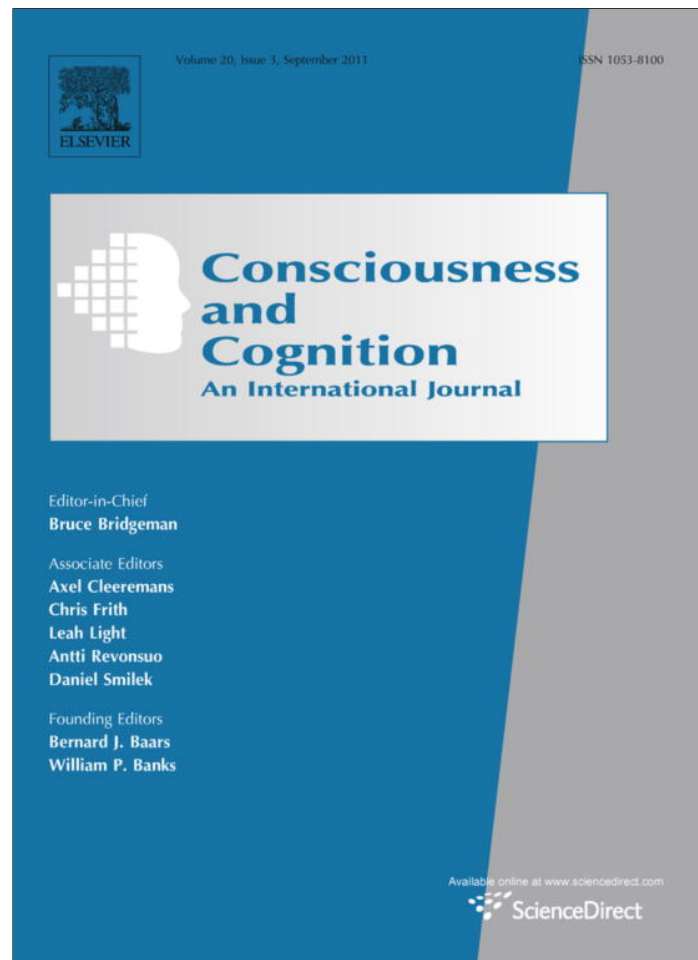


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## Unconscious activation of task sets

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### ABSTRACT

Using an explicit task cuing paradigm, we tested whether masked cues can trigger task-set activation, which would suggest that unconsciously presented stimuli can impact cognitive control processes. Based on a critical assessment of previous findings on the priming of task-set activation, we present two experiments with a new method to approach this subject. Instead of using a prime, we varied the visibility of the cue. These cues either directly signaled particular tasks in Experiment 1, or certain task transitions (i.e., task repetitions or switches) in Experiment 2. While both masked task and transition cues affected task choice, only task cues affected the speed of task performance. This observation suggests that task-specific stimulus–response rules can be activated only by masked cues that are uniquely associated with a particular task. Taken together, these results demonstrate that unconsciously presented stimuli have the power to activate corresponding task sets.

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### 1. Introduction

Even stimuli that we are not aware of can affect our behavior. This is the main message from many studies using the masked priming paradigm (Dehaene et al., 1998; Klotz & Neumann, 1999; Kunde, Kiesel, & Hoffmann, 2003, 2005; Kunde, 2004; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003; for reviews, see Kiesel, Kunde, & Hoffmann, 2007; Kouider & Dehaene, 2007). In a typical masked priming paradigm, a visual target stimulus requires a speeded forced-choice response. The target is preceded by a visual prime stimulus that appears only briefly (usually about 20–30 ms) and it is pre- and/or post-masked by other, commonly irrelevant stimuli, or by the target itself, as with metacontrast masking (see Breitmeyer, 1984), which renders the prime essentially invisible. As the unconscious nature of the prime is crucial for interpreting results from masked priming studies, researchers commonly test whether the prime can be consciously reported, often by using a separate signal detection task.

The typical findings in masked priming studies are congruency effects: responding is faster and more accurate if prime and target are assigned to the same response (i.e., are congruent) than if they call for different responses (i.e., are incongruent). For instance, in the study of Dehaene et al. (1998), participants categorized numerals between 1 and 9 as smaller or larger than 5 by pressing one of two keys accordingly. The target number was preceded by a briefly presented and sandwich-like masked prime number. Performance was better if the prime number and the target number fell into the same response category (i.e., if they were both smaller or both larger than 5) than if they did not. This (often replicated) priming effect suggests that response selection can be affected by unconscious stimulus information, presumably by priming associated responses.

Recent studies have asked whether the impact of unconscious stimuli is restricted to activating response tendencies or whether they can also affect cognitive control processes. Cognitive control processes are traditionally conceptualized as

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strongly related to, and depending on consciousness, in the sense that these processes require and rely on conscious decision-making and awareness (Dehaene & Naccache, 2001; Jack & Shallice, 2001; for an overview, see Hommel, 2007). These “conscious” processes of cognitive control are oftentimes contrasted against “non-conscious” automatic actions. For example, Jack and Shallice emphasize that the underlying processes engaged by conscious action are different from those engaged by automatic action. Similarly, Dehaene and Naccache (2001) claim that, while processing is possible without consciousness, consciousness is required for specific cognitive control processes.

According to this view, masked stimuli that do not reach consciousness should not be able to influence cognitive control processes. In recent years, however, this view was challenged by a number of studies (e.g., Hughes, Velmans, & De Fockert, 2009; Lau & Passingham, 2007; Mattler, 2003, 2005, 2006, 2007; van Gaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008; van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009). These studies provided evidence that masked stimuli can trigger or at least affect cognitive control processes, such as the inhibition of unwanted responses (Hughes et al., 2009; van Gaal et al., 2008, 2009), shifting attention (Mattler, 2003, Exp. 3; Scharlau & Ansorge, 2003), and activating task sets (Lau & Passingham, 2007; Mattler, 2003, Exp. 5; 2006, Exp. 3, 2007, Exp. 3). Especially this last observation is surprising from a conscious-control point of view, as the implementation of task sets has been considered to represent one of the most central jobs of cognitive control (e.g., Meyer & Kieras, 1999; Monsell, 1996).

The activation of task sets is commonly investigated by means of the task switching paradigm. In a task switching experiment, participants perform one of two (or more) tasks in each trial (e.g., to categorize a target number as odd or even) but occasionally are to switch to the other task (e.g., to decide whether the target number is smaller or larger than 5; see Kiesel, Kunde, & Hoffmann, 2006; Sudevan & Taylor, 1987). With the explicit task cuing procedure (Meiran, 1996) that was used in the present experiments, a task cue is presented at the beginning of each trial, informing the participant which task to perform in that trial. The common observation is that response times (RTs) are elevated after a task switch, suggesting that some kind of cognitive control processes, like for example reconfiguration of the cognitive system for processing another task, has to take place (e.g., Rogers & Monsell, 1995). Given that the same stimuli require different responses in the two tasks, participants need to figuratively “rewire” the relevant stimulus–response mappings. It is assumed that when performing different tasks, participants adopt so-called task sets, which, as a basic definition, are a representation of the task and its S–R-mappings. When one of the possible tasks is about to be carried out, the associated task set is activated to enable the participant to perform the task. There is no generally agreed upon definition for the term task set (see, for example, Kiesel et al., 2010; Rogers & Monsell, 1995). Within the given context, an operational definition is sufficient. Whenever participants perform a task, we assume that prior to task execution the corresponding task set was activated. There are theories that assume that a task set is not activated as a whole, but that the activation is composed of several single steps in which different aspects of the task set become activated (e.g., Koch & Allport, 2006; Mayr & Kliegl, 2000; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001). These models of task-set activation will be discussed in more detail later on when we discuss the results of our experiments.

Recently, Mattler (2003, 2005, 2006, 2007) reported evidence that task sets might be activated by unconscious stimulus information, suggesting that the activation of task sets might not rely on conscious decisions. However, as we will argue, this evidence is not as straightforward as it has been taken to be, so that a reevaluation is in order. In the following section, we justify this claim based on the examination of the central findings from two of Mattler's (2003, 2006) studies. As we will show, Mattler's method is likely to have invited artifacts that render strong conclusions from his observations premature. We then present results from two experiments that introduced a new methodological strategy that helps circumventing these problems.

## 2. Priming of task sets or perceptual priming?

To investigate whether masked primes can activate task sets, Mattler (2003, Exp. 5) presented masked task-set primes in a task cuing experiment with random task sequences (Meiran, 1996; Rogers & Monsell, 1995). The target stimuli were high- or low-pitched tones played by either a piano or a marimba. The two tasks required responding to either the pitch of the tone (high vs. low) or to its timbre (piano vs. marimba). Tasks were cued by presenting four stimuli at the corners of an imaginary square: three irrelevant squares and one diamond. The diamond could appear at any of the four possible positions and its horizontal location signaled the task. The task cues were fully visible but they were preceded by a briefly presented prime display. The prime display also consisted of three squares and one diamond, and the diamond could appear in either the same horizontal location as the following task cue (the congruent condition) or in another location (the incongruent condition). The four stimuli making up the prime display were slightly smaller than the four stimuli of the cue display and fit into their shape, so to allow for metacontrast masking (Breitmeyer, 1984) of the primes by the cues. Mattler (2003) observed better performance in congruent than in incongruent trials, a finding that he took as a clear hint to subliminal priming of task sets. If a congruent prime activates the proper task set, so the idea, the participant has more time to implement the task before the onset of the target, leading to faster responses.

Even though this is a possible conclusion, there is another, presumably more plausible explanation for the observed priming effect. As described, the primes were perceptual identical to the cues, and on congruent trials the diamond appeared in both prime and cue display at the exact same location. Therefore, it is conceivable that responding in congruent trials was faster because of unconscious perceptual priming but not due to the unconscious activation of task sets. Indeed, presenting

an invisible prime at the same location as a target stimulus has been demonstrated to accelerate target detection (Scharlau & Ansoorge, 2003; Scharlau & Neumann, 2003), presumably because the prime already triggers the necessary shift of attention towards the target location. Likewise, unconscious primes facilitate the processing of perceptually identical targets beyond mere priming through response congruency (Bodner & Dypvik, 2005; Bodner & Masson, 2003). Given that in Mattler's (2003) study primes and targets were not only perceptually identical but also appeared at the same location, the observed priming effect may be mainly or even completely due to perceptual priming. Unfortunately, basically the same argument can be made for the related studies of Mattler (2005, 2007) and Lau and Passingham (2007), in which prime and task cue were perceptually similar in congruent trials.

Additionally to behavioral data, Lau and Passingham (2007) presented fMRI data. They used two tasks, a phonological task (judging whether the target word was bisyllabic) and semantic task (judging whether the target word referred to a concrete object), that involve spatially different brain areas. When a masked incongruent prime (i.e., a prime that indicates the other task than the target) was presented, activity in the area associated with the instructed task decreased, and activity in the brain area associated with the primed task increased compared to conditions with masked congruent primes. This indicates that the masked prime activated the respective task and the task set associated with it. In contrast to the behavioral data, these results cannot be explained by perceptual processes and thus, as the authors note themselves, “challenge critics to reconsider the limits of unconscious processing” (p. 5809).

To circumvent the problem of identical primes and task cues, Mattler (2006) used two task cues for each task in a similar task switching experiment. Primes and task cues were arrows pointing left, right, up, and down. Right- and left-pointing arrows indicated the timbre task, and up- and down-pointing arrows indicated the pitch task. This resulted in three types of possible relations between prime and task cue: identical pairs, i.e., prime and task cue were the same; congruent pairs, i.e., prime and task cue were associated with the same task, but were not identical; and incongruent pairs where prime and task cue referred to different tasks. In this setting, perceptual priming by sensory similarity can be ruled out when comparing merely congruent with incongruent pairs of prime and task cue. Additionally, as only a single stimulus was presented both in the prime and the cue display, stimuli always appeared at the same location—thus ruling out an attentional advantage. In this setting, Mattler (2006) again observed an impact by the masked primes. If the prime was associated with the same task as the cue, responses were faster and more accurate than if the prime was associated with the other task. The strongest priming effect was found when prime and cue were identical, which underlines that perceptual processes played a role in this and previous findings. But the more intriguing finding is that responding was still faster for congruent compared to incongruent prime cue pairs. Mattler took this as evidence that at least parts of the overall congruency effect indicates task-set activation and is not located at perceptual or motor stages.

However, there still remains an alternative explanation for these findings that does not require any task-set activation by masked primes. According to Logan and Schneider (2006; see also Schneider & Logan, 2005), cues that are assigned to the same task become part of the same ad hoc category, so that they can prime each other. Logan and Schneider reported evidence for this assumption in an experiment that used pairs of task cues like *day–night* for one task and *noun–verb* for another task. They found a repetition priming effect when the cue in the current trial was identical to the cue in the preceding trial (e.g., *day* and *day*), and also a task repetition effect when the task repeated, but the cue differed (e.g., *day* and *night*), which suggests “a priming effect for related cues and facilitation in mediator retrieval” (Logan & Schneider, 2006, p. 1255). Applying this logic to Mattler's (2006) study suggests that participants created one category of horizontally oriented arrows and another for vertically oriented arrows. If so, processing, say, a left-pointing cue would prime the other member of the corresponding category: the right-pointing cue. Thus, the presentation of a masked prime may lead to facilitated cue encoding of both related cues—but not to task-set priming.

The priming effect of related cues was originally meant to spread from one trial to the following trial. This means that when two cues associated with the same task are presented in consecutive trials, the first cue primes the second through residual activation in short term memory. However, the same mechanism may operate if two cues are presented consecutively in a single trial, like in the design Mattler (2006) used. The prime would thus not only prime the representation of the identical task cue but also the representation of the other task cue that is associated with the same task. Consequently, the approach to map two task cues to one task does not avoid priming of the task cue. If either of the two cues is presented to the participant after one of them was used as a prime, its encoding is facilitated due to the associative activation that took place before. Thus, the impact of the prime would again be located at an early, perceptual and categorical level but not provide conclusive evidence for unconscious task-set priming.

One aim of these experiments was to corroborate and extend these recent findings, especially the fMRI data found by Lau and Passingham (2007), by conclusive behavioral data. To see whether such conclusive evidence can be provided, we devised two experiments that took the possible methodological objections into account. We did so by dropping the prime altogether and by manipulating the visibility of the task cue itself so that participants were aware of the cue in some but not in other trials. This method did not only prevent possible artifacts arising from prime–cue interactions, but it also allowed for a theoretically more interesting dependent measure: Rather than only looking whether unconscious information would speed up or slow down responding in a task switching context, as in the previous studies, we tested whether such information would be sufficient to trigger task-set activation all by itself. Hence, our dependent measure was not only the speed of task processing but also the choice of task. Considering these two dependent variables allows us to observe differential aspects of unconscious task-set activation, which further contributes to specific theories of task-set activation.

### 3. Experiment 1

In the first experiment, we presented masked and non-masked task cues on a trial-to-trial basis. Target stimuli were the numbers 1–9, excluding the 5, and participants made manual binary-choice responses to indicate either the magnitude (smaller vs. larger than 5) or the parity of the target number (odd vs. even). The two tasks were signaled by the letters *w* and *b*, which in the test language (German) bear no relation to the names of the tasks. In some trials, these task cues were non-masked and appeared for 150 ms, and thus clearly visible. In these trials, participants should have no difficulty to consciously identify the cues and prepare the corresponding task. In other trials, however, cues were presented only briefly (30 ms) and sandwiched by masks. In these trials, participants should be unable to become aware of the cues (an assumption that we tested in a separate recognition test), in which case they were instructed to choose freely which task to carry out on the target stimuli, with the restriction that each task should be chosen approximately equally often. In this respect, these trials resemble voluntary task switching (e.g., Arrington & Logan, 2004b, 2005; Forstmann, Brass, Koch, & Von Cramon, 2006; Mayr & Bell, 2006).

In voluntary task switching, the task to perform is internally generated by the participant, as no cue or fixed task sequence predetermines the task in any trial. Despite this voluntary decision for a task repetition or switch, robust switch costs emerge in this paradigm. Also, other basic phenomena in task switching can be observed and seem to be independent of the experimental design (Yeung, 2010). Some studies, in contrast, suggest that cued task sets may be activated in a different way than internally selected ones (Forstmann et al., 2006; Gollan & Ferreira, 2009). By additionally presenting a masked task cue during the voluntary task selection, we explore whether task choice processes are susceptible to unconscious influences. Without conscious knowledge of the masked task cue, the subsequent choice of a task is internally determined, at least at the level of phenomenal experience. So our study does contribute to the debate about differences between externally and internally generated task sets. Finally, in contrast to earlier studies using a masked prime and a visible task cue, we were able to explore if cognitive control processes can be triggered by unconscious stimuli alone without additional visible stimuli.

When participants are allowed to “freely” choose the task they want after a masked cue, there is obviously no experimental control any more on whether the next trial would be a task switch or task repetition. To gain such control we devised a two-trial design structure, and focused on performance on the second trial of such trial pairs. Each pair of trials consisted of a first trial in which the cue was always clearly visible, and a second trial in which the visibility of the cue was varied (half of the cues were non-masked, the other half masked). After the second trial, the participants were asked to indicate which task they had actually performed in this second trial. This two-trial procedure allows us to clearly determine if the second trial is a repetition or a switch trial because task identity in the first trial is always instructed by clearly visible cues.

Our main question was whether masked—and presumably invisible—cues would be able to directly prime task-set activation. If so, participants should exhibit a significant tendency to carry out the task indicated by the cues.

#### 3.1. Method

##### 3.1.1. Participants

Twenty-four students (eight males) of the University of Würzburg with an average age of 22 years participated in the experiment in fulfillment of course requirements or payment (6 Euro). All reported having normal or corrected-to-normal vision, and were not familiar with the purpose of the experiment.

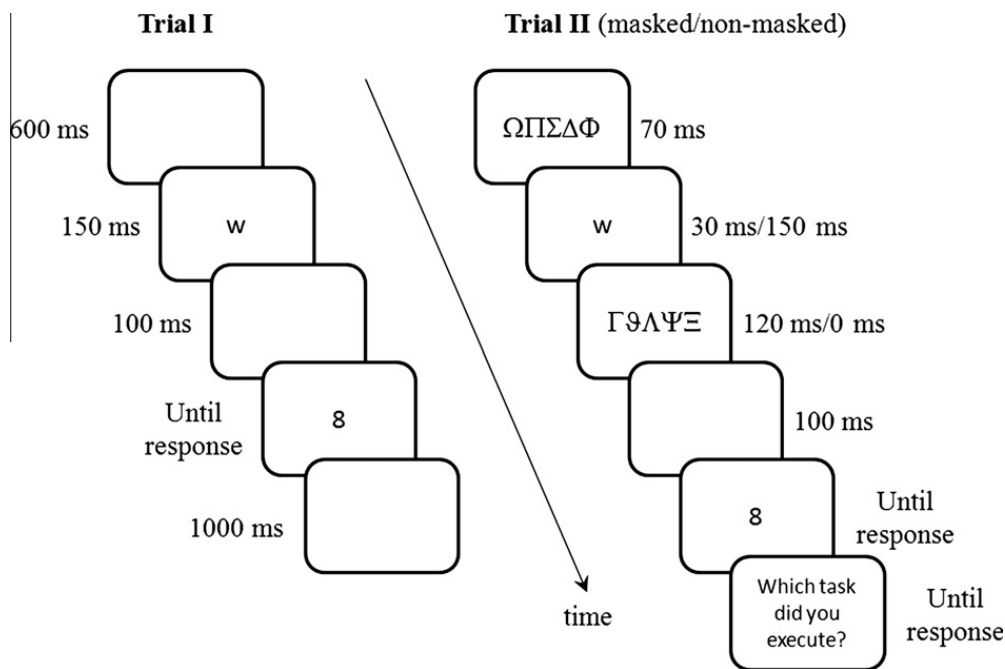
##### 3.1.2. Apparatus and stimuli

The experiment took place in a dimly lit room. An IBM compatible computer with a 17 in. VGA-Display and the software package E-Prime™ were used for stimulus presentation and response sampling. Stimulus presentation was synchronized with the vertical retraces of a 100-Hz monitor. Responses were executed with the index fingers of both hands and collected with external response keys. All stimuli were presented in white on a black background. Cues were either the letter *w* or *b*, and targets were the numbers 1–9, excluding the 5. In trials with masked primes, the pre- and postmask consisted of a random string of 5 Greek letters chosen from: Ω, Π, Σ, Δ, Φ, Γ, ϑ, Λ, Ψ, or Ξ).

##### 3.1.3. Procedure and design

Throughout the whole experiment, trials were presented in pairs (see Fig. 1). In the first trial of each pair (Trial I), a non-masked, clearly visible task cue was presented for 150 ms. After a blank screen of 100 ms, the target appeared and lasted until a response was given. Next to an inter-trial-interval of 1000 ms, the second trial of the pair (Trial II) started with a 70 ms premask. Then the task cue was presented, either for 150 ms without a postmask (non-masked) or for 30 ms and followed by a 120 ms postmask (masked). After a blank screen of 100 ms, the target appeared until a response was given.

Participants were instructed to respond as fast and as accurate as possible. The mapping for both tasks (smaller/larger – left/right response; odd/even – left/right response) and the task cue letter to task assignment (*w/b* – magnitude/parity task) was counterbalanced across participants. At the end of Trial II participants were presented with the question “Welche Aufgabe hast Du als 2. Aufgabe ausgeführt?” (German for “Which task did you execute as the second task?”) and had to indicate their task choice by pressing the 1- or 3-key on the number keyboard. This response was not speeded. After an inter-trial-interval of 600 ms, the experiment continued with the next trial pair. The data analysis was restricted to the data from Trial-II trials.



**Fig. 1.** Sequence of events in the trial pairs. In the first trial of each trial pair (Trial I), the cue is always non-masked. In the second trial of each trial pair (Trial II), the cue is presented either non-masked with a duration of 150 ms or masked with a duration of 30 ms.

Each possible combination of task cue and target (2 letters  $\times$  8 numbers) was used for both types of trials, which leads to  $16 \times 16$  possible combinations of trial pairs. Considering the factor cue visibility in Trial II, this amounts to 512 trial pairs overall, of which 50% are task switches and 50% are task repetitions, both in the visible and in the masked condition. After a practice block of 32 trials which featured only supraliminal cues, these 512 trial pairs were presented in pseudo-random order in blocks of 64 trial pairs with self-paced breaks between blocks. An experimental session lasted approximately 60 min.

### 3.1.4. Assessment of cue visibility

A visibility test with 96 trials was presented directly after the main experiment. Participants were fully informed about the structure of a trial and the presence of masked task cues. They had to perform a forced-choice discrimination task. For this task, we applied only masked cue trials for which the sequence of stimuli was exactly the same as in the main experiment. Participants were asked to identify the cue and had to press the according key (*w* or *b*) on the keyboard. Participants were instructed to take their time and to try to be as accurate as possible. In order to avoid that unconscious priming effects influence the free response choice (Bodner & Mulji, 2010; Kiesel, Wagener, et al., 2006; Schlaghecken & Eimer, 2004), there was an interval of 800 ms after target offset in which no response was possible (see Vorberg et al., 2003).

While detection performances may vary throughout an experiment, we chose not to test cue visibility after each trial, but at the end of the experiment, as is the state of the art procedure in this field of research. One advantage of this approach is that participants are not informed about the presence of masked cues until the end of the main experiment. This also leads to a conservative estimate of subjective cue visibility, as during the visibility test, participants are aware of the presence of masked cues and focus their attention on the detection of these, which is not the case in the main experiment. This procedure is additionally conservative because participants have maximum training with the masked stimuli and visibility tests tend to be higher for more practiced stimuli (cf. Pohl, Kiesel, Kunde, & Hoffmann, 2010). This, in our view, outweighs other factors like fatigue that may lead to an underestimation of  $d'$  values.

## 3.2. Results

Only the data from Trial-II trials were analyzed (in Trial I, mean RTs were 1147 ms with a mean error rate of 10.0%, which is probably due to the brief cue duration). Accordingly, the factor task repetition/switch refers to the relationship between the tasks performed in Trial II and in the preceding Trial I. We analyzed data from trials with masked cues and trials with non-masked cues separately. In both cases, we first analyzed whether the cues had an effect on the task choice, that is, how often participants chose the cued task and the non-cued task. To assess task performance in trials with non-masked cues, we then analyzed RTs and errors as a function of task repetition/switch. In trials with masked cues, we analyzed whether the task choice (cued task vs. non-cued task was performed, as indicated by the participants at the end of Trial II) and task repetition/switch affected RTs and error rates. For the RT analysis, error trials and trials with RTs deviating more than 2.5 standard deviations from the mean RT of each participant and each condition were excluded. In trials with masked

cues, error trials were defined as trials in which the participant made an error with respect to the task he/she reported to have performed, not with respect to the task that was cued.

### 3.2.1. Non-masked cues

**Task choice.** Participants performed the cued task in 93.0% of the trials (see Fig. 2). That is, in 7.0% of the trials participants chose the wrong task or made an error when reporting the performed task at the end of the trial.

**RT and error rates.** Participants responded faster (843 ms vs. 1055 ms) in task repetition than in task switch trials,  $t(23) = 5.27$ ,  $p < .001$ , and they made marginally fewer errors (6.9% vs. 8.4%) in task repetition than in task switch trials,  $t(23) = 1.96$ ,  $p = .062$ .

### 3.2.2. Masked cues

**Task choice.** Participants reported to have performed the task that was indicated by the cue in 53.9% of all trials (see Fig. 2). This differs significantly from chance level of 50%,  $t(23) = 2.32$ ,  $p = .029$ .

We further analyzed if participants were biased to repeat or to switch the task, as in voluntary task switching, a repetition bias is typically found. Indeed, we observed a tendency to repeat the task. Participants repeated the task from Trial 1 in 62.3% of all trials, which differs significantly from chance level,  $t(23) = 4.29$ ,  $p < .001$ . Task choice did not influence this repetition bias,  $t(23) = 1.54$ ,  $p = .137$ , which was found both when the task was performed according to the task cue (61.9% repetitions) and when it was not performed according to the task cue (63.1% repetitions).

**RT and error rate.** RT and error rate data were submitted to a  $2 \times 2$  repeated measures ANOVA with the within-subject factors task choice (cued task was performed vs. non-cued task was performed) and task repetition/switch (means are shown in Table 1). RT analysis revealed a main effect of task repetition/switch,  $F(1, 23) = 20.56$ ,  $p < .001$ . Participants responded faster in task repetition trials (1182 ms) than in task switch trials (1445 ms). The main effect of task choice was also significant,  $F(1, 23) = 7.45$ ,  $p = .012$ . Participants responded faster (1283 ms) when they executed the cued task than when they executed the non-cued task (1344 ms). Both factors did not interact,  $F(1, 23) < 1$ .

Analysis of error rates revealed a main effect of task repetition/switch,  $F(1, 23) = 7.94$ ,  $p = .01$ . Participants made fewer errors (6.9%) in task repetition trials than in task switch trials (11.6%). The main effect of task choice was not significant,  $F(1, 23) = 2.20$ ,  $p = .152$ . The interaction between task choice and task repetition/switch was significant,  $F(1, 23) = 5.49$ ,  $p = .028$ . Participants made more errors (13.1% vs. 10.1%) when they performed the cued task than when they performed the non-cued task in a task switch trial,  $t(23) = 2.16$ ,  $p = .042$ . In trials with task repetitions, however, error rates were similar in cued (6.7%) and non-cued (7.2%) task choices,  $t(23) = .60$ ,  $p = .552$ . Thus, we consider a speed-accuracy-tradeoff as unlikely because there is no main effect of task choice on error rate that contradicts the main effect of task choice on RT.

### 3.2.3. Cue visibility

Cue visibility was assessed by computing the signal detection measure  $d'$ , treating the cue  $w$  as signal and the cue  $b$  as noise. Participants' discrimination performance for the fully masked cues was  $d' = 0.29$ , with a mean hit rate of 53.3% and a mean false alarm rate of 43.6%. This value tended to deviate from zero  $t(23) = 1.98$ ,  $p = .06$ .

To further rule out that partially visible cues may account for the observed effects, we assessed the relationship between each participant's individual  $d'$  score and the effect of masked cues on RT. We adopted a procedure suggested by Greenwald, Klinger, and Schuh (1995; see also Draine & Greenwald, 1998; Greenwald, Draine, & Abrams, 1996) and regressed the RT

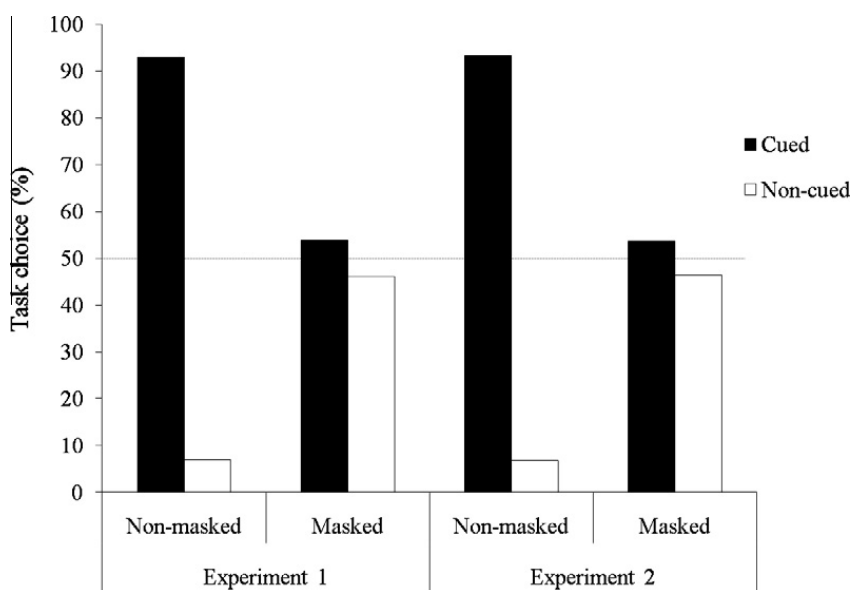


Fig. 2. Proportions of participants' choices of cued and non-cued tasks for non-masked and masked cues in both experiments.

**Table 1**

Mean performance scores (RT and error rate) in Experiment 1 and 2.

	Experiment 1 Cue visibility			Experiment 2 Cue visibility		
	Non-masked cue	Masked cue		Non-masked cue	Masked cue	
		Cued task	Non-cued task		Cued task	Non-cued task
<i>RT</i>						
Repetition	843	1156	1207	1116	1192	1201
Switch	1055	1411	1480	1359	1584	1579
<i>Error rate</i>						
Repetition	6.9	6.7	7.2	3.5	1.8	2.8
Switch	8.4	13.1	10.1	6.7	7.2	11.1

difference of trials with cue-consistent task choices and trials with cue-inconsistent task choices onto individual  $d'$  scores. The intercept of the regression analysis was 50 ms and deviated significantly from zero ( $p = .046$ ). This indicates that the significant effect of task choice on RT is observable even with a  $d'$  score of zero and thus presumably at zero visibility. Additionally, this analysis showed that  $d'$  scores and the effect of task choice on RT are not significantly correlated ( $r = .227$ ,  $p = .287$ ), which further implies that the observed effects are independent of individual cue visibility and are not due to conscious perception of some of the cues.

### 3.3. Discussion

In trials with non-masked cues, the results replicate the typical finding of task switching studies by showing better performance for task repetitions than task switches. Furthermore, participants indicated to have performed the cued task in most of the trials, confirming that participants followed the instructions and suggesting that the cues were clearly visible.

More importantly, there are two findings that reveal an impact of masked task cues on task-set activation. Participants chose the cued task more often than the non-cued task and they were faster performing the cued than the non-cued task. Both findings seem to indicate that the masked cues activated task sets. The influence on task choice reflects an activation of the cued task that induces a bias to actually perform this task. Analogue to the findings that the free choice of motor responses is influenced by masked primes, possibly through motor preactivation (Bodner & Mulji, 2010; Kiesel, Wagoner, et al., 2006; Schlaghecken & Eimer, 2004), the free choice which task set to apply seems to be influenced by the masked cues. Furthermore, the faster responses in the cued task suggest that the currently required S–R-mapping (which is an instance of the task set) was more active for the cued task. This enabled participants to apply the S–R-rules faster and thus to respond more quickly to the target if they performed the cued task.

Regarding task choice, it would have been theoretically possible for participants to randomly perform any response without actually making any task choice and then to “reconstruct” which task fits their response and accordingly answer the question which task they performed. Such a strategy would, however, lead to a specific error pattern for targets that require different (incongruent targets) rather than the same (congruent targets) responses in both tasks. With congruent targets, only one response is correct for both tasks, and the other response is incorrect for both tasks. For example, if odd numbers and numbers bigger than 5 are mapped to the left side response, a random response to the congruent target number 7 is incorrect in about 50%, as a right side response is incorrect for both tasks (while a left response is correct for both tasks). This reconstruction strategy would thus lead to noticeably high error rates with congruent targets. An analysis of error rates with the additional factor of target congruency shows that error rates for congruent and incongruent targets in masked trials do not differ significantly,  $p = .244$ , while there were actually (which is a typical finding in task switching) less errors with congruent targets (6.9%) than with incongruent targets (9.2%). Thus, we consider a strategy of post hoc task reconstruction highly unlikely.

Even though these results are consistent with the idea that unconscious stimuli can trigger task-set activation, there is an important objection one might raise. In a typical task switching experiment, participants may respond correctly without performing different tasks at all, and thus without actually switching task sets. Instead, it is possible to map the responses directly to a combination of both the cue and the target. This strategy was proposed by Logan and Bundesen (2003, 2004) and is referred to as a compound stimulus strategy. In short, the compound stimulus strategy states that “subjects encode the cue, encode the target, and respond to the compound” (Logan & Bundesen, 2004, p. 839). Imagine that, for example, for one given participant the task cues  $w$  and  $b$  signal the parity and the magnitude task, respectively. Further assume that a left key response is required for odd and smaller than 5 judgments, while a right key response signals even and larger than 5 judgments. When responding, the participant may not apply any knowledge regarding the magnitude task and the parity task but respond to the combination of cue and number instead. Thus, he or she might press the left key whenever the cue–target combination is  $w1$ ,  $w3$ ,  $w7$ ,  $w9$  (for odd numbers in the parity task), or  $b1$ ,  $b2$ ,  $b3$ , and  $b4$  (for small numbers in the magnitude task), and the right key for the other combinations.

The compound stimulus strategy, as Logan and Bundesen noted (see also Arrington & Logan, 2004a), can be interpreted in two ways. The first approach is to use cues and targets and directly associate them with a response in episodic memory



without interpreting them. In the given example, the cue *w* and the target 9 always lead to the left key response. Once this cue–target combination was presented and the participant has responded, the cue target compound consisting of both stimuli is stored in episodic memory and associated with the left side response. When the cue target compound is perceived again, the participant retrieves the memorized association between cue target compound and the correct key press to execute the response. A second possibility is that the participant interprets the cue and the target, and uses the combination of both (the compound retrieval cue) to retrieve the necessary information from semantic memory (e.g., the cue *b* and the target 9 retrieve “odd”, and the corresponding response is executed). This is especially plausible with familiar stimuli like numbers, with which categories like *odd* or *even* are already available in semantic memory (Arrington & Logan, 2004a). This compound cue retrieval strategy uses only one task set consisting of the mapping of categories to responses like odd-left, even-right, smaller-left, and larger-right. In each trial processing involves to identify the cue, identify the target, and respond according to what the joint retrieval cue pulled from memory. In either case, the results of Experiment 1 can be interpreted as a result of stimulus compound strategies, in which the masked cue in combination with the target activates the response without activating task sets.

To rule out that participants apply the stimulus compound strategy, we devised another experiment in which cue target compound strategies were not viable by using transition cues (see Forstmann, Brass, & Koch, 2007; Forstmann, Brass, Koch, & Von Cramon, 2005; Rushworth, Hadland, Paus, & Sipila, 2002; Schneider & Logan, 2007) instead of task cues.

## 4. Experiment 2

In standard task switching experiments, each task cue is associated with a specific task and thus tells the participant directly which task to apply. This leads to the possibility of the aforementioned stimulus compound strategy which allows correct responding in task switching experiments without actually switching between the tasks. One method to avoid this problem is to use transition cues instead of task cues. Transition cues are not associated with any particular task but instruct the participant to either repeat the just-performed task or to switch the task. We used the cue *b* to signal a repetition of the preceding task, and the cue *w* to signal a switch to the other task. Now, a combination of the cue and the target does not give sufficient information to determine the required response, as the same cue–target combination can result in different responses, depending on the task performed in the preceding trial. Whereas a cue in the previous experiment was always linked to a certain task, and in combination with the target to a certain response, transition cues result in either task, requiring different responses to the same cue–target combination, thus rendering stimulus compound strategies useless.

### 4.1. Method

#### 4.1.1. Participants

Fifteen students (13 females) of the University of Würzburg with an average age of 22 years participated in this experiment in fulfillment of course requirements or payment (6 Euro). All reported having normal or corrected-to-normal vision, and were not familiar with the purpose of the experiment.

#### 4.1.2. Apparatus, stimuli, procedure, and design

Apparatus, stimuli, procedure, and design were the same as in Experiment 1. Instructions differed only regarding the use of transition cues. Participants were instructed to perform the task that was directly indicated in Trial I by the cue “Größe” (German for “magnitude”) or “Parität” (German for “parity”), and to repeat this task if the cue *b* was presented in Trial II, and to switch to the task that was not performed in Trial I if the cue *w* was presented in Trial II.

### 4.2. Results

As in Experiment 1, only data from Trial-II trials were analyzed. For the RT analysis, trials with RTs deviating more than 2.5 standard deviations from the mean RT of each participant and each condition were excluded, as were trials containing errors. In trials with masked cues, error trials were defined as trials in which the participant made an error with respect to the task he reported to have performed, not the task which was cued.

#### 4.2.1. Non-masked cues

*Task choice.* Participants performed the cued task in 93.2% of the trials (see Fig. 2). That is, in 6.8% of the trials participants chose the wrong task or made an error when reporting at the end of the trial which task was performed.

*RT and error rates.* Participants responded faster with task repetitions (1116 ms) than task switches (1359 ms),  $t(14) = 6.47, p < .001$ , and made fewer errors with task repetitions (3.5%) than task switches (6.7%),  $t(14) = 5.23, p < .001$ .

#### 4.2.2. Masked cues

*Task choice.* Participants chose the task that was indicated by the cue in 53.7% of these trials (see Fig. 2). This differs significantly from chance level,  $t(14) = 2.40, p = .031$ .

We observed a tendency to repeat the task. Participants repeated the task from Trial I in 65.1% of all trials, which differs significantly from chance level,  $t(14) = 3.30, p = .005$ . Task choice did not influence this repetition bias,  $t(14) = 0.63, p = .536$ .

which was found both when the task was performed according to the task cue (65.3% repetitions) and when it was not performed according to the task cue (65.0% repetitions).

*RT and error rates.* RTs and error data were submitted to a  $2 \times 2$  repeated measures ANOVA with the factors task choice (cued task was performed vs. non-cued task was performed) and task repetition/switch (means are shown in Table 1). There was a main effect of task repetition/switch,  $F(1, 14) = 13.28$ ,  $p = .003$ , with mean RTs of 1196 ms for task repetitions and mean RTs of 1581 ms for task switches. Task choice did not influence RT,  $F(1, 14) < 1$ , with mean RTs of 1390 ms for non-cued and 1388 ms for cued task performance. The factors task choice and task repetition/switch did not interact,  $F(1, 14) < 1$ .

For error rates, there was a main effect of task repetition/switch,  $F(1, 14) = 12.41$ ,  $p = .003$ , with mean error rates of 2.3% for task repetitions and 9.1% for task switches. Further, there was a main effect of task choice,  $F(1, 14) = 5.44$ ,  $p = .035$ . Participants made fewer errors when they performed the cued task (4.5%) than when they performed the non-cued task (6.9%). The interaction of task repetition/switch and task choice was marginally significant,  $F(1, 14) = 4.25$ ,  $p = .058$ . In switch trials, participants made fewer errors when they performed the cued task (7.2%) compared to the non-cued task (11.1%),  $t(14) = 2.64$ ,  $p = .019$ , whereas in repetition trials, task choice had no impact on error rates,  $t(14) = 0.96$ ,  $p = .355$ .

#### 4.2.3. Cue visibility

Participants' discrimination performance for the fully masked cues was  $d' = -.05$ , and did not deviate from zero  $t(14) = -.636$ ,  $p = .54$ . Thus, participants were not able to discriminate the primes.

#### 4.2.4. Between experiments comparison

To formally analyze the different effects of task choice on RT in Experiments 1 and 2, we conducted an ANOVA with the between subjects factor Experiment (Experiment 1 vs. Experiment 2) and the within-subject factor task choice with RT as dependent variable.

This analysis yielded a marginally significant interaction of Experiment and task choice on RT,  $F(1, 37) = 3.103$ ,  $p = .086$ . This interaction reflects that there is no effect in Experiment 2 ( $-2$  ms), but a significant effect in Experiment 1 (61 ms). The main effects of Experiment and task choice did not reach significance (both  $F < 1$ ). Another ANOVA with the between subjects factor Experiment and the cues' effect on task choice as dependent variable showed no main effect of Experiment on task choice (53.9% vs. 53.7%),  $F(1, 37) = .008$ ,  $p = .928$ .

### 4.3. Discussion

In contrast to Experiment 1, stimulus compound strategies were not viable in Experiment 2, and yet, participants still chose the cued task more often than the non-cued task. This suggests that the transition cues, though not consciously perceived, activated the corresponding task set, which in turn induced the tendency to perform that task. However, task performance was only slightly influenced by the masked cues. Mean response times did not differ for cued and non-cued tasks and error rates differed only in task switch but not in task repetition trials. Hence, participants chose the cued task more often than the non-cued task but did not execute it any faster, as was the case in Experiment 1. This suggests that the impact on RTs observed in Experiment 1 was a consequence of the presence of cue–target compounds.

## 5. General discussion

The aim of the present study was to investigate whether subliminally presented stimuli can activate task sets under experimental conditions that rule out possible artifacts due to prime–cue interactions. Experiment 1 provided preliminary evidence that even masked, and presumably subjectively invisible task cues can trigger task-set activation. However, the design of this experiment could have led participants to make use of the cue–stimulus compound strategies considered by Logan and Bundesen (2004). These strategies were prevented by the design of Experiment 2, where cues no longer signaled a particular task but, instead, informed participants to stay on the same task or to switch. Accordingly, there was no contingency of tasks and cues, which rules out any contribution from cue–task or stimulus–cue–task associations or learning. Nevertheless, masked transition cues affected the choice of tasks, even though the speed of task performance was unaffected.

Task-set activation in response to a randomly varying cue is widely considered a cognitive control process (e.g., Altmann, 2004; Hoffmann, Kiesel, & Sebald, 2003; Koch, 2001; Meiran, 1996; Rogers & Monsell, 1995) that requires conscious awareness (Dehaene & Naccache, 2001; Jack & Shallice, 2001; Smith & Jonides, 1999; see Hommel, 2007, for an overview). Our observation that task choices are impacted by stimuli that participants are not aware of is inconsistent with this assumption and suggests that processing of masked cues is not fundamentally different from processing of non-masked cues, and that conscious awareness has no functional role in task-set activation. This conclusion is consistent with previous claims (Mattler, 2003, 2006), but, as we have explained, is based on what we consider more solid evidence that cannot be accounted for in terms of perceptual priming or prime–cue interactions. Our results fit and add nicely to the fMRI study of Lau and Passingham (2007) that likewise suggested that task sets can be activated by unconscious stimuli. Moreover, we could also show that unconscious stimulus information can trigger task-set activation all by itself without additional presenting visible stimuli. Whereas possible differences regarding task-set activation (and other aspects) between externally cued tasks and

internally selected tasks are still under debate, this result shows that task-set activation is susceptible to unconscious influences regardless of the specific experimental design.

This conclusion fits with observations from studies on the implicit learning of task-switching sequences (Gotler, Meiran, & Tzelgov, 2003; Koch, 2001). In the study of Koch (2001), participants were cued to switch between three tasks. However, instead of the typical random sequence of tasks, there was a fixed task sequence that repeated every 9 trials. Participants were not informed about this fixed sequence and were unable to report any knowledge of the task sequence after the experiment. Yet, when the fixed sequence was replaced by another task sequence, overall RT increased. This suggests that the task sets that accorded to the fixed sequence were unconsciously activated, thus reducing RT with the fixed sequence and prolonging RT when the sequence changed. A problem with this design was that the fixed task sequence went along with a fixed cue sequence. Gotler et al. (2003) used a fixed task sequence, but applied two cues per task to disentangle task sequence and cue sequence. Results were comparable to those by Koch, with longer RTs in the fixed sequence blocks than in random blocks. Thus, these studies demonstrated some kind of “automatic ‘priming’ of task sets that is not mediated by intentional processes” (Koch, 2001, p. 1478).

The fact that masked task cues affect both task choices and the speed of task performance (Experiment 1), whereas masked task-transition cues affect task choices only (Experiment 2) provides a theoretically important hint to the underlying mechanisms. Several authors have suggested two-stage models of task switching that, roughly speaking, distinguish between processes devoted to the selection of a task set and processes responsible for the implementation of this task set (e.g., Koch & Allport, 2006; Mayr & Kliegl, 2000; Rogers & Monsell, 1995; Rubinstein et al., 2001). For example, Rubinstein et al. (2001) distinguish between *goal shifting* and *rule activation*. The goal shifting stage's function is to identify and keep track of the currently relevant task, whereas the rule-activation stage is responsible for the implementation of the relevant stimulus–response mappings. In the explicit cuing paradigm, the task cue would provide the information which task to perform next, which first leads to the selection of the appropriate goal (task) and then to the activation of the corresponding mappings. From this perspective, our findings might be taken to imply that masked task cues affect both stages whereas masked transition cues affect goal selection only. Yet, as task switching theories differ immensely regarding the underlying processes when switching between different tasks, these considerations should be seen as speculative at the moment.

The reason for the different findings regarding task and transition cues is likely to be related to the fact that task cues are contingent on particular tasks, whereas transition cues are not. This means that a given task cue is likely to become associated with the representation of the task and the task-specific mappings it signals, just like a conditioned stimulus becomes associated with the unconditioned stimulus it precedes in time. In contrast, transition cues precede each task equally often and should thus be associated with all task representations alike. If we now assume that the choice of a task is affected by the information a task or transition cue provides, whereas the speed to execute a stimulus–response rule is affected by the degree to which a set of task-specific rules is primed by existing cue–mapping associations, it is clear that transition cues can only target task choices while task cues can affect both task choice and rule execution. This scenario also seems to fit with the idea of Forstmann et al. (2007) that “direct task cues may lead to automatic activation of the associated task set, whereas such direct, stimulus-based automatic task-set activation is not possible when using transition cues” (p. 398).

To conclude, we found evidence that the activation of task sets can be affected by stimuli that people are not aware of, even under conditions ruling out perceptual priming and prime–cue interactions. This adds to the increasing evidence that cognitive control processes are systematically affected by unconscious information. However, what exact process is impacted depends on the type of stimulus. Unconscious stimuli that are uniquely associated with particular task sets seem to activate all the stimulus–response mappings the set comprises of, thereby speeding up performance based on these mappings. In contrast, unconscious stimuli that point to a particular task, but that are not contingent on a specific task or task elements, can bias or even induce the decision which task to perform, but do not speed up the subsequent performance of the task. This dissociation is consistent with dual-process models of task switching in general and with models distinguishing between goal selection and task set implementation in particular.

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