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Attentional modulation of masked semantic priming by visible and masked task cues

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ABSTRACT

In contrast to classical theories of cognitive control, recent evidence suggests that cognitive control and unconscious automatic processing influence each other. First, masked semantic priming, an index of unconscious automatic processing, depends on attention to semantics induced by a previously executed task. Second, cognitive control operations (e.g., implementation of task sets indicating how to process a particular stimulus) can be activated by masked task cues, presented outside awareness. In this study, we combined both lines of research. We investigated in three experiments whether induction tasks and presentation of visible or masked task cues, which signal subsequent semantic or perceptual tasks but do not require induction task execution, comparably modulate masked semantic priming. In line with previous research, priming was consistently larger following execution of a semantic rather than a perceptual induction task. However, we observed in experiment 1 (masked letter cues) a reversed priming pattern following task cues (larger priming following cues signaling perceptual tasks) compared to induction tasks. Experiment 2 (visible letter cues) and experiment 3 (visible color cues) showed that this reversed priming pattern depended only on apriori associations between task cues and task elements (task set dominance), but neither on awareness nor on the verbal or non-verbal format of the cues. These results indicate that task cues have the power to modulate subsequent masked semantic priming through attentional mechanisms. Task-set dominance conceivably affects the time course of task set activation and inhibition in response to task cues and thus the direction of their modulatory effects on priming.

1. Introduction

Application of cognitive control operations such as implementation of task sets, which indicate how to process a particular stimulus, or goal-based modulation of stimulus processing through attentional mechanisms has been traditionally assumed to be confined to a conscious strategic processing mode (Dehaene & Naccache, 2001; Posner & Snyder, 1975; Schneider & Shiffrin, 1977). In classical models of cognitive control (Posner & Snyder, 1975; Schneider & Shiffrin, 1977), application of such cognitive control operations is therefore thought to require stimulus awareness and an intentional decision to initiate the process. Automatic processes, such as processes triggered by unconsciously perceived masked stimuli, are assumed to be unrelated to cognitive control operations. This strong link between cognitive control and consciousness in classical models has been challenged from two lines of research (for a review, Ansorge, Kunde, & Kiefer, 2014): Firstly, several studies showed that masked cues, which cannot be consciously identified, modify cognitive control settings such as tendencies to inhibit a prepared response (van Gaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008; van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009) and activate task sets (Lau & Passingham, 2007; Mattler, 2003, 2005, 2006, 2007; Reuss, Kiesel, Kunde, & Hommel, 2011). For instance, masked task cues, which signal to perform a certain task, can trigger task sets and influence task choices (Reuss et al., 2011).

Secondly, automatic processing elicited by masked stimuli has been found to be modulated by cognitive control settings such as activated task sets, stimulus expectations or temporal attention (Kiefer & Martens, 2010; Kunde, Kiesel, & Hoffmann, 2003; Naccache, Blandin, & Dehaene, 2002; Neumann, 1990). This field of research is illustrated by experiments showing a modulation of masked semantic priming, as index of unconscious automatic processing (for details see below), through an attentional focus established by a previously performed induction task (Kiefer & Martens, 2010). The present set of experiments further elucidates this interplay between cognitive control and

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unconscious automatic processing. More precisely, by combining both lines of research described above, our study aims at addressing the following novel research questions: (i) Do task cues associated with a given task set, whether masked and invisible or unmasked and clearly visible, have the power to trigger task sets and to modulate subsequent masked semantic priming via attentional mechanisms, even when no task has to be executed? (ii) Are these effects of task cue presentation on unconscious priming comparable to the well-documented carry-over effects from previously performed induction tasks?

1.1. Masked priming as a paradigm to elicit automatic processes

A typical example of automatic processes are processes underlying priming effects by masked stimuli, which are not consciously perceived. In the present work, we focus on masked semantic priming within a lexical decision task (LDT), a paradigm, which has been widely used to study attentional effects on unconscious automatic processing (for reviews, see Ansorge et al., 2014; Kiefer, 2012): When participants have to classify whether a target letter string is a meaningful word or a pronounceable, but meaningless pseudoword, reaction times (RT) are faster and more accurate if the target word (e.g., lemon) is preceded by a semantically related word (e.g., sour) compared to an unrelated word (e.g., house). This semantic priming effect is also observed, when conscious prime perception is eliminated by presenting pattern masks (e.g., letter strings) before and after the prime, suggesting that facilitation arises from unconscious automatic activation of the semantic prime representation (Deacon, Hewitt, Chien-Ming, & Nagata, 2000; Kiefer & Spitzer, 2000; Marcel, 1980). In addition to this pure form of masked semantic priming within the LDT, there are mixed paradigms using semantic (e.g., living vs. non-living) or evaluative (e.g., pleasant vs. unpleasant) category decision tasks, in which the semantic categories are mapped to different motor responses (e.g., living: left hand response; non-living: right hand response). Unlike in the LDT, primes and targets of the different category congruency conditions differ in category decision tasks not only with regard to semantic relatedness or category congruency, but also with regard to response congruency (e.g., Damian, 2001). As a consequence, response-related processes can contribute in addition to semantic processes (Kiefer, Liegel, Zovko, & Wentura, 2017; Kiefer, Sim, & Wentura, 2015; Ortells, Kiefer, Castillo, Megias, & Morillas, 2016). However, masked stimuli do not only prime semantic representations or motor responses, but have also the power to activate cognitive control operations including activation of task sets. We elaborate this issue in the next section.

1.2. Activation of task sets by visible and masked task cues

In task switching research, task cues are typically used to inform participants about the nature of the upcoming task and to trigger implementation of a currently relevant task set (Schuch & Koch, 2003). A task set is broadly defined as an adaptive configuration of the cognitive system as a prerequisite for performing a given task (Gilbert & Shallice, 2002; Rogers & Monsell, 1995). It includes the task rules and corresponding stimulus-responses mappings. Implementation of task sets is assumed to require cognitive control operations, which configure the system accordingly (Miyake et al., 2000). Several lines of evidence indicate that task sets can be triggered by the presentation of task cues. Research on task switching showed that visible task cues, which inform about the nature of the upcoming task, reduce reaction time in task switching trials by activating the appropriate task set in advance (Kiesel et al., 2010). Even when task cues are masked and not available for conscious report, they trigger the associated task set. In task set priming experiments, faster responses in a target task were observed when it was preceded by a masked task cue indicating the same task (i.e. a congruent task cue) compared to a task cue indicating a different task (i.e. incongruent task cue, Lau & Passingham, 2007; Mattler, 2003, 2005, 2006, 2007). At a neural level, presentation of an incongruent masked task cue increases activity in brain regions involved in processing the cued but currently irrelevant task (Lau & Passingham, 2007). Altogether, these task set priming effects have been interpreted to reflect unconscious task set activation triggered by unconsciously perceived task cues.

However, as perceptual priming effects cannot be excluded in this sort of masked task set priming experiments, Reuss and colleagues developed a new procedure to demonstrate unconscious task set activation (Reuss et al., 2011). In this procedure, participants were presented with visible or masked task cues, which were not consciously perceived, followed by an imperative stimulus, on which one of two possible tasks had to be performed (numerical magnitude vs. parity decision). In trials with visible task cues, the task indicated by the task cue had to be performed. In trials with masked task cues, participants could choose the task they wanted to perform and were requested to report the performed task thereafter. It was assessed whether masked task cues induced a trend to perform the task indicated by the unconscious cue. In line with the suggestion of unconscious task set activation, participants more likely chose to perform the task indicated by the masked task cue (Reuss et al., 2011). Moreover, RT was faster when the actually performed task was congruent with the preceding masked task cue. Hence, these results demonstrate that even unconsciously presented stimuli are able to activate corresponding task sets. The question arises whether these task sets automatically activated by task cues have the potential to modulate subsequent automatic masked semantic priming.

1.3. Attentional influences on unconscious automatic processes

Unlike classical theories of automaticity and cognitive control (Posner & Snyder, 1975; Schneider & Shiffrin, 1977), refined theories propose that automatic processes are sensitive to influences of cognitive control settings (Kiefer & Martens, 2010; Kunde et al., 2003; Naccache et al., 2002; Neumann, 1990; Spruyt, De Houwer, & Hermans, 2009). More specifically, this class of theories assumes that automatic processes such as unconscious semantic activation during masked priming depend on the attentional sets activated prior to masked prime presentation (Kiefer & Martens, 2010; Spruyt et al., 2009). This has been demonstrated in experiments with the induction task paradigm described below. The study at hand aims to further generalize this account to attentional sets that have been activated through other means than task execution, namely the mere presentation of a (masked) task cue.

According to the attentional sensitization model (Kiefer & Martens, 2010), a semantic task set should enhance masked semantic priming, whereas a perceptual task set should attenuate masked semantic priming. Attentional sensitization of automatic semantic processing by an activated semantic task representation is achieved by enhancing the sensitivity of task-relevant semantic pathways. A perceptual task set, in contrast, is assumed to attenuate the sensitivity of the task-irrelevant semantic pathway, while enhancing the sensitivity of perceptual pathways. Enhancement and attenuation of the sensitivity in corresponding processing pathways is achieved by increasing/decreasing the probability that neurons fire at a given activation level (increase/decrease of baseline activity) through appropriate top-down signals (Kiefer & Martens, 2010). A recent neuroimaging study further showed that attentional sensitization of unconscious semantic cognition is accompanied by a temporary and dynamic integration of brain areas into different functional networks depending on the active task set (Ulrich, Adams, & Kiefer, 2014).

Attentional top-down influences of task sets on unconscious semantic priming can be investigated with the induction task paradigm that exploits the temporal dynamics of task set activation (for an overview, see Kiefer, 2012; Kiefer & Martens, 2010; Martens, Ansorge, & Kiefer, 2011). In the induction task paradigm, prior to the masked priming procedure, participants are engaged in different induction tasks (e.g., semantic classification vs. perceptual classification) designed to induce a specific task set (e.g., a semantic or perceptual task set). The induction tasks are followed immediately by a primed decision task (e.g., a primed LDT). In some of these experiments (Kiefer & Martens, 2010; Martens et al., 2011), the time interval between the response to the induction task and the onset of the prime (RPI) (either 200 or 800 ms) was varied in order to obtain information on how the influence of the induction task on masked priming unfolds over time. A semantic induction task is expected to sensitize semantic processing pathways and thus to enhance semantic priming only at the short RPI (200 ms). At the long RPI (800 ms), the task set is assumed to be inhibited because participants have time to prepare the switch to the upcoming LDT. This assumption of task set inhibition at long RPIs is based on the task switching literature suggesting that a task representation is active for about 600 ms after task completion (Rogers & Monsell, 1995), but is actively inhibited thereafter in preparation for a new task (Koch, Gade, Schuch, & Philipp, 2010; Mayr & Keele, 2000).

In line with the attentional sensitization model, unconscious semantic priming was enhanced by a semantic and attenuated by a perceptual task set at the short RPI (Kiefer & Martens, 2010; Martens et al., 2011). At the long RPI, significant priming was found after the perceptual, but not after the semantic induction task. The priming effects at the long RPI suggest that after 800 ms the task set of the induction task had been abandoned and a reconfiguration of the cognitive system in preparation for the upcoming LDT had taken place (Kiefer & Martens, 2010): Semantic pathways are sensitized when the perceptual induction task had been abandoned, but they are desensitized when the semantic induction task had been abandoned. In support of the selection of time intervals for the short and long RPI conditions in these studies mentioned above, a more fine grained variation of RPIs in one study (Martens & Kiefer, 2009) indicated that the reversal of priming effects as a function of induction task and RPI emerges at RPIs longer than 800 ms after the response in the induction task. At an intermediate RPI of 500 ms, priming as a function of induction task resembled the pattern at the RPI of 200 ms. This result pattern is compatible with the notion of a backward inhibition mechanism (Mayr & Keele, 2000) that suppresses irrelevant task sets in preparation of the next task (for critical discussions, see Koch et al., 2010; Koch, Poljac, Muller, & Kiesel, 2018). These findings with the induction task paradigm are in line with other research demonstrating effects of temporal attention (Kiefer & Brendel, 2006; Naccache et al., 2002), action intentions (Ansorge & Neumann, 2005; Ansorge, Heumann, & Scharlau, 2002; Eckstein & Perrig, 2007) stimulus expectations (Kiesel, Kunde, Pohl, Berner, & Hoffmann, 2009; Kunde et al., 2003) and feature-specific attention (Spruyt, De Houwer, Everaert, & Hermans, 2012) on unconscious priming. Hence, there is converging evidence for cognitive control influences on unconscious automatic processing (for a review see, Ansorge et al., 2014).

1.4. Overview of the present study

As outlined before, task cues whether presented visibly or masked and outside awareness have the power to trigger the corresponding task set and to facilitate subsequent performance in a target task. At the same time, it is known that task sets established by executed tasks modulate subsequent unconscious masked semantic priming. The present study combines these lines of research and provides the following novel theoretical and empirical contributions: It is open, whether task sets activated by mere task cue presentation, without executing a subsequent task, have the potential to differentially sensitize processing streams similar to induction tasks, whereby subsequent masked semantic priming is modulated. Across three experiments, the present research therefore compared for the first time attentional influences on masked semantic priming originating from previously performed induction tasks with those originating from mere presentation of task cues.

To test these assumptions, we developed for the present study a novel experimental paradigm (Fig. 1) by combining the induction task (Kiefer & Martens, 2010) and the task cue procedures (Reuss et al., 2011). Participants were presented with two trial types: Induction task trials and task cue-only trials. Both trial types were followed by a primed LDT using masked primes, which were semantically related or unrelated to the target words of the LDT (masked semantic priming paradigm). The induction task trials started with a task cue, which indicated whether a perceptual (visual shape decision) or semantic (living/non-living classification) induction task on a subsequent object picture had to be performed. The different induction task trials in the present study were randomized and intermixed with task cue-only trials. A recent study (Kiefer, 2018) demonstrated the effectiveness of randomized induction task presentation to modulate subsequent masked semantic priming, but it did not include task cue-only trials, the novel empirical and theoretical aspect of the present work. Furthermore, we implemented in the current research only short response prime intervals (RPI), in which the prime was presented 400 ms after the response in the induction task. The long RPI condition was omitted due to its irrelevance for the purpose of the present study, because task sets have been found to be inhibited at intervals longer than 500 ms after task completion (Houghton, Pritchard, & Grange, 2009; Kiefer & Martens, 2010; Mayr & Keele, 2000). In task cue-only trials, the task cue was presented without a subsequent induction task and was immediately followed by the masked prime and the lexical decision target. Participants were informed that in some trials the first task was missing so that their focus should rest on the LDT. As we assumed that task set activation is sufficient to implement the corresponding cognitive control settings (Ansorge et al., 2014; Kiesel et al., 2010), task sets should influence attentional sensitization of unconscious processing both, by executing an induction task and by mere task cue presentation. As masked semantic priming is assumed to benefit from a sensitization of semantic pathways (Kiefer & Martens, 2010), we expected larger priming following a semantic induction task or semantic task cue than following a perceptual induction task or perceptual task cue.

Using the research by Reuss et al. (2011) as starting point, the first experiment assessed, whether unconsciously perceived masked task cues (letters A and B) are able to modulate subsequent masked semantic priming. Similar to this earlier task cue experiment (Reuss et al., 2011), the task cue was only presented visibly at a long duration in induction task trials, but was briefly presented and masked in task cue-only trials. Participants were neither informed of the presence of the masked task cues nor of the presence of the masked primes. Contrary to our expectations, the pattern of priming effects differed between induction task and task cue-only trials in this first experiment. We therefore conducted two further experiments to identify factors underlying this unexpected finding: In the second experiment, we tested whether presenting the task cues in the task cue-only trials visibly and at the same duration as in induction task trials would alter the pattern of subsequent priming effects. In the third experiment, task cues were presented non-verbally as red and blue colored squares in order to exclude the possibility that unnoticed connotations of the task cue letters A and B used in experiments 1 and 2 influenced priming in task cue-only trials. Furthermore, we tested whether task set dominance of the induction tasks, i.e. existence of links between elements of the task sets in the induction task (Jost, Hennecke, & Koch, 2017), moderates the pattern of subliminal semantic priming effects subsequent to mere task cue presentation. To briefly foreshadow the results of experiments 2 and 3, only task set dominance, but neither task cue visibility nor verbal or non-verbal format of the task cues were identified as relevant factors to modulate the priming pattern in task cue-only trials.

2. Experiment 1

In this first experiment, we sought to establish the effects of masked task cue presentation on subsequent masked semantic priming. To this end, we used the novel experimental paradigm combining the induction task and task cue procedures. This allowed us to compare task set induced modulation of masked semantic priming following either the

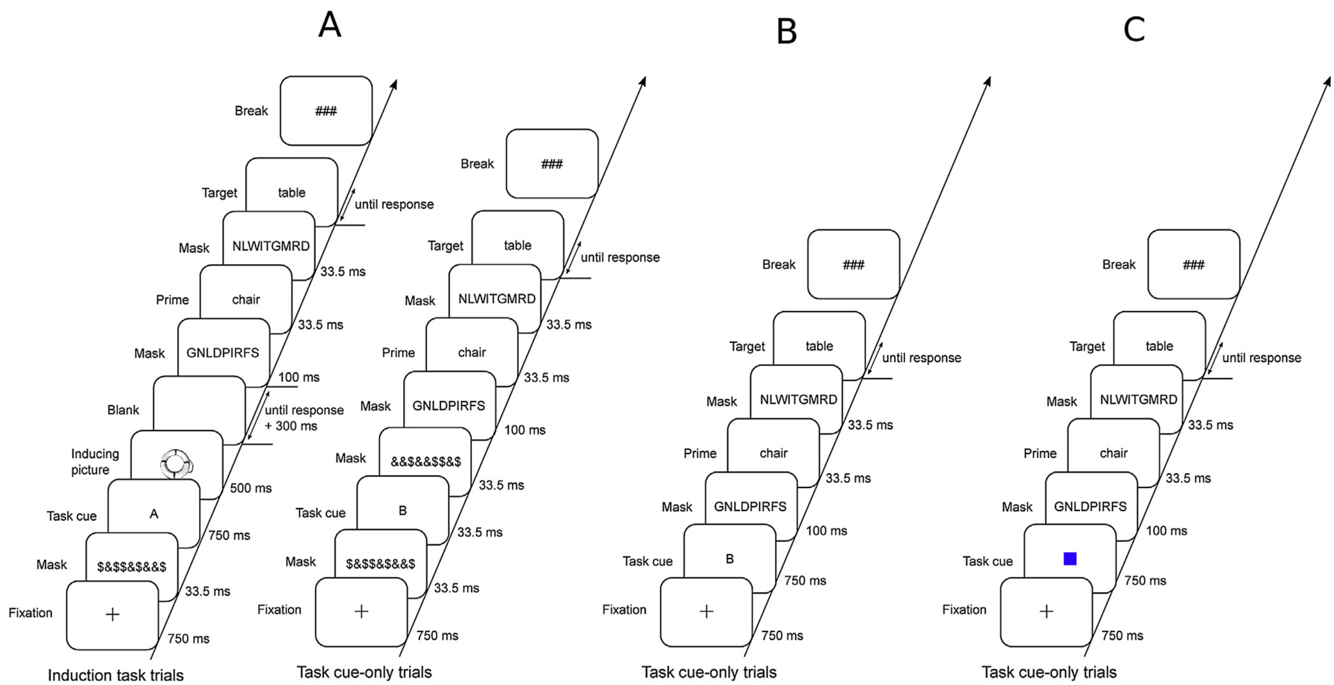

Fig. 1. Temporal sequence of trials in the paradigm combining induction tasks, task cues and masked semantic priming. The induction task intended to elicit the corresponding task set. The semantic induction task required semantic classification of the object picture (forced choice living/non-living decision), whereas the perceptual induction task required a forced choice perceptual classification decision of the shape of the object (round/elongated). (A) Experiment 1: Induction task trials and trials with masked letter task cues. (B) Experiment 2: Trials with visible letter task cues. Induction task trials (not shown) were identical to (A), besides the removal of the forward mask before the task cue. (C) Experiment 3. Trials with visible color task cues. Induction task trials (not shown) were identical to (A), besides the removal of the forward mask before the task cue and the colored square as task cue as in (C).

execution of a perceptual vs. semantic decision task or following mere presentation of corresponding masked task cues. Similar to Reuss et al. (2011), the masked prime was shortly presented after the masked task cue because task set activation by subliminally presented cues might be short-lived. We assumed that a masked prime following a semantic induction task or a masked semantic task cue (i.e., during conditions of an increased sensitization of semantic pathways) should elicit larger semantic priming effects than when following a perceptual induction task or a perceptual task cue (i.e., during conditions of a decreased sensitization of semantic pathways).

2.1. Methods

2.1.1. Participants

Twenty-four healthy, right-handed (according to the handedness test by Oldfield, 1971), native German speakers with normal or corrected-to-normal vision participated in this experiment. The data of two participants were discarded from analysis due to prolonged reactions times (RT) in the induction tasks (individual mean RT 2 SD above the sample mean). The remaining twenty-two participants (10 men and 12 women) had a mean age of 22.7 years (range 19–34). In this and the subsequent experiments, all participants gave informed, written consent after the experimental task had been explained. Participants were naïve to the purpose of the experiment. Procedures in all experiments were approved by the ethical committee of Ulm University.

2.1.2. Material

2.1.2.1. Tasks for inducing task sets. Stimuli were 320 grey-scale pictures of living and non-living objects, which were taken from an earlier study with the induction task paradigm (Kiefer & Martens, 2010). Pictures (170 × 216 pixels, 72 pixels/in. resolution) showed a common object against a black background and were adjusted to comparable levels of brightness and contrast. At a viewing distance of 90 cm, pictures had a visual angle of 3.2 × 3.8°. One hundred-sixty pictures were used for the perceptual induction task. Half of these displayed an object with a round shape and the other half an object with a long shape (living and non-living objects were equally distributed across the shapes). Another 160 pictures were used for the semantic task: eighty pictures showed living objects and eighty non-living objects, (shape was balanced across conditions). According to an earlier pilot study (Kiefer & Martens, 2010), pictures for the perceptual and the semantic tasks (see below) were matched for response times and error rate.

2.1.2.2. Masked priming paradigm. Primes and targets were the same as in earlier priming studies (Kiefer & Martens, 2010). The set consisted of 320 German word–word and 320 word–pseudoword pairs. Primes and targets were on average five letters long (range 3–9) and subtended at a viewing distance of 90 cm a visual angle of about 2.58° in width and 0.88° in height. The word–pseudoword pairs served as distractors and were not further analyzed. The word–word combinations consisted of 160 semantically related pairs (“hen”–“egg”) and 160 semantically unrelated pairs (“car”–“leaf”). Critical prime–target combinations were equated in word length and frequency (Ruoff, 1990) of the primes and of the targets across conditions (pseudowords were only matched in length). Prime–target combinations were divided into four lists. The assignment of a list to a given experimental condition (different inductions tasks or task cues only, see below) was counterbalanced across participants. It was ensured that the picture of the induction task was not semantically related to the prime and the target within one trial. As the theoretical focus of the present study rested upon the modulation of masked priming by previously performed induction tasks, we were only interested in interactions between the factors semantic relatedness and induction task, but not in the main effect of semantic relatedness. For that reason, potential confounds arising from unnoticed insufficient matching of primes and targets of the semantic relatedness conditions in linguistic variables other than word length and word frequency do not compromise the interpretation of these theoretically relevant higher-order interactions.

2.1.3. Procedure

Six-hundred forty trials, divided into eight blocks of 80 trials each, were presented in randomized order. Breaks were provided between the blocks. The trials of the induction task/task cue-only conditions and the masked priming paradigm were combined such that all conditions of the induction tasks/task cues and the masked priming paradigm co-occurred equally often and were entirely balanced. Hence, conditions and response requirements in both tasks were varied independently of each other, thus preventing systematic carry-over effects.

There were two types of trials: trials with a visible task cue followed by an induction task vs. trials with a masked task cue without a following induction task to be performed. The masked task cue-only trials served to assess whether the task cue activates the corresponding task set, which in turn modulates following masked semantic priming. In each trial (see Fig. 1A), participants were first presented with a fixation cross for 750 ms and then with a string of 10 symbols consisting of a random sequence of "&" and "$" (33.5 ms), which served as forward mask for task cue-only trials. The symbol string was also shown in induction task trials, in order to prevent participants to distinguish between trial types prior to cue presentation. Thereafter, the sequence of events differed between induction task and task cue-only trials. In induction task trials (320 trials), the task cue (letters "A" or "B") was presented for 750 ms, followed by the induction picture (500 ms). The task cue "A" signaled participants to perform a perceptual decision, whereas the task cue "B" indicated a semantic decision. Participants had to decide as fast and as accurately as possible (i) in the perceptual task, whether the object of the induction picture had a round or elongated shape, and (ii) in the semantic task, whether the picture showed a living or non-living object. There was a blank screen, until the response to the induction task was given by pressing one of the designated buttons, and another blank screen (300 ms) after the response. Then, a random letter string (forward mask) consisting of 10 capital letters was presented (100 ms), followed by the prime word (33.5 ms) and another random letter string (33.5 ms), which served as backward mask. Thereafter, the target stimulus was shown that either formed a real word or a pronounceable pseudoword. Participants had to decide as fast and as accurately as possible whether the target was a real word or not. Responses were indicated by pressing one of two buttons with the right index or middle finger. The target remained on the screen until a response was given. After a blank screen of 300 ms, three hash marks prompted the participant to initiate the next trial by a button press. In task cue-only trials (320 trials), after the random symbol string (forward mask), the task cue (letters "A" or "B") was flashed for 33.5 ms, followed by another random symbol string (33.5 ms; backward mask). Immediately thereafter, the forward mask and the primed LDT was presented using the same stimulation parameters as for the induction task trials. Participants were not informed of the presence of the task cue and the prime between the masks. They were instructed to passively view the masking strings and to concentrate on the LDT.

All stimuli were displayed in white font against a black background on a cathode ray tube computer monitor synchronously with the screen refresh (refresh rate = 16.67 ms). Participants first received task instructions and practiced the induction tasks and LDT separately. Subsequently, they practiced the tasks in the same sequence as in the main experiment.

After the main experiment, participants were informed of the presence of the task cue and of the prime between the masks and were asked if they had recognized that masked stimuli had been presented. None of the participants reported awareness of these stimuli. An objective measure of task cue and prime visibility was obtained thereafter within a simple visual discrimination task (see also Kiefer & Martens, 2010), in which sequence of events and stimulation parameters were identical with the task cue-only trials of the main experiment. In the task cue identification test, participant performed a visual discrimination task on 40 masked task cues (20 letters A and 20 letters B) and 40 letter strings. Each letter string comprised nine repetitions of the identical capital letter (e.g., AAAAAAAAA), which was randomly selected in each trial. Participants had to decide whether the masked stimulus was a single letter (A or B) or a letter string. After the response in this visual discrimination task, participants performed the primed lexical task. In the masked prime identification test, participants had to discriminate between masked prime words (40 trials) and capital letter strings (40 trials). Masked words were either semantically related or unrelated to a subsequently presented unmasked context word (20 trials of each condition), i.e. the lexical decision target, which was included to keep the stimulation of the identification test identical to the main experiment. Furthermore, it served to test whether the lexical decision target helped to identify the masked prime (backward priming). After masked prime identification, the LDT had to be performed. Instructions for masked stimulus identification stressed accuracy over response speed. Participants were also requested to make the best guess when they did not feel confident about the correct response. The entire experimental session including instructions, training, main experiment and masked stimulus identification tests lasted about 2 h. Archived data of all experiments can be downloaded from a public repository (Kiefer, Trumpp, Schaitz, Reuss, & Kunde, 2018).

2.2. Results

2.2.1. Masked task cue and prime visibility test

In order to assess visibility of the masked task cues and primes in the identification test following the priming phase, we calculated d′ sensitivity measures (Green & Swets, 1966) from each participant's hit rates (correct responses to task cues, masked prime words) and false alarm rates (erroneous responses to letter strings). With regard to task cue visiblity, d′ measures were significantly larger than zero for the perceptual (d′ = 0.30) and semantic task cues (d′ = 0.34) in two-tailed one-group t-tests, all $ts(21) > 3.6$, all $ps < .01$, all $ds > 0.07$, but did not significantly differ from each other in a two-tailed paired *t*-test, ($t(21) = 0.37$, $p = .71$, $d = 0.07$.

With regard to masked prime word visibility, d′ measures in all conditions (combination of task cue type and semantic relatedness) were not significantly different from zero in two-tailed one-group t-tests, all $d' < 0.19$, all $ts(21) < 1.41$, all $ps > .17$, all $ds < 0.29$, indicating that participants could not identify the masked word primes. Furthermore, a repeated-measures analysis of variance (ANOVA) with the factor task cue type and semantic relatedness of prime and target did not yield significant effects for any factor (all $Fs < 1.63$, $p > .21$) suggesting that masked prime identification was comparable across conditions. In particular, there were no signs that backward priming from the target enhanced the visibility of the prime.

As d′ measures of masked task cue identification were small, but significantly deviated from zero, task cues might be marginally identifiable, although no participant reported awareness of the masked cues and masked primes in the post-experimental debriefing. In order to assess, whether task cue visibility affected priming effects, d′ measures of perceptual and semantic task cue identification were correlated with the magnitude of priming (RT difference unrelated - related) in the corresponding task cue condition. None of the correlations were significant (perceptual: $r = -0.18$, $p = .42$; semantic: $r = 0.10$, $p = .64$). Hence, there are no signs that potential residual task cue visibility influenced the magnitude of priming. We also assessed whether potential residual prime visibility had influenced the magnitude of priming and performed correlation analyses relating d′ measures of masked prime visibility to the magnitude of priming, separately for the different conditions. None of the correlations were significant (all $|r| < 0.30$, all $ps > .17$).

2.2.2. Induction tasks

For reaction time (RT) analysis, mean RT of the correct responses was calculated for each induction task condition. Outlying reactions (mean RT ± 2SD) were excluded from analysis (3.9% of the entire data set). It was checked that this outlier criterion also captured anticipations (RT < 200 ms). A two-tailed paired *t*-test yielded significantly faster reactions in the perceptual (508 ms) than in the semantic (531 ms) induction task, ($t(21) = -2.65$, p = .014, d = 0.56. An analysis of sequence effects including the factors task set repetition (repetition of the same task set, e.g., perceptual - perceptual, in two subsequent trials) and trial type repetition (repetition of the same trial type, e.g., induction task - induction task, in two subsequent trials) revealed no task set repetition costs. Task switch costs were found only for trial type repetition trials (see Supplementary Material, analyses 1). Error rate (ER) in the perceptual (3.23%) and semantic (3.15%) induction task was comparable according to a corresponding *t*-test, ($t(21) = 0.20$, p = .83, d = 0.04.

2.2.3. Masked priming

Analysis of RT data in the masked priming paradigm was based upon mean RT of the correct responses in each experimental condition. Outlying reactions were excluded using the same criteria as for the induction task (4.6% of the entire original data set, outlying reactions from the previous induction task were not additionally excluded from the analysis of the RT data of the LDT). Repeated-measures ANOVAs on mean RT and ER with the within-subject factors trial type (induction task vs. task cue-only), task set (perceptual vs. semantic) and semantic relatedness (related vs. unrelated) were performed. For the RT data, the main effect for semantic relatedness, $F(1, 21) = 40.28$, $p < .001$, $\eta_p^2 = 0.657$, the two-way interaction between trial type and semantic relatedness, $F(1, 21) = 5.09$, $p = .035$, $\eta_p^2 = 0.195$, as well as the three-way interaction between trial type, task set, and semantic relatedness, $F(1, 21) = 6.35$, $p = .020$, $\eta_p^2 = 0.232$, were significant. This three-way interaction was due to a differential modulation of masked semantic priming (faster reactions in semantically related than in unrelated trials) by the task set depending on the trial type (see Fig. 2): For induction task trials, priming was numerically larger for the semantic (16 ms) than for the perceptual task (8 ms). In fact, Newman-Keuls post-hoc tests revealed significant priming only following the semantic (p = .011), but not following the perceptual task (p = .18). For task cue-only trials, the reversed pattern was found: Priming was numerically larger following the perceptual task cue (28 ms) than following the semantic task cue (15 ms), although priming effects were significant in both conditions according to Newman-Keuls tests (all ps < .014). Paired one-tailed t-tests on priming scores (RT difference unrelated - related) were applied to further confirm the reversed pattern of priming effects as a function of task sets (perceptual vs. semantic) following induction task and task cue-only trials. This analysis yielded only a marginal significant difference in the priming scores between perceptual and semantic task sets for task cue-only trials, $t(21) = 1.62$, p = .055, d = 0.35. For induction task trials, the difference in priming scores was far from being significant, $t(21) = -1.14$, p = .13, d = 0.25.

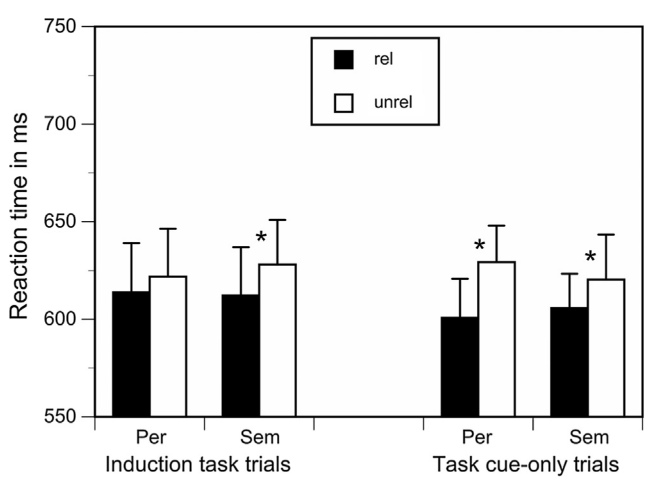

Fig. 2. Experiment 1 (masked letter task cues). Lexical decision mean latencies as a function of semantic relatedness (related vs. unrelated), trial type (induction task vs. task cue-only), and task set (perceptual vs. semantic task set). In this and the next figure, the vertical lines depict the upper 95% confidence interval of the mean of each condition. The asterisks indicate significant priming effects (p < .05). Rel: semantically related prime target pairs; unrel: semantically unrelated prime target pairs. Per: Perceptual task set; Sem: Semantic task set.

As indicated by the two-way interaction trial type and semantic relatedness, priming was overall larger in task cue-only than in induction task trials, but this difference was most pronounced for the perceptual task set. An equivalent ANOVA performed on ER only revealed a significant effect of semantic relatedness with lower ER for semantically related (2.2%) than for semantically unrelated trials (5.8%), $F(1, 21) = 33.21$, $p < .0001$, $\eta_p^2 = 0.613$. Other effects were not significant (all *F*s < 1.5, all ps > .23). Analyses of sequence effects on RT including the factors task set repetition and trial type repetition are provided in the Supplementary Material, analyses 2 and 3. These analyses indicated that the pattern of priming effects was not moderated by these aspects of trial order.

2.3. Discussion

Performing a perceptual vs. semantic induction task modulated subsequent masked semantic priming as expected and in congruency with earlier findings (Kiefer & Martens, 2010; Martens et al., 2011; Ulrich et al., 2014): Significant priming was only observed following semantic induction, whereas priming was attenuated following perceptual induction. Unlike most earlier studies, in which the induction task conditions were blocked, this experiment replicates previous results using randomized presentations of induction tasks. In line with a most recent study (Kiefer, 2018), this shows that attentional tasks sets modulate subliminal semantic priming also on a trial-by-trial basis suggesting a rapid re-configuration of unconscious processing streams by task sets: A semantic induction task sensitizes semantic pathways leading to a larger magnitude of subsequent priming than the perceptual induction task, which desensitizes semantic pathways. In comparison to earlier experiments, the magnitude of masked semantic priming was relatively small in the semantic induction task condition. Furthermore, the difference in the magnitude of priming between induction task conditions was not significant. Possibly, the randomized presentation of the different induction task trials in combination with the task cue-only trials, in which participants had to focus on the lexical decisions, absorbed cognitive resources, thereby reducing the magnitude of masked priming. In line with this interpretation, there is convergent evidence that the magnitude of unconscious priming depends on attentional allocation and on the availability of cognitive resources (Kentridge, Heywood, & Weiskrantz, 1999; Kiefer & Brendel, 2006; Kiefer & Martens, 2010; Martens & Kiefer, 2009; Naccache et al., 2002).

Although the mere presentation of masked task cues modulated the magnitude of priming, task sets modulated masked semantic priming differentially compared with induction task trials, contrary to our initial predictions, as shown by the triple interaction between trial type, task set and semantic relatedness. Unlike in induction task trials, priming was larger following a perceptual task cue compared with a semantic task cue, although a formal test of the difference in the magnitude of priming as a function of task set in task cue-only trials only yielded a marginally significant difference.

These reversed effects of task sets on priming in task-cue compared with induction task trial resemble earlier observations of induction task effects, when the interval between the response in the induction task and the onset of the prime (RPI) was 800 ms and larger (Kiefer & Martens, 2010; Kiesel et al., 2010; Martens & Kiefer, 2009; Martens et al., 2011). Similar to the present experiment in the task cue-only condition, at long RPIs priming was larger after perceptual induction than after semantic induction. With regard to the differential effect of induction task as a function of RPIs the task set might be inhibited after task completion (Kiefer & Martens, 2010; Kiesel et al., 2010; Martens & Kiefer, 2009; Martens et al., 2011) in preparation for an upcoming new task (here: the LDT). One may therefore similarly explain the reversed masked task cue effects on semantic priming on the grounds of task set inhibition: It is possible that the task sets triggered by masked task cues are rapidly inhibited after about 100 ms, because participants were not required to perform the induction task, but prepared for the upcoming lexical decision. One may assume that both the preceding task set associated with the task cue and the new task set, which supports the LDT, occur concurrently and might jointly influence sensitization of semantic processing. As the LDT partially depends on semantic processing (Yap, Balota, Cortese, & Watson, 2006), the task set of the LDT increases the sensitivity of semantic pathways to some extent. Following a perceptual task cue, both the suppression of the perceptual task set and the activation of the task set for the upcoming LDT may conjointly increase the sensitivity of semantic pathways, thereby enhancing masked semantic priming (Kiefer & Martens, 2010; Martens et al., 2011). Following the semantic task cue, however, the semantic task set is suppressed, resulting in a desensitization of semantic pathways. The activation of the task set for the LDT may increase the sensitivity of semantic pathways to some extent, but the conflicting desensitizing influence of the suppressed semantic task set might have produced a net decrease of the sensitivity of semantic pathways compared with the perceptual task cue condition.

Masked semantic priming was numerically enhanced in task cue-only trials after the perceptual cue (29 ms) compared with any other condition. In particular, the increase of the priming effect in relation to trials with a perceptual induction task (8 ms) was striking. Several factors most likely have boosted the magnitude of priming after the perceptual cue, even compared with the semantic induction task condition (16 ms): In addition to a sensitization of semantic processing pathways, as discussed above, the lack of performing a demanding task just prior to masked prime presentation might have provided more cognitive resources for masked prime processing and might have enhanced priming in relation to the semantic induction task condition (see also the discussion above, Martens & Kiefer, 2009). However, the general difference in magnitude of priming between induction task and task cue-only trials cannot be unequivocally interpreted because the interval between the task cue and the primed lexical decision target was much shorter in task cue-only trials.

Results of the masked task cue visibility test indicated that masking of the task cues was not perfect and allowed some slight above chance visual discrimination performance. However, correlation analyses did not reveal an association between task cue visibility and the magnitude of priming. As the task cue visibility test only indexes that task cues (single letters A or B) could be discriminated from letter strings to some extent, participants might not be aware of the identity of the letters. Furthermore, all participants reported to be subjectively unaware of the masked task cues presented in the main experiment in the post-experimental debriefing. Hence, although masked task cues appeared to be marginally perceptible, it is unlikely that the observed effects in the main experiment were driven by conscious task cue perception.

In conclusion, the present experiment showed that the mere presentation of masked task cues associated with task sets had reversed effects on subsequent priming compared with the condition, in which an induction task had actually to be performed following the cues. One possibility to explain these differential effects on priming for induction task vs. task cue only trials is the assumption that task sets triggered by briefly presented and largely unconsciously perceived masked task cues are rapidly inhibited within a few hundred milliseconds in preparation for the upcoming LDT. However, task sets triggered by visible task cues might be activated for a longer period of time.

3. Experiment 2

In this second experiment, we tested the possibility that the reversed pattern of priming effects as a function of perceptual and semantic task cues was due to rapid task set suppression, when task cues were masked and largely unconsciously presented. As task sets triggered by visible task cues might be activated for a longer period of time, task cues were presented in this new experiment visibly with the same stimulus duration (750 ms) as in induction task trials. Duration of the cue in task cue-only trials had to be kept comparable to induction task trials so that participants could not recognize the trial type right from the beginning of the trial. If masking the task cue in task cue-only trials had led to rapid task set inhibition in experiment 1, presenting the task cue visibly in experiment 2 should result in maintained task set activation and in an attentional sensitization of semantic pathways similar to performed induction tasks. As a consequence, the pattern of priming effects subsequent to perceptual and semantic task cues should be comparable to induction task trials.

At this place, it is important to distinguish between indirect influences of task sets on priming based on attentional sensitization and more direct effects based on task set application: Although less likely with masked task cues, presentation of visible task cues without a following induction task might lead to a misapplication of the associated task set to the lexical decision target or even to the masked prime (Ansorge et al., 2014; Heider, Spruyt, & De Houwer, 2017). Consider the situation, in which the “living” response of the semantic induction task and the “word” response of the LDT are constantly mapped on the same finger. Misapplication of the task set indicated by the task cue might then lead to a faster word response in the LDT, when the lexical decision target denoted a living compared to a nonliving object. Furthermore, it is also conceivable that misapplication of the semantic task set of the induction task to the lexical decision target or masked prime might interfere with processing of the semantic relationship between prime and target, thereby reducing the magnitude of priming. The perceptual task set might be semantically more neutral because it refers to the visual appearance of objects and not to the meaning of words (for a discussion, also see Kiefer et al., 2017). Please note that due to the large number of prime-target words required in this sort of experiments a balancing of the semantic properties of these words with regard to the living/non-living or round/elongated dimensions was impossible. We therefore systematically varied in experiment 2 the assignments of responses to the different decision categories for the induction tasks. By comparing lexical decision latencies and priming effects under different response assignment conditions, we can identify effects of task set misapplications: If task set misapplication had influenced the results in the task cue-only trials, lexical decision latencies and/or pattern of priming effects should differ across the different response assignment conditions.

3.1. Methods

3.1.1. Participants

Thirty-one healthy, right-handed (Oldfield, 1971), native German speakers with normal or corrected-to-normal vision contributed data to this experiment. The data of seven participants had to be excluded from analysis, four due to a high error rate in the induction and the lexical decision tasks (individual mean ER 2 SD above the sample mean) and three because their identification rate exceeded the confidence interval of chance performance in the masked prime identification test (more than 61% correct responses). The remaining twenty-four participants (12 men and 12 women) were in the age range of 19–29 years, with a mean of 22.8 years.

3.1.2. Material and procedure

The stimulus sets for induction tasks, primes and targets and the timing of events were identical to experiment 1 with a few modifications: The duration of the task cue in task cue-only trials was set to 750 ms as in induction task trials, and the masks before and after the task cues were removed (Fig. 1B). Furthermore, in order to control for misapplication of the task set of the induction tasks, we created two versions A and B with different assignments of the responses to the decision categories of the induction tasks. Half of the participants received version A, the other half version B. In version A, participants responded to "round" (perceptual induction task) and "living" (semantic induction task) with the index finger, whereas they responded to "elongated" (perceptual induction task) and non-living (semantic induction task) with the middle finger. In version B, response assignments to the decision categories in the induction tasks were reversed. In the LDT, participants responded as in experiment 1 with the index finger to words and with the middle finger to pseudowords in all versions. This allowed us to record RTs to words uniformly with the strongest finger to obtain reliable RT measurements.

3.2. Results

3.2.1. Masked prime visibility test

According to two-tailed one group tests on d′ measures (for details see experiment 1), performance did not significantly deviate from chance level (d′ = 0) in all combinations of semantic relatedness and task cue type conditions (all d′s < 0.18, all $ts(23) < 1.81$, all ps $>$ .08, all ds < 0.36), except the semantically related condition after the semantic task cue, d′ = 0.23, $t(23) = 2.55$, p = .02, d = 0.52. A repeated measures ANOVA on d′ measures with the within-subject factors semantic relatedness and task cue type yielded a significant main effect of semantic relatedness, $F(1, 23) = 12.78$, $p = .0016$, $\eta_p^2 = 0.357$, while the main effect of task cue type and the interaction between both factors were not significant (all $Fs < 0.90$, all $p > .35$). Hence, although prime visibility was comparable after perceptual (d′ = 0.05) and semantic task cues (d′ = 0.15), the possibility that backward priming rendered the masked prime words partially recognizable could not be entirely excluded: d′ was larger for semantically related (d′ = 0.21) than for unrelated primes (d′ = −0.01). In order to assess whether residual prime visibility had influenced the magnitude of priming, we performed correlation analyses relating d′ measures of masked prime visibility to the magnitude of priming, separately for the different conditions. As none of the correlations were significant (all $|r| < 0.45$, all ps $>$ .13), it is unlikely that potential residual prime visibility had influenced the pattern of priming effects.

3.2.2. Induction tasks

Analysis of the data of the induction task was identical to experiment 1 (4.1% outliers). Two-tailed dependent t-tests showed that RT in the perceptual induction task was significantly shorter compared to RT in the semantic induction task, 682 vs. 737 ms, $t(23) = -5.04$, $p < 0.001$, d = 1.03. An analysis of sequence effects including the factors task set repetition and trial type repetition revealed no task set repetition costs. Task switch costs were found only for trial type repetition trials (see Supplementary Material, analyses 1). An analogue analysis of ER did not yield significant differences (perceptual: 2.6%, semantic: 2.8%), $t(23) = -0.39$, p = .70, d = 0.08.

3.2.3. Masked priming

RT data of the masked priming task were trimmed and analyzed as in experiment 1 (outliers 4.1%). A repeated measures ANOVA with the within-subject factors trial type, task set and semantic relatedness and the between-subject factor response assignment (version A and B) was performed on mean RT as dependent variable. This analysis yielded main effects of the factors trial type, $F(1, 22) = 10.31$, $p = .004$, $\eta_p^2 = 0.319$, and semantic relatedness, $F(1, 22) = 126.88$, $p < .0001$, $\eta_p^2 = 0.852$. Response times were faster in task cue-only trials than in induction task trials as well as in semantically related than in semantically unrelated trials (semantic priming effect). The two-way

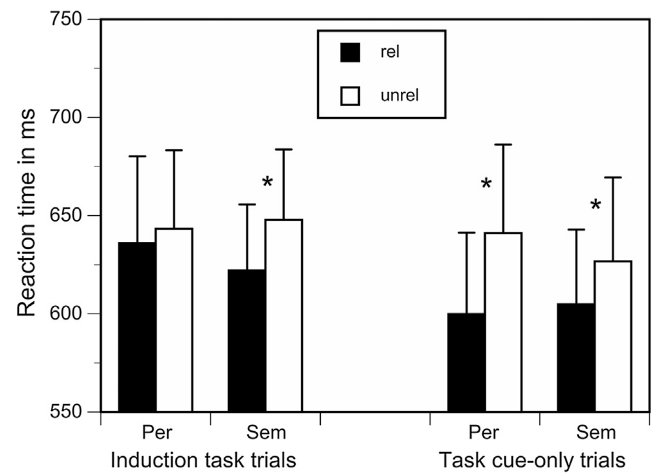

Fig. 3. Experiment 2 (visible letter task cues). Lexical decision mean latencies as a function of semantic relatedness (related vs. unrelated), trial type (induction task vs. task cue-only), and task set (perceptual vs. semantic task set). The asterisks indicate significant priming effects ($p < .05$). Rel: semantically related prime target pairs; unrel: semantically unrelated prime target pairs. Per: Perceptual task set; Sem: Semantic task set.

interaction between trial type and semantic relatedness indicated a larger priming effect in task cue-only trials compared to induction task trials. Most importantly, the three-way interaction between trial type, task set and semantic relatedness was significant, $F(1, 22) = 7.55$, $p = .012$, $\eta_p^2 = 0.256$. As in experiment 1, the effects of task sets on semantic priming differed between induction task and task cue-only trials (Fig. 3). In induction task trials, priming was numerically larger following semantic (26 ms) than following perceptual induction (7 ms). Newman-Keuls post-hoc tests yielded significant priming only subsequent to semantic (p = .012), but not subsequently to perceptual induction (p = .53). In task cue trials, the pattern of priming was reversed compared to trials with induction tasks, similar to experiment 1: Priming was numerically larger following a perceptual (41 ms) than following a semantic task cue (21 ms), although post-hoc tests yielded significant priming in either condition (all ps $< .011$). Paired one-tailed t-tests on priming scores (RT difference unrelated - related) were applied to further confirm the reversed pattern of priming effects as a function of task sets (perceptual vs. semantic) following induction task and task cue-only trials. This analysis yielded significant differences in priming scores between perceptual and semantic task sets for both induction task, $t(23) = -2.52$, p = .01, d = 0.51, and task cue-only trials, $t(23) = 1.85$, p = 038, d = 0.37.

The quadruple interaction including the factor version, $F(1, 22) = 0.34$, $p = .57$, $\eta_p^2 = 0.015$ was not significant. Hence, as also shown in Supplementary Fig. 1, the pattern of priming effects was numerically comparable across the different response assignments (versions A and B). When performing an identical ANOVA on ER, only the main effect of semantic relatedness was significant, $F(1, 22) = 31.07$, $p < .0001$, $\eta_p^2 = 0.585$: ER was lower for related (2.0%) than for unrelated trials (4.1%). All other effects were not significant (all $Fs < 3.5$, all ps $> .07$). In particular, the factor version did not reliably influence ER (all $Fs < 1.8$, all ps $> .19$). Analyses of sequence effects including the factors task set repetition and trial type repetition did not yield signs for a modulation of the pattern of priming effects by these aspects of trial order (Supplementary Material, analyses 2 and 3).

3.3. Discussion

Experiment 2 aimed to assess, whether task sets triggered by clearly visible task cues would modulate subsequent masked semantic priming via attentional sensitization similarly to actually performed induction tasks. We tested the assumption that the reversed pattern of priming effects following masked task cues compared to induction tasks observed in experiment 1 might reflect rapid task set inhibition (Kiefer & Martens, 2010; Kiesel et al., 2010), when the task set is activated by an unconscious task cue. Task set inhibition should lead to a desensitization of the corresponding processing pathways, resulting in a reversed pattern of priming effects compared with induction task trials (for more details, see the discussion of experiment 1). We hypothesized that presentation of visible task cues might result in more sustained task set activation and, as a consequence, in a temporally extended sensitization of semantic pathways in task cue-only trials. Furthermore, in order to control for possible influences of task set misapplication, response assignments in the induction tasks were varied.

The results of experiment 2 were clear-cut and replicated the results of experiment 1: We observed with visible task cues in task cue-only trials a pattern of priming effects, which was reversed compared to induction task trials. In induction task trials, in support of the notion of a sensitization of semantic pathways by a semantic task set, priming was larger following the semantic induction task than following the perceptual induction task. In task cue-only trials, however, priming was larger subsequent to a perceptual task cue than subsequent to a semantic task cue. Similar to experiment 1, priming was numerically largest subsequent to a perceptual task cue compared to any other condition, presumably due to the conjoint influences of increased sensitization of semantic pathways and availability of more cognitive resources than in induction task trials (for details, see the discussion of experiment 1). Response assignment in the induction tasks did not significantly influence neither overall RT/ER nor the pattern of priming effects. As a caveat, it should be noted that response assignment was varied between-subjects with only 12 participants in each group. The present design was therefore not particular sensitive to detect the critical four-way interaction including the between-subject factor response assignment. In fact, post-hoc power calculations with Gpower (Erdfelder, Faul, & Buchner, 1996) indicated that for n = 12 per group only large effects (dz = 0.9) can be detected with a reasonable power (beta = 0.7). However, as the pattern of priming effects was also numerically comparable for both response assignment groups (see Supplementary Fig. 1), the non-significant four-way interaction does not simply reflect a lack of statistical power to yield this effect. It is therefore very unlikely that task set misapplication systematically affected priming and was the relevant factor for the reversed pattern of priming effects in task cue-only trials.

In conclusion, experiment 2 with visible task cues fully replicated the results of experiment 1, in which task cues were presented masked in task cue-only trials. There were also no signs for a moderation of the effects by the factor response assignment. Hence, neither visibility of the task cues nor task set misapplication appear to be the relevant factors underlying the reversed pattern of masked semantic priming effects in task cue-only trials. However, it is conceivable that unknown connotations of the task cue letters could be the driving factor for the task cue effects in task cue-only trials: The letters A and B used in experiments 1 and 2 as task cues could have activated preexisting verbal associations, which act as mindsets (Spruyt et al., 2009). It is therefore possible that in task cue-only trials mindsets induced by connotations of the letters, but not the experimentally associated task sets had influenced priming effects. Furthermore, task cue letters could be associated with the induction tasks in general and some of the response categories in particular. The letter A, which was used to signal the perceptual induction task, could be easily associated with the task instruction to decide about the “Aussehen” (Engl. “appearance”) of the inducing objects. The letter B, which was used to signal the semantic induction task, could be readily linked with the task instruction to decide about “Bedeutung” (Engl. “meaning”) of the objects. Furthermore, this letter could be linked to the response category “belebt” (Engl. “living) of the semantic induction task. We tested the influence of these cue-related variables in experiment 3 with non-verbal color task cues.

4. Experiment 3

If the task cue effects on priming in the task cue-only trials of experiment 1 (masked cue) and experiment 2 (visible cue) had its origin in verbal associations activated by the task cue letters, this potential mechanism underlying task cue effects can be avoided, when semantically neutral non-verbal task cues such as colored squares are presented. Task cue effects with non-verbal task cues should be exclusively based on experimentally associated task sets. In the third experiment, the task cues indicating the semantic and perceptual task set were therefore presented as squares colored with a blue and red hue, respectively. This experiment allowed us to test, whether presentation of non-verbal color task cues would lead to a priming pattern in task cue-only trials similar to induction task trials. As piloting work indicated that masking the colored squares did not reliably suppress cue awareness, color task cues were presented visibly as in experiment 2.

A very recent task switching study (Jost et al., 2017) indicated that dominant task sets with strong stimulus-response bindings (left and right stimulus locations were mapped to left and right hand responses) received stronger inhibition, when the task had been abandoned, compared with weaker task sets based upon arbitrary mappings (e. g, left-hand button press mapped to a red stimulus). Similarly to the dominant task with strong stimulus-response bindings in the Jost et al. (2017) study, there were associations between the task cue letters and elements of the induction tasks (high cue-task compatibility) in the previous two experiments (see the discussion of experiment 2). It is therefore conceivable that in situations with high cue-task compatibility corresponding task sets are rapidly activated, but also rapidly inhibited in preparation of the upcoming LDT.

In the present experiment, we therefore tested the hypothesis that the pattern of priming effects in task cue-only trials, which was reversed compared to induction task trials in the previous experiments, were moderated by task set dominance. In order to create experimental versions with dominant and weaker task sets of the induction task, we varied assignments of the colored squares to the perceptual vs. semantic task cue conditions and response assignments of the induction tasks in order to manipulate cue-task compatibility in experiment 3. In the version with dominant task sets (high cue-task compatibility), the red square indicated the perceptual induction task, the blue square the semantic induction task. The decision categories “round” (German: rund) of the perceptual induction task and “living” (German: belebt) of the semantic induction task were mapped on the index finger, the decision categories “elongated” (German: länglich) of the perceptual induction task and non-living (German: unbelebt) were mapped on the middle finger. In the version with weaker task sets (low cue-task compatibility), task cue assignment was reversed. As a consequence of these assignments, in the dominant version the color words of the task cues and the words for the decision categories mapped on the index finger shared the same initial letter for our German speaking participants: task cue “*r*ot” (English: red) – decision category “*r*und”, task cue “*b*lau” (English: blue) – decision category “*b*elebt”. In the weaker version, there was no correspondence between the initial letters of the color words and of the words referring to the decision categories.

We assumed that in the dominant version participants could use the correspondence of initial letters of the words denoting the task cue color and the decision categories mapped on the salient index finger to create strong links between elements of the task sets. In the weaker version, it was harder to form links between the elements of the task sets. Unlike in the earlier Jost et al. study (2017), in which more dominant and weaker task sets were directly contrasted, the differential relation between the properties of the induction task and those of the subsequent LDT must be considered within our paradigm. In the LDT, the relation between all elements of the task set (stimulus features, decision and response categories) was arbitrary and remained constant in both conditions. However, high cue-task compatibility in the induction task should yield more dominant task sets (i.e. high activation strength) in relation to the LDT, whereas low cue-task compatibility should result in task sets with presumably similar lower activation strength as the task set of the LDT. The latter condition is therefore termed as 'weaker task set' condition. In task cue-only trials, dominant task sets of the induction tasks might be rapidly suppressed in preparation of the upcoming LDT. As a consequence, the task sets are already inhibited at the time point of masked prime presentation leading to a reversed pattern of priming effects compared with induction task trials. Activation and inhibition of weaker task sets, in contrast, might take longer so that task sets are still activated at the time point of masked prime presentation.

4.1. Methods

4.1.1. Participants

Thirty healthy, right-handed (Oldfield, 1971), native German speakers with normal or corrected-to-normal vision participated. All participants were tested for intact color vision with the Ishihara color tables (Velhagen & Broschmann, 1997). The data of six participants had to be excluded from analysis: Data of four participants due to exceptionally slow reactions in the induction and the lexical decision tasks (individual mean RT 2 SD above the sample mean) and data of two further participants due to an identification rate exceeding the 95% confidence interval of chance performance in the masked prime identification test (61% correct). The remaining twenty-four participants (12 men and 12 women) were in the age range of 19–32 years, with a mean of 23.9 years.

4.1.2. Material and procedure

The stimulus sets for primes and targets, the timing of all events were identical to experiment 2, with the exception that squares colored in red and blue hues, respectively, served as task cues (Fig. 1C). The squares had a size of 2 × 2 cm (57 × 57 pixels) and were colored either in red (red: 176, yellow: 16, blue: 32) or in blue hue (red: 48, yellow: 40, blue: 216). Colors were adjusted such that luminance of the red (12.4 Cd/m^2) and blue squares (12.6 Cd/m^2) was equated. We created two versions A and B with dominant and weaker task sets of the induction task sets, respectively, by varying task cue assignment and response assignment. In version A, the red square was the task cue for the perceptual induction task, whereas the blue square was the task cue for the semantic induction task. The decision categories round (German: "rund") and living (German: "belebt") were assigned to the index finger, the decision categories elongated (German: "länglich") and nonliving (German: "unbelebt") were assigned to the middle finger. Hence, in version A the first letters of the words denoting the task cue colors (red, German "*r*ot"; blue, German "*b*lau") and the words denoting the decision categories mapped to the index finger were identical. Due to these links between task elements, the task sets in this version were therefore considered to be dominant. In version B, the assignment of the task cue colors to the different induction tasks and the response assignments were reversed. In this version, there were no links between the elements of the task sets. Task sets in version B were therefore considered to be weak. Half of participants received version A and the other half version B in a counterbalanced fashion.

4.2. Results

4.2.1. Masked prime visibility test

Two-tailed one group tests on d′ measures of prime visibility (for details see experiment 1) for the different combinations of task cue type and semantic relatedness conditions did not yield significant differences from zero (all d′s < 0.19, all *t*s < 1.9, all *p*s > .07, all ds < 0.39). A repeated measures ANOVA on d′ measures with the within-subject factors semantic relatedness and task cue type as well as the between-subject factor task set dominance (version A: dominant task set; version B: weak task set) also did not reveal significant main effects or interactions, all *F*s < 0.41, all *p*s > .53, all $\eta_p 2s < 0.03$. This indicates that primes were clearly invisible in all experimental conditions. Furthermore, correlation analyses relating d′ measures of masked prime visibility to the magnitude of priming, separately for the different conditions, did not reveal significant correlations (all |r| < 0.46, all ps > .13). It is therefore unlikely that potential residual prime visibility had influenced the pattern of priming effects.

4.2.2. Induction tasks

Trimming of the data of the induction task was identical to the previous experiments (4.8% outliers). A repeated measures ANOVA with the within-subject factor induction task (perceptual vs. semantic) and the between-subject factor task set dominance on mean correct RT revealed a main effect of induction task, $F(1, 22) = 12.67$, $p = .002$, $\eta_p^2 = 0.365$: Reactions were significantly faster in the perceptual (670 ms) than in the semantic (720 ms) induction task. Effects involving the factor task set dominance were not significant ($F < 0.1$, $p > .82$ all $\eta_p^2s < 0.001$). An analysis of sequence effects including the factors task set repetition and trial type repetition revealed no task set repetition costs. Task switch costs were found only for trial type repetition trials (see Supplementary Material, analyses 1). A corresponding ANOVA on ER did not yield any significant effects ($F < 1$, $p > .40$, all $\eta_p^2s < 0.04$). ER in the perceptual (1.52%) and semantic (1.75%) induction tasks was comparable.

4.2.3. Masked priming

RT data of the masked priming task were trimmed and analyzed as in the previous experiments (outliers 3.9%). A repeated measures ANOVA with the within-subject factors trial type, task set and semantic relatedness and the between-subject factor task set dominance was performed on mean RT as dependent variable. This analysis yielded main effects of the factors trial type, $F(1, 22) = 8.33$, $p = .009$, $\eta_p^2 = 0.274$, and semantic relatedness, $F(1, 22) = 70.81$, $p < .0001$, $\eta_p^2 = 0.763$ (Fig. 4). Lexical decisions in task cue-only trials were faster than in induction task trials. There was also a semantic priming effect with shorter RT in semantically related trials than in semantically unrelated trials. The four-way interaction between all factors was also significant, $F(1, 22) = 5.51$, $p = .028$, $\eta_p^2 = 0.200$: As expected, the modulation of semantic priming by task sets in induction task and task cue-only trials differed between versions with stronger and weaker task sets (versions A and B). Neuman-Keuls post hoc tests assessing mean differences for the four-way interaction revealed for induction task trials in both versions significant priming only following semantic induction (all ps < .02), but not following perceptual induction (all ps > .32), thus replicating induction task effects on semantic priming observed in this and earlier studies. In task cue-only trials, however, the pattern of priming effects was reversed in versions with dominant and weak task sets, respectively. In the version with dominant task sets, we found significant priming following a perceptual task cue ($p = .008$), but not following a semantic task cue ($p = .19$). In the version with weaker task sets, we observed significant priming following a semantic task cue ($p = .02$), but not following a perceptual task cue ($p = .58$).

In order to further explore the four-way interaction, we calculated separate ANOVAs for the versions with dominant and weaker task sets with the within-subject factors trial type, task set and semantic relatedness. In the version with dominant task sets, besides the main effect of semantic relatedness, $F(1, 11) = 57.49$, $p < .0001$, $\eta_p^2 = 0.839$, the three-way interaction between trial type, task set and semantic relatedness was significant, $F(1, 11) = 10.47$, $p = .008$, $\eta_p^2 = 0.488$ (Fig. 4A). Comparable to the previous experiments, task sets differentially modulated semantic priming subsequently to induction task and task cue-only trials. In induction task trials, priming was numerically larger subsequently to semantic (50 ms) than subsequently to perceptual induction (15 ms). Newman-Keuls post-hoc tests revealed significant priming only following the semantic induction task ($p = .0006$), but not following the perceptual induction task ($p = .29$).

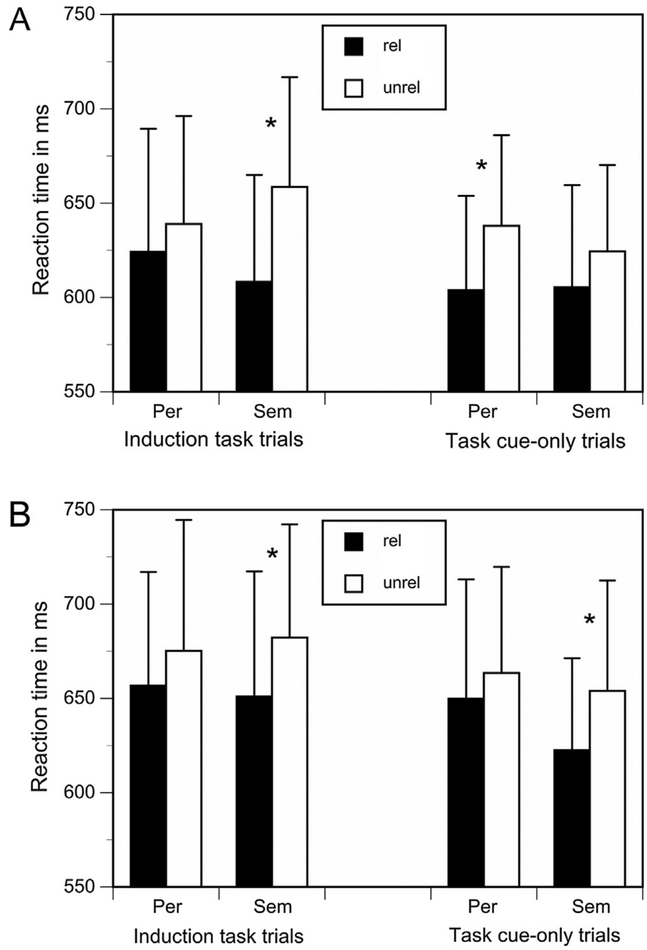

Fig. 4. Experiment 3 (visible color task cues). Lexical decision mean latencies as a function of semantic relatedness (related vs. unrelated), trial type (induction task vs. task cue-only), and task set (perceptual vs. semantic task set). (A) Results for the version with dominant task sets of the induction task. (B) Results for the version with weak task sets of the induction task. The asterisks indicate significant priming effects ($p < .05$). Rel: semantically related prime target pairs; unrel: semantically unrelated prime target pairs. Per: Perceptual task set; Sem: Semantic task set.

In task cue-only trials, the reversed pattern was found: Priming was larger following a perceptual (34 ms) than following a semantic task cue (19 ms). According to post-hoc tests, priming was only significant following the perceptual ($p = .011$), but not following the semantic task cue ($p = .12$).

In a comparable analysis for the version with weaker task sets, the main effects of trial type, $F(1, 11) = 4.845$, $p = .049$, $\eta_p^2 = 0.306$, and semantic relatedness, $F(1, 11) = 22.59$, $p = .0006$, $\eta_p^2 = 0.672$, as well as the two-way interaction between trial type and task set were significant, $F(1, 11) = 5.15$, $p = .044$, $\eta_p^2 = 0.319$ (Fig. 4B). Unlike in the version with dominant task sets, with weaker task sets the three-way interaction was far from being statistically reliable, $F(1, 11) = 0.08$, $p = .78$, $\eta_p^2 = 0.007$, whereas the two-way interaction between task set and semantic relatedness approached significance, $F(1, 11) = 3.97$, $p = .071$, $\eta_p^2 = 0.265$. Priming was numerically larger following a semantic task set (31 ms) than following a perceptual task set (16 ms). This difference in priming scores (RT difference unrelated - related) as a function of task set (pooled across trial types) was significant in a one-tailed paired *t*-test, $t(11) = 1.99$, $p = .036$, $d = 0.699$. Task set differences in priming were comparable for induction task (perceptual: 18 ms; semantic: 31 ms) and task cue-only trials (perceptual 14 ms; semantic: 31 ms), as already revealed by the post-hoc tests for the four-way interaction reported above. Hence, in the version with weaker task sets induction tasks and task cues similarly modulated subsequent priming. However, more fine grained comparisons with paired one-tailed t-tests on priming scores yielded a significant difference in the priming scores between perceptual and semantic task sets only for induction task trials of the dominant task set condition, $t(11) = -2.46$, $p = .016$, $d = 0.72$, but not for any other combination of conditions, all $t(11) < 1.4$, all $p > 09$, all $d < 0.39$.

For the ER data, we also performed a repeated measures ANOVA with the within-subject factors trial type, task set and semantic relatedness and the between-subject factor task set dominance (versions A and B). We observed a main effect of semantic relatedness, $F(1, 22) = 39.88$, $p < .0001$, $\eta_p^2 = 0.644$, indicting lower ER for semantically related trials (1.8%) than for unrelated trials (3.8%). There was also a significant interaction between trial type and task set dominance, $F(1, 22) = 9.52$, $p = .005$, $\eta_p^2 = 0.302$, but post-hoc tests did not reveal reliable differences between conditions ($p > .08$). Numerically, with dominant task sets ER was larger in induction task trials (3.4%) than in task cue-only trials (2.2%), whereas with weaker task sets ER was larger in task cue-only trials (3.5%) than in induction task trials (2.2%). Other main effects or interactions were not significant (all *F*s < 2.62, $p > .12$, $\eta_p^2 < 0.106$). Analyses of sequence effects including the factors task set repetition and trial type repetition did not yield signs for a modulation of the pattern of priming effects by these aspects of trial order (Supplementary Material, analyses 2 and 3).

4.3. Discussion

In experiment 3, it was assessed whether the differential effects of task cues vs. induction tasks on masked semantic priming observed in the previous experiments (i) were due to some unknown semantic connotations associated with the task cue letters and (ii) were moderated by task set dominance. In order to exclude the influence of semantic connotations associated with letters, we used non-verbal colored squares as task cues in the present experiment. Furthermore, we created two experimental versions with more dominant and weaker task sets of the induction tasks. As hypothesized, task set dominance moderated the pattern of priming effects in the task cue-only trials. With dominant task sets (version A), we replicated with color task cues the differential pattern of priming effects in induction task vs. task cue-only trials as observed in experiments 1 and 2. In induction task trials, priming was larger following semantic induction than following perceptual induction, in line with the induction task effects on priming found in the present and earlier studies (e.g., Kiefer & Martens, 2010; Martens et al., 2011). In task cue-only trials, priming was larger following a perceptual task cue than following a semantic task cue as in experiments 1 and 2. Results of version A with the dominant task sets of the induction tasks indicate that the previously observed task cue effects with letters generalize to non-verbal task cues and renders the possibility unlikely that semantic connotations of the task cues drove the task cue effects.

With weaker task sets (version B), however, the pattern of priming effects in task cue-only trials differed from that with dominant task sets and was comparable to induction task trials. Following semantic induction or following a semantic task cue, priming was larger than following perceptual induction or following a perceptual task cue. Hence, the reversed pattern of priming effects in task cue-only trials compared with induction task trials was confined to dominant task sets. The present findings are in line with the previous observation that dominant task sets receive stronger inhibition than weaker task sets in preparation for an upcoming task (Jost et al., 2017). In task cue-only trials, in which the task set of the induction task had to be suppressed in preparation for the upcoming LDT, the dominant task sets of version A were already inhibited at the time point of masked prime presentation. In version B, activation and inhibition of the weaker task sets took longer so that task sets were still activated at the time point of masked prime presentation. In line with this interpretation, participants performing version B with the weaker task sets tended to react generally slower in the LDT than those presented with the more dominant task sets of version A. Furthermore, in the version with weaker task sets participants tended to respond more erroneously in the LDT following task cue-only trials than following induction task trials, whereas a tendency towards an opposite error pattern was observed for more dominant task sets. Although not significant, this indicates that in the version with weaker task sets it was more demanding to switch to the LDT, possibly due to delayed activation and subsequent inhibition of the task set of the induction task. Finally, in line with the notion of stronger task set suppression for dominant task sets in preparation for the upcoming lexical decision task (Jost et al., 2017), task set switch costs were only found for weak task sets, but were absent for dominant task sets (see Supplementary Material). As in the Jost et al. (2017) study, we did not administer a formal manipulation check for the effectiveness of the task set dominance manipulation. However, the observed effects of task set dominance on RTs in the induction tasks and in the LDT discussed above indicate that our manipulation of task set dominance by varying cue-task compatibility was successful.

It should be noted that task set dominance was manipulated between subjects with only 12 participants per group yielding low statistical power. Nevertheless, the quadruple interaction including the between-subject factor task set dominance was significant. Furthermore, we replicated the theoretically relevant three-way interaction in the group with dominant task sets. Both significant effects indicate that the design was sensitive enough to detect differences in priming effects between induction task and task cue-only trials despite the small sample size. However, the lack of significant differences between task set conditions (perceptual vs. semantic) for the comparisons within each trial type conditions (induction task, task cue-only) separately for each task set dominance groups might be due to low statistical power because of the small sample size within each experimental group.

Variation of task set dominance across versions A and B only altered the pattern of priming effects in the task cue-only trials, but not in the induction task trials. Of course, stronger suppression of dominant task sets compared with weaker task sets should also be observed in induction task trials. However, in induction task trials suppression should occur in a later time window than realized in the present experiments: In induction task trials, task sets are expected to be suppressed at about 800 ms after the response in the induction task (e.g., Kiefer & Martens, 2010; Martens et al., 2011). In the present study, a much shorter response prime interval (RPI) of 400 ms was used, in which task sets are typically still active (Kiesel et al., 2010). Differential task set suppression effects on subliminal semantic priming as a function of task set dominance should be found only at RPIs of 800 ms and longer (see for instance, Martens & Kiefer, 2009).

Finally, one might expect faster reactions in the induction task for dominant than for weaker task sets due to more efficient task set implementation (Jost et al., 2017). Although mean RT differences were numerically obtained in the expected direction (dominant task set: 689 ms; weak task set 701 ms), this effect was not statistically reliable ($p = .83$). Perhaps, this general effect of task set dominance was overshadowed by other, more complex task switching influences: For instance, when including the factors task set repetition (e.g., perceptual task set in two subsequent trials) and trial type repetition (execution of induction tasks in two subsequent trials) in a further analysis (see Supplementary Material, analyses 1), task set repetition was only associated with shorter RTs than task set switch for weaker task sets. For stronger task sets, task switching did not significantly affect RTs. Hence, in line with the notion of stronger task set suppression for dominant task sets (Jost et al., 2017) in preparation for the upcoming LDT, task set switch costs were only found for weak task sets, but were absent for dominant sets.

However, we did not find significant task set repetition costs, i.e. significantly slower reactions in task set repetition trials than in task set switch trials. It is well possible that the absence of significant task set repetition costs is due to a lack of sensitivity of the present design because this study was not designed to reveal such effects, but focused on masked priming. For instance, in contrast to earlier studies on backward inhibition effects in task switching (Philipp, Jolicoeur, Falkenstein, & Koch, 2007; Schuch & Koch, 2003), the time intervals between the relevant three tasks, induction task 1, LDT, induction task 2 in the next trial ($n - 2$ repetition trial: ABA, $n - 2$ switch trial: CBA) was not constant between all elements of the sequence: The time interval between the LDT and the induction task 2 in the next trial (interval between B and A) was highly variable because initiation of the next trial was self-paced. Furthermore, the number of trials per condition was low (about 20) additionally reducing experimental sensitivity. These differences in the experimental set up might have reduced $n - 2$ backward inhibition effects. Another possibility for the absence of $n - 2$ repetition costs is that, due to the paired presentation of induction task and lexical decision task, task-pair representations were formed (Hirsch, Nolden, & Koch, 2017). The sequence of trials could thus be conceived as task-pair repeats and switches, which reduces $n - 2$ repetition costs.

5. General discussion

In the present study, we elucidated for the first time top-down control of unconscious automatic semantic priming triggered by mere presentation of task cues. In particular, we compared attentional task set influences on masked semantic priming in two conditions: In one condition, the masked prime was presented after executing an induction task which served to activate a corresponding task set (semantic or perceptual). In the other condition, the masked prime was presented after a task cue associated with a semantic or perceptual task set without carrying out the indicated task. To this end, we developed a novel paradigm, in which induction task trials were randomly intermixed with task cue-only trials prior to a primed LDT. The rationale of this approach was that semantic processing of an unconsciously perceived prime word is enhanced or attenuated depending on the semantic or perceptual nature of the task set triggered apriori by the induction task or task cue. Our research was based on the assumption that an activated semantic task set should enhance unconscious semantic priming, whereas an activated perceptual task set should attenuate semantic priming. Across three experiments, we assessed the influence of task cue visibility, type of task cue, response assignments and task set dominance on the masked semantic priming pattern in task cue-only trials.

5.1. Effects of induction task on following masked semantic priming

In induction task trials, task sets modulated masked semantic priming as expected. In congruency with earlier studies (Kiefer & Martens, 2010; Martens et al., 2011; Ulrich et al., 2014) and in support of the attentional sensitization model (Kiefer & Martens, 2010), subliminal semantic priming was larger subsequent to the semantic than subsequent to the perceptual induction task. In fact, reliable priming was only obtained following semantic, but not following perceptual induction. In contrast to previous studies, in which perceptual and semantic induction tasks were performed in separate blocks, in the current work trials with both types of induction tasks were presented intermixed in a randomized order. This shows that attentional task sets re-configure unconscious processing streams also rapidly on a trial-by-trial basis: A semantic induction task sensitizes semantic pathways leading to a larger magnitude of subsequent priming than the perceptual induction task, which desensitizes semantic pathways. Overall, the present results confirm refined theories of automaticity, which propose that unconscious automatic processing is susceptible to attentional control settings (Kiefer & Martens, 2010; Spruyt et al., 2009).

5.2. Effects of task cues on following masked semantic priming

In task cue-only trials, mere presentation of task cues modulated masked semantic priming suggesting that triggered task sets influenced attentional sensitization of unconscious semantic processing. However, contrary to our initial predictions, the pattern of semantic priming as a function of task set was reversed compared with induction task trials in the first two experiments. Whether the task cue was masked and largely invisibly (experiment 1) or whether the cue was clearly visible (experiment 2), priming was consistently larger following a perceptual cue than following a semantic cue. Furthermore, variation of response assignments in the induction tasks of experiment 2 did neither influence general lexical decision latencies nor the pattern of priming effects. This observation renders it unlikely that in task cue-only trials misapplication of the task sets of the induction tasks interfered with priming, resulting in the reversed pattern of priming compared with induction task trials. We therefore assumed that task sets triggered by task cues without an accompanying induction task are rapidly suppressed in preparation for the upcoming LDT. According to this explanation, task set suppression leads to a stronger sensitization of semantic pathways after a perceptual cue, similar to perceptual induction tasks, when the task had been abandoned for more than 800 ms (Kiefer & Martens, 2010).

In line with the notion of task set suppression in response to mere task cue presentation, analyses of RTs in the induction task revealed in all experiments task switch costs (shorter RT in task set repetition compared to task set switch trials) restricted to trial type repetition trials, i.e. to trial sequences with two subsequently performed induction tasks. In trial type switch trials, i.e. when an induction task trial was preceded by a task cue-only trial, task switch costs were absent. The presence of switch costs only for trial type repetition trials could suggest that task sets had some residual activation, when an induction task had been performed in the preceding trial. In contrast, the absence of switch costs in trial type switch trials, i.e. in trials when an induction task was preceded by a task cue-only trial, could indicate that task sets associated with the task cues were successfully suppressed within the preceding trial in preparation of the upcoming LDT (Jost et al., 2017; Kiesel et al., 2010; Koch et al., 2010; Mayr & Keele, 2000). Alternatively, this observation is also compatible with the notion that switch costs depend on response selection and/or execution in the preceding trial: Switch costs have been found to be reduced when task preparation took place in response to a task cue, but response selection and execution was prevented by a no-go signal (Philipp et al., 2007; Schuch & Koch, 2003). However, as we lay out in more detail below, task set suppression might play a more important role in our task cue paradigm than in the previous task switching studies including no-go trials.

Similar analyses of trial type repetition effects on RTs in the LDT revealed RT benefits, when the current task cue-only trial was preceded by another task cue-only trial compared to a preceding induction task trial. This indicates that the task set triggered by mere task presentation is more efficiently suppressed in preparation for the upcoming LDT (Kiesel et al., 2010), when participants perform two task cue-only trials in succession. As a result of this task set suppression, reactions were faster in the LDT after two subsequent task cue-only trials. In induction task trials, trial type repetitions had either no effect on lexical decision latencies (Exp. 2 and 3 with visible task cues in task cue-only trials) or were associated with slower RTs for trial type repetitions (two subsequent induction task trials), presumably due to an increased effort to abandon the task set of the induction task after having performed two induction tasks in succession.

The interpretation of the pattern of priming and trial sequence effects after mere task cue presentation in terms of rapid task set suppression in preparation for the upcoming LDT seems to contradict earlier findings in task switching research: Similar to the absence of task switch cost after no-go trials described above, task set inhibition effects (n − 2 backward inhibition effects) have been found to be reduced when response selection and execution was prevented by a no-go signal (Philipp et al., 2007; Schuch & Koch, 2003). Apparently, as in our task cue-only trials response selection and execution was not possible due to the missing induction task, this trial type forms a sort of no-go trial. However, affordances with regard to conflict resolution between competing task sets and thus with regard to task set inhibition (Koch et al., 2010) differ between the present task cue paradigm and earlier task switching paradigms including no-go trials (Philipp et al., 2007; Schuch & Koch, 2003). Unlike in these earlier task switching paradigms, in our task cue paradigm the task cue is presented without any potentially task-relevant stimulus and rapidly followed by the primed LDT without a no-go signal. In order to avoid misapplication of the task set associated with the task cue to the target word of the LDT (e.g., performing erroneously a living/non-living decision instead the correct word/pseudword decision), the cued task set including attended word dimensions had to be suppressed in favor of the requested LDT. It is therefore reasonable to assume that in our task cue paradigm (dominant) task sets activated by mere task cue presentation were rapidly inhibited due to the large conflict between task sets, even if the task set had not be executed up to the responses selection or execution stage.

The analyses of sequence effects also revealed that trial type repetition did not moderate the pattern of priming effects in task cue-only trials as a function of task set and trial type ($F < 2.34$, $p > .14$; Supplement Material, analyses 3). This indicates that attentional influences of task sets associated with task cues on masked priming in task cue-only trials did not depend on the trial type in the preceding trial. In particular, task cues were also effective to modulate priming, when they were presented after another task cue-only trial, and not only when they were presented in the preceding trial in combination with an executed induction task. Most likely, as randomized presentation of task cue-only trials and induction task trials rendered the occurrence of task cue-only trials unpredictable, task sets were consistently triggered in response to task cues and subsequently inhibited in preparation for the upcoming LDT, even if execution of the induction task was not necessary in two subsequent trials.

It is important to emphasize that the present experiments do not provide information about the precise timing of task set activation and inhibition in response to mere task cue presentation because the interval between task cue and masked prime onset (cue-prime SOA) was not systematically varied. Furthermore, the cue-prime SOA was longer with visible task cues (850 ms: Exp. 2 and 3) than with masked task cues (166 ms: Exp. 1), in order to make the start of task cue-only trials comparable to induction task trials. Despite these differences in cue-prime SOAs across experiments, the pattern of priming effects subsequent to mere task cue presentation was remarkably stable, besides the effects of task set dominance, which will be discussed in the next paragraph. An earlier pilot study of our working group with masked task cues and a somewhat longer cue-prime SOA (266 ms) also yielded the same pattern of results although the critical three-way interaction between semantic relatedness, trial type and task set just failed to reach the conventional significance level. Most likely, task set inhibition in response to mere task cue presentation occurs quite rapidly within about 150 ms in the present paradigm because participants have to suppress the irrelevant task set of the induction task in favor of the upcoming LDT. Future studies could systematically vary the cue-prime SOA in order to precisely determine the temporal dynamics of task set activation and inhibition in task cue-only trials in masked and unmasked task cue conditions.

5.3. The moderating role of task set dominance in task cue effects on masked semantic priming

The idea of task set suppression in task cue-only trials has been corroborated in experiment 3, in which non-verbal colored squares were used as task cues. In this experiment, dominance of the task set of the induction task (Jost et al., 2017) was varied in two different versions: In the version with dominant task sets, verbal labels for task cue colors and response categories shared initial letters so that elements of the task sets were linked. In line with earlier work, we assumed that dominant task sets are rapidly activated, but at the same time receive strong and rapid inhibition in preparation for the upcoming task (Jost et al., 2017). In the version with the weaker task sets, task cue colors and response categories did not share initial letters so that elements of the task sets had no apriori links. These weaker task sets are assumed to be more slowly activated, but less strongly inhibited, when abandoned (Jost et al., 2017). The pattern of masked semantic priming effects is assumed to depend on the precise state of task set activation or suppression during the time window of masked prime presentation. In line with these assumptions, in the version with the more dominant task sets the pattern of masked semantic priming following perceptual and semantic task cues in task cue-only trials was reversed compared with induction task trials. Priming following the perceptual task cue was larger than following the semantic cue. This replicates the pattern of priming in the task cue-only trials of experiment 1 and 2 and indicates that it is not confined to letter cues, but also extends to non-verbal color cues.

Note that in experiments 1 and 2, there was a correspondence between the task cue letter ('B') and the initial letter of one response category in the semantic induction task ('belebt' [engl. 'living']), similar to the version with the dominant task set in experiment 3. Furthermore, cue-task mapping was facilitated because the letters A and B can be easily associated with the corresponding induction tasks (A: 'Aussehen' [engl. 'appearance'] for the perceptual induction task; B: 'Bedeutung' [engl. 'meaning'] for the semantic induction task). In the subsequent LDT, the relations between all elements of the task set were arbitrary. Hence, comparable to experiment 3, in which task set dominance concerned the relation between the induction tasks and the subsequent LDT, i.e. the tasks, between which the switches had to be performed, the task sets of the induction tasks in experiments 1 and 2 can also be considered as dominant in relation to the LDT (see also the discussion in the introductory paragraph to experiment 3). However, unlike in experiment 3, the comparison condition with weaker task sets in the induction tasks was missing in experiments 1 and 2 so that we could not isolate the impact of these compatible cue-task mappings neither on the pattern of priming effects nor on general performance (for the latter aspect, see the discussion of experiment 3). When designing these experiments, given the complex nature of the entire paradigm, we were concerned that participants were not able to perform the correct induction task, if the cue–task mapping was too difficult. As the Jost et al. (2017) study was not published, when we ran experiments 1 and 2, the role of task set dominance for task set suppression had not been recognized at this time.

Most likely, the same task set suppression mechanism for dominant task sets was engaged in the task cue-only trials of experiments 1 and 2. In the version with the weaker task sets of the induction task, the pattern of priming in task cue-only trials was comparable to the induction task trials: Priming subsequent to a semantic task cue was larger than to a perceptual task cue. This indicates that weaker task sets were still activated when the masked prime words were presented. Of course, the present research could not determine, when the weaker task sets triggered by a task cue in task cue-only trials are suppressed in preparation for the upcoming LDT.

The presently observed reversed effects of task cues on masked semantic priming in the conditions with dominant task sets seem to contradict earlier observations of facilitatory effects of masked task cues on subsequent performance: For instance, reactions were faster, when the performed task followed a congruent task cue (Lau & Passingham, 2007; Mattler, 2003, 2005, 2006, 2007). Likewise, participants more likely chose to perform the task indicated by a preceding masked task cue (Reuss et al., 2011). However, this discrepancy with regard to the direction of task cue influences can be attributed to important differences in the experimental procedure: In the present paradigm, participants had to prepare for the upcoming LDT right after task cue presentation, which required suppressing the irrelevant, but competing task set triggered by the task cue. In the earlier studies, however, participants were prepared to execute the cued task in response to the upcoming target. As a consequence, activation of the cued task set was maintained and facilitated execution of the following target task. Moreover, in the earlier studies the task sets associated with the task cues can be considered as weak because apriori associations between elements of the task sets were absent. It would be interesting to assess whether in task set priming paradigms, as used in the earlier studies, facilitatory effects of masked task cues on subsequent performance would also be observed with dominant task sets.

Taken the pattern of results together, our study shows that task cues, whether visible or masked and invisible, trigger task sets that differentially modulate attentional sensitization of unconscious semantic processing pathways. The direction of these attentional influences triggered by task cues are moderated by task set dominance, at least in the task switching situation of the present experimental paradigm. Dominant task sets triggered by mere task cue presentation are rapidly inhibited leading to a reversed pattern of masked semantic priming compared with induction tasks. Weaker task sets triggered by mere task cue presentation, in contrast, are active for a longer time and result in priming effects comparable to induction tasks. On a more general note, the observation that even masked task cues bias subsequent prime processing resonates with increasing evidence showing that unconscious information in general has the potential to affect cognitive control settings (see also Reuss, Desender, Kiesel, & Kunde, 2014).

5.4. Implications for task switching research and practical applications

The effects of task cues on masked semantic priming found in the present study are not only relevant for research on top-down control of unconscious semantic processing. The reversed effects of task cues on semantic priming in conditions with dominant task sets give important insights in factors influencing the temporal dynamics of task set activation and suppression. Our results suggest that dominant task sets triggered by task cues are suppressed within a few hundred milliseconds in situations, when the cued task set is not executed as in our task cue-only trials and when participants are about to implement and execute a competing task set (here: LDT). Weaker task sets, in contrast, appear to be activated for a longer period of time, when triggered under such conditions. Together with the earlier study on $n - 2$ task repetition costs (Jost et al., 2017), the present task cue effects on priming highlight the moderating role of task set dominance in the suppression of task sets. Relative subtle properties of the task sets, such as aprori associations between elements of the task sets, determine the temporal dynamics of task set activation and suppression in the context of a competing task set. The observed suppression of dominant task sets, when triggered by cues, in favor of the upcoming task has also implications for practical applications in human-machine interaction. Cues are frequently used to alert and to prepare an operator for a subsequent action. For instance, in driver assistance systems of cars visual cues are intended to inform the driver about upcoming obstacles or other dangerous situations. If such a cue is presented within the context of a competing task set, the present research suggests that the cued task set can be rapidly suppressed under such circumstances. This would potentially result in reversed cuing effects, i.e. poorer performance, when the driver actually performs the cued action. Hence, cuing could lead in such situations to unwanted behavioral costs that undermine the intended function of the cue to facilitate performance.

5.5. Conclusion

The present research compared attentional modulation of masked semantic priming originating from previously performed induction tasks with those originating from mere presentation of task cues across three experiments. We assumed that a task set with a focus on semantics would enhance subsequent subliminal semantic priming via attentional sensitization of semantic pathways, whereas a task set with a focus on perceptual information would attenuate semantic priming by desensitization of semantic pathways. In support of these predictions and in line with earlier work, subliminal semantic priming was consistently larger following semantic induction task trials than following perceptual induction task trials. However, the priming pattern following mere presentation of perceptual and semantic task cues without subsequent induction task depended on task set dominance. When the task sets of the induction task were dominant, i.e. when there were apriori associations between elements of the task sets, priming was larger following a perceptual cue than following a semantic cue. Hence, for dominant task sets the priming pattern after mere presentation of task cues was reversed compared with induction task trials. In contrast, for weaker task sets, i.e. when apriori associations between elements of the task sets were absent, the priming pattern as a function of task cues was comparable to induction task trials. In line with previously observed greater inhibition effects for dominant than for weak task sets in task switching, the reversed priming pattern in task cue-only trials most likely reflects rapid suppression of irrelevant dominant task sets in preparation for the upcoming LDT. Modulation of subliminal semantic priming by cues associated with dominant task sets depended neither on awareness nor on format of the task cue. This research provides insights in factors determining the dynamics of cue induced task set activation and suppression and further elucidates mechanisms underlying attentional control of unconscious semantic processing.

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Conflict of interest

None to be declared.

Role of the funding source

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Appendix A. Supplementary material

Archived raw data and aggregate data of all experiments are available at https://osf.io/263ht/. Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2019.02.013.

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