced by the presence of forward masks—relative to the slopes with no forward masks in Experiment 1 and 2, and in Experiment 3 in the comparison between weak and strong forward masks. Whereas the latter cases accord with the view that the suppressive effect of the forward mask is realized as an effect on the rate of evidence accumulation (e.g., Vorberg et al., 2003), the initially mentioned cases cast doubt on the generality of this view. To reconcile the entire set of findings, one could assume that the power of the experiments was insufficient to reveal the significance of the slope reductions, which were found numerically in each of the nonsignificant cases. Alternatively, suppression of priming effects in the action system might result from a more complex mechanism. One possibility to refine the account that we presumed in the context of the accumulator model of Vorberg and colleagues (2003) consists in the assumption that forward masks may cause a delayed start of the evidence accumulation process leading to smaller priming effects with the same slope of the priming function.

Finally, the suppressive effect of forward masks cannot be reduced to the effects of forward masks on prime visibility. In all our experiments, weak forward masks did not reduce prime visibility, but they reduced priming effects significantly in each experiment. This pattern of results suggests that the suppressive effect of forward masks on processing for action can become effective independent of effects of forward masks on processing for perception. This interpretation accords with the distinction of Milner and Goodale (1995) between one system of processing for action and another system of processing for perception. In this perspective, as mentioned above, backward masks can modulate processing for perception while processing for action remains unaffected (e.g., Albrecht, Klapötke, & Mattler, 2010; Mattler & Palmer, 2012; Vorberg et al., 2003). Our findings replicate this dissociation between priming effects and prime visibility in conditions without forward masks. Beyond this, however, the present study shows that forward masks can hinder processing for action regardless of the well-known effects of forward masks on processing for perception. Therefore, the present findings support the view that priming effects and prime visibility are not directly related despite the fact that variables like SOA can affect both in parallel ways. The current study additionally points to potential pitfalls that arise when priming effects are simply compared between two conditions without and with (strong) forward masks because this comparison could easily lead to the misperception that priming effects depend on prime visibility/consciousness. Further research is needed to distinguish the effects of forward masks on the two processing systems.

The locus of the suppressive effect of forward masks is difficult to determine on the basis of the present study. Even though the suppressive effect of forward masks increased with strong forward masks, it was virtually independent of the spatial layout of the masks with respect to the prime because priming effects were diminished by both overlapping (Experiment 3) and nonoverlapping forward masks (Experiment 1 and 2). The influence of forward masks on processing for action has received less attention in the literature than the effects of forward masks on processing for perception. However, the literature on forward masking effects on processing for perception can inform future accounts of the suppressive effects of forward masks on processing for action. Effects of spatially nonoverlapping forward masks (paracontrast masks) on perception have been related to lateral inhibitory effects of the masks on the prime at cortical levels (e.g., Macknik & Livingstone, 1998). Inhibitory processes could embrace the fact that the degree of action suppression is higher when the inner contour of the masks was spatially close to the prime rather than spatially distant (Experiment 1 and 2). On the other hand, effects on prime perception caused by forward masks that overlap spatially with the prime have been related to processes of spatio-temporal integration of the two stimuli. Temporal integration is particularly effective in forward masking, especially when the prime is presented to the same eye(s) as the mask (Breitmeyer, 1984). Therefore, spatio-temporal integration might contribute to forward masking effects at precortical levels. Further research is needed to localize the source of the suppressive effects of forward masks.

Forward masks have often been employed in priming studies to reduce the visibility of the prime (e.g., Dehaene et al., 1998; Draine & Greenwald, 1998). Our findings from action priming call for caution when interpreting priming effects in conditions that include forward masks because forward masks might suppress priming independent of the effects of the forward mask on prime visibility. More specifically, the proposal that semantic priming effects increase with increasing prime visibility (Van den Bussche, Van den Noortgate, & Reynvoet, 2009; Wernicke, 2014) might be due to the suppressive effects of the forward masks used in these studies rather than due to a direct effect of conscious perception of the prime (see Wernicke & Mattler, 2019). Future studies should examine the mechanisms that cause the suppressive effect of forward masks to complete our understanding of visual processing for action that is independent of consciousness.

*Keywords: consciousness, priming, visual perception, subliminal perception, reaction time*

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Neither of the experiments reported in this article was formally preregistered. Requests for the stimuli or materials can be sent via email to the contact author at uwe.mattler@psych.uni-goettingen.de. The data have been made publically available and can be accessed via the following link: https://osf.io/qscvu/?view_only=19ddbd1af22b4293b4c06bb86596565d

Commercial relationships: none.
Corresponding author: Uwe Mattler.
Email: uwe.mattler@psych.uni-goettingen.de.
Address: University of Göttingen, Georg-Elias-Müller Institute for Psychology, Department of Experimental Psychology, Göttingen, Germany.

## Footnote

[1] When primes are associated with a specific motor response, one can find several terms for the effects of priming stimuli in the literature. These include *action priming*, *response priming*, *visuo-motor priming*, or *target priming*. To distinguish these particular effects of primes from other effects, the literature uses terms like *semantic*, *categorical*, *perceptual,* and *cue priming*. Because the present study is linked to the distinction proposed by Milner and Goodale (1995) and the study of Vorberg et al. (2003), we follow this literature and use the term *action priming* in the present paper. Beyond that, we use the terms *priming by color* or *priming by form* when the color or the form of a stimulus is the feature that is considered the source of priming effects.

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