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Attentional Sensitization of Unconscious Cognition: Task Sets Modulate Subsequent Masked Semantic Priming

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According to classical theories, automatic processes are autonomous and independent of higher level cognitive influence. In contrast, the authors propose that automatic processing depends on attentional sensitization of task-congruent processing pathways. In 3 experiments, the authors tested this hypothesis with a modified masked semantic priming paradigm during a lexical decision task by measuring event-related potentials (ERPs): Before masked prime presentation, participants attended an induction task either to semantic or perceptual stimulus features designed to activate a semantic or perceptual task set, respectively. Semantic priming effects on the N400 ERP component, an electrophysiological index of semantic processing, were obtained when a semantic task set was induced immediately before subliminal prime presentation, whereas a previously induced perceptual task set attenuated N400 priming. Across experiments, comparable results were obtained regardless of the difficulty level and the verbal or nonverbal nature of the induction tasks. In line with the proposed attentional sensitization model, unconscious semantic processing is enhanced by a semantic and attenuated by a perceptual task set. Hence, automatic processing of unconscious stimuli is susceptible to top-down control for optimizing goal-related information processing.

Keywords: automatic processes, unconscious cognition, attentional control, semantic priming, subliminal perception

Automatic processes are traditionally thought to occur autonomously and independently of top-down control. Classical theories of automaticity therefore assume that automatic processes (a) are independent of capacity-limited attentional resources, (b) are not prone to interference from other processes, (c) can act in parallel, and (d) are unconscious (Posner & Snyder, 1975; Schneider & Shiffrin, 1977). According to this classical view of automaticity, automatic processes are triggered invariantly and independently of the current configuration of the cognitive system. Top-down control by attention, action goals, and task sets is restricted to processes that are conscious and depend on cognitive resources. Classical theories therefore assume that cognitive control is exclusive to the domain of conscious cognition.

Although lacking direct empirical support, this classical view is implicit in present theorizing about automaticity and strongly influences contemporary conceptions of cognitive control (e.g., van Elk, van Schie, & Bekkering, 2009). On the basis of the assumption that automatic processes are autonomous, a behavioral or neurophysiological effect has to be invariant in order to index a "truly automatic" process (Pessoa, Kastner, & Ungerleider, 2003): An *automatic process* is typically defined as not subject to the influence of attention, cognitive resources, or task demands. Otherwise, this process is said to be "controlled." For instance, a frequent operational definition for the automaticity of semantic processing includes in it a manipulation of attentional orientation to a word (Deacon & Shelley-Tremblay, 2000). If behavioral or neurophysiological effects associated with semantic processing of word meaning are only obtained for an attended but not for an unattended word, then it is concluded that semantic processing is "controlled" (Kellenbach & Michie, 1996; McCarthy & Nobre, 1993; Rees, Russell, Frith, & Driver, 1999). Likewise, variations of semantic processing as a function of the task orientation toward a word, such as attention to word meaning versus letter form, has been taken as evidence for the "controlled" nature of semantic processing (Henik, Friedrich, Tzelgov, & Tramer, 1994; Maxfield, 1997). Similar operational definitions of automaticity, which are essentially influenced by the classical view, can be found in other areas of psychology and neuroscience such as in object or face recognition (Pessoa, McKenna, Gutierrez, & Ungerleider, 2002; Wiese, Schweinberger, & Neumann, 2008) and emotional processing (Pessoa et al., 2002). Even the Stroop interference effect in color naming (Stroop, 1935) is modulated by top-down factors such as intention (Kuhl & Kazén, 1999). This effect is thought to indicate competition between task-irrelevant "automatic" processes of word reading and task-relevant processes of color naming (J. D. Cohen, Dunbar, & McClelland, 1990). Given that attention and task demands are commonly observed to modulate behavioral and neurophysiolog-

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ical effects, there remain but few processes that actually meet the full classical criteria for automaticity.

Refined Theories of Automaticity

This classical conceptualization of automaticity still predominates and is unsatisfactory: According to the classical criteria, almost all kinds of cognitive processes must be classified as controlled because of their sensitivity to attention, rendering therefore any theoretical distinction between automatic and controlled processes practically meaningless. Furthermore, the classical conceptualization of automaticity implies a considerable inflexibility of the cognitive system: Conscious goal-directed information processing would be massively influenced by various unconscious processes. Such inflexibility would place tremendous demands on conscious control, because the intended action could only be ensured by inhibiting numerous interfering response tendencies (Botvinick, Braver, Barch, Carter, & Cohen, 2001).

A number of recently refined theories of automaticity allow for more flexibility and adaptability of unconscious cognition (Kiefer, 2007; Naccache, Blandin, & Dehaene, 2002; Neumann, 1984). These theories converge on the assumption that the cognitive system has to be configured in a specific way in order for automatic processes to occur. Unlike classical theories, these theories assume that automatic processes are critically dependent on higher level, top-down factors such as attention, intention, and task sets that orchestrate the processing streams toward greater optimization of task performance. Given this dependency on the precise configuration of the cognitive systems, one may also speak of "conditional automaticity" (Bargh, 1989; Logan, 1989).

The notion of top-down control of automatic processing is explicitly incorporated in the theory of direct parameter specification (DPS) by Neumann (1990). This theory seeks specifically to explain unconscious response preparation (for unconscious response priming, see the following paragraph). Neumann assumes that the intention to act must be established prior to the onset of the unconscious stimulus. The DPS theory posits that unconsciously registered information from the environment can be used to specify an open parameter of an action plan, thereby unconsciously triggering a prepared response. Unconscious information will only be processed and influence the motor response to a target stimulus to the extent that it matches current intentions.

Masked Semantic Priming as a Tool for Studying Automatic Processes

Although automatic processes are assumed to be triggered by both consciously and unconsciously perceived stimuli (e.g., Hommel, 2000), we focus in this article on automatic processes under subliminal viewing conditions, because for unconscious perception, it can be ensured that processing occurs "automatically," that is, without any contribution of intended, controlled processes. In contrast, for the processing of consciously perceived stimuli, it cannot be excluded that controlled processes also contribute (Jacoby, 1991; Koivisto, 1998). Priming (i.e., facilitatory) effects elicited by unconsciously perceived masked stimuli are therefore an ideal tool with which to study automatic processes in isolation: Several studies have reliably demonstrated that a masked prime stimulus beyond conscious perception facilitates the response to a subsequently presented visible target (for a review, see Kiefer, 2007).

Response priming and semantic priming paradigms, which differ with regard to the relation between prime and target, have been widely used to study automatic processing under subliminal viewing conditions: (a) In response priming (Neumann & Klotz, 1994), prime and target indicate either the same (e.g., right-hand response) or a different motor response, but do not show any meaningful relation. For instance, geometrical objects are used as primes and targets, which are assigned with congruent or incongruent response alternatives. Participants have typically to decide for the target stimulus whether it is associated with a right-hand or a left-hand response. Response priming effects, that is, faster responses to targets when the prime indicates the same rather than a different response, arise from automatic visuomotor response preparation processes triggered by the presentation of the unconsciously perceived masked prime (Dehaene et al., 1998; Klotz & Neumann, 1999; Neumann & Klotz, 1994; Verleger, Jaskowski, Aydemir, van der Lubbe, & Groen, 2004; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). (b) In semantic priming (Neely, 1991), prime and target are meaningfully related words (or pictures) in one condition (e.g., *table-chair*) and unrelated words (or pictures) in the other condition (e.g., *car-hen*). In contrast to the response priming paradigm, primes in the congruent and incongruent conditions always afford the same response in the target task, thereby ruling out any response congruency effects. Nevertheless, responses to targets that have been preceded by a semantically related prime are performed more quickly than responses to targets paired with unrelated primes (Carr & Dagenbach, 1990; Kiefer, 2002; Kiefer & Brendel, 2006; Kiefer & Spitzer, 2000). These masked semantic priming effects reflect unconscious access to the meaning of the prime and automatic preactivation of the semantic target representation. In addition to this pure form of response and semantic priming paradigms, there are mixed paradigms possible, in which primes and targets of the different relatedness conditions differ with regard to both semantic relatedness and response congruency (e.g., Damian, 2001). We used (pure) masked semantic priming in the present study to elucidate top-down influences on automatic processes because semantic priming with visible or subliminal primes have been subject to intensive behavioral and neurophysiological investigations in the past (for reviews, see Deacon & Shelley-Tremblay, 2000; Kiefer, 2007; Kutas & Van Petten, 1994; Neely, 1991). This earlier work provides a rich empirical basis, with which our theoretical framework and experimental findings can be compared.

Recordings of electrical brain activity complement behavioral measures of semantic priming effects and may be used to capture priming effects during target processing with a temporal resolution of milliseconds. In the event-related potentials (ERPs) of the electroencephalogram, the N400 ERP component is a negative potential deflection that peaks at about 400 ms at centroparietal electrode sites. Several studies showed that the N400 specifically reflects semantic processing (Kutas & Hillyard, 1980). In semantic priming paradigms, N400 amplitude to targets is attenuated (i.e., less negative) for semantically related prime–target combinations compared with unrelated pairings. Although the negative deflection often temporally overlaps with a large positive component (late-positive complex) and does not necessarily appear as a negative potential in absolute terms, this phenomenon is known as the

N400 priming effect (Bentin, McCarthy, & Wood, 1985; Kiefer, 2005; Kiefer, Weisbrod, Kern, Maier, & Spitzer, 1998). Intracranial ERP recordings (Nobre & McCarthy, 1995) and source analyses of scalp potentials (Kiefer, Schuch, Schenck, & Fiedler, 2007) have implicated a region in the anterior-medial temporal lobe in generating the N400 ERP component. N400 amplitude is modulated by both consciously perceived and masked, unconsciously perceived primes (Deacon, Hewitt, Chien-Ming, & Nagata, 2000; Kiefer, 2002; Kiefer & Brendel, 2006; Kiefer & Spitzer, 2000). In contrast to behavioral measures, which reflect the output of the entire processing chain, ERPs have the advantage of directly capturing semantic processes online during task performance.

An Attentional Sensitization Model for Top-Down Control of Unconscious Cognition

Although refined theories of automaticity converge on the assumption that automatic processes are susceptible to top-down control, there is as yet no general theoretical framework that accounts for a number of top-down factors and different forms of automatic processes: The DPS theory is limited to visuomotor response preparation in the context of action intentions (Neumann, 1990). Other present approaches are confined to the role of the allocation of attention in time and therefore neglect other top-down factors such as attentional capacity, intentions, or task sets (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Naccache et al., 2002).

In order to improve on these theories and their limitations, we propose an attentional sensitization model that accounts for a number of modulatory top-down factors such as attention, intention, action goals, and task sets across a broad class of automatic processes (e.g., different forms of priming). The attentional sensitization model is based on the core idea that conscious and unconscious perception is governed by similar computational principles and susceptible to top-down modulation in a comparable manner, as we have suggested previously (Kiefer, 2007). From this perspective, it follows that principles of top-down modulation found in the domain of conscious cognition (Botvinick et al., 2001; Hamker, 2005; Müller, Reimann, & Krummenacher, 2003; Pessoa et al., 2003) can be transferred to that of unconscious and automatic processes.

The attentional sensitization model of top-down control on unconscious cognition developed here essentially builds on evidence of the functional and neural correlates of visual attention (for an overview, see Pessoa et al., 2003). Attention is thought to enhance perceptual sensitivity for target stimuli through two possible mechanisms operating individually or together: One mechanism increases activation in response to targets (Posner, Snyder, & Davidson, 1980), the other reduces competition from distracting stimuli by biasing processing in favor of the target (Desimone & Duncan, 1995). Attention can be guided by internal goals or task representations (top-down attentional feedback), or it may be driven by salient external stimuli (bottom-up sensory-driven attention), which capture attention (Ansorge & Horstmann, 2007). In the present work, we focus on attentional modulation by internal goals and task representations.

It has been shown that the maintenance of goals and task representations crucially depends on neural circuits in prefrontal cortex (Bode & Haynes, 2008; Duncan, 2001; Mayr, Diedrichsen, Ivry, & Keele, 2006). These prefrontal task representations influence processing of sensory and semantic information in posterior brain areas through long-range neuroanatomical connections (Webster, Bachevalier, & Ungerleider, 1994). This connectivity permits temporary functional coupling between prefrontal attentional control regions and posterior target regions (Eger, Henson, Driver, & Dolan, 2007). Experiments in nonhuman primates have demonstrated that learning during a categorization task is accompanied by adaptive tuning of neurons in prefrontal cortex in response to the task-relevant stimulus dimensions (Freedman, Riesenhuber, Poggio, & Miller, 2001).

In turn, the prefrontal cortex sends a top-down signal that modulates activity of single neurons in sensory brain areas in the absence of any sensory stimulation (Tomita, Ohbayashi, Nakahara, Hasegawa, & Miyashita, 1999) and significantly increases baseline activity in the corresponding target region (Reynolds, Chelazzi, & Desimone, 1999). Similarly, the presentation of an attentional cue indicating task-relevant stimulus dimensions is associated with increased activity in prefrontal areas of human participants (Bode & Haynes, 2008; Hopfinger, Buonocore, & Mangun, 2000; Hopfinger, Woldorff, Fletcher, & Mangun, 2001). In posterior brain areas, the target region of attentional control, attention to specific stimulus dimensions increases the baseline activity level in the corresponding sensory region, even when visual stimulation is kept constant. For instance, baseline activity in motion- and color-sensitive areas of human visual cortex is enhanced by cuing attention to these visual attributes even when the stimuli do not actually move or change in color (Chawla, Rees, & Friston, 1999). The prefrontal top-down signal is able to modulate the visual system on a very fine-grained scale: The observed increase of baseline activity in visual brain areas is retinotopically specific; that is, it reflects the precise spatial location the observer is currently attending to (Munneke, Heslenfeld, & Theeuwes, 2008). Likewise, the attentional focus on faces or scenes enhances activity in parts of the visual system known to preferentially process faces (fusiform face area) and scenes (parahippocampal place area), respectively (Greene, Braet, Johnson, & Bellgrove, 2007). This increase in baseline activity in posterior brain areas as a result of the prefrontal attentional top-down signal typically leads to an improvement in behavioral performance (Eger et al., 2007).

On the basis of these findings, the attentional sensitization model assumes that top-down control over unconscious cognition is exerted by prefrontal top-down signaling that regulates the sensitivity of the different processing pathways to incoming sensory information (Reynolds, Pasternak, & Desimone, 2000): Processing in task-relevant pathways is enhanced by increasing the gain of the neurons in the corresponding areas, whereas processing in task-irrelevant pathways is attenuated by a decrease of the gain. Gain is a parameter in neural network modeling, which influences the probability that a neuron fires at a given activation level. If gain is high, then the likelihood of firing is increased in comparison to low gain. Single-cell recordings in nonhuman primates have shown that the likelihood of a neuron firing, given a constant sensory input, is enhanced when the stimulus dimension that is preferentially processed by the neuron is attended to (Treue & Martínez Trujillo, 1999). We thus assume that an attentional sensitizing mechanism gradually enhances and attenuates stimulus processing irrespective of whether the stimulus is consciously perceived or not.

It follows from these assumptions of the attentional sensitization model that, in a manner similar to controlled processes, automatic processes (a) should depend on available attentional resources and (b) are susceptible to top-down control by currently active task representations. Attentional sensitization of automatic processing by task representations is achieved by enhancing the sensitivity of task-relevant pathways and by attenuating the sensitivity of task-irrelevant pathways. The proposed attentional sensitizing mechanism is assumed to orchestrate the conscious and unconscious information-processing streams in congruency with the current task representations.

Although we propose that attentional top-down control of both unconscious and conscious cognition shares basic computational principles, top-down control for conscious processing is certainly more flexible. For this reason, we distinguish between two types of top-down control: preemptive and reactive control (see also Ansorge & Horstmann, 2007; Kiefer, 2007). In preemptive control, top-down influences are initiated in advance of stimulus presentation. Preemptive control can be exerted for both conscious and unconscious stimulus presentation, whereas only consciously perceived stimuli are susceptible to reactive control in response to ongoing or completed stimulus processing. For that reason, subliminal information cannot be used for determining further strategic processing steps in a deliberate fashion (Merikle, Joordens, & Stolz, 1995). This means that top-down control of unconscious cognition must occur implicitly on the grounds of currently activated action goals or the outcome of overt behavior. As a consequence, intentional application of control and online modification is restricted to controlled processes (Dehaene et al., 2006). Finally, attentional influences on unconscious cognition are presumably facilitatory; that is, they depend on differential attentional sensitization, whereas active inhibition of task-irrelevant information appears to be confined to controlled processing of consciously perceived stimuli (Merikle et al., 1995; Neely, 1977; Posner & Snyder, 1975). Thus, conscious "strategic" stimulus processing allows for a greater adaptability and flexibility of top-down control than "automatic" processing under unconscious viewing conditions.

Top-Down Effects on Masked Priming

Several reports of the top-down modulation of masked response and semantic priming support the proposed attentional sensitization model. (a) Unconscious priming has been shown to depend on attentional top-down amplification: In a masked semantic priming study (Kiefer & Brendel, 2006), an attentional cue was presented that prompted participants to attend to the stimulation stream during either the time window of masked prime presentation or already 1 s earlier. In the latter long-cue prime interval condition, subjects disengaged attention when the masked prime was finally presented. Kiefer and Brendel (2006) obtained a semantic priming effect on the N400 ERP component, but only when the masked prime was presented within the time window of attention. In a similar study, masked response priming was only obtained when the onset of the prime–target pairs was temporally predictable and therefore attended to (Naccache et al., 2002). Furthermore, masked semantic priming was significantly reduced when the masked prime was preceded by a difficult task requiring greater attentional resources compared with an attentionally undemanding task (Martens & Kiefer, 2009). (b) Top-down control processes can constrain processing of unconsciously perceived stimuli if they misguide overt behavior: Within a response priming paradigm, the effects of unconsciously presented masked primes on reactions to targets were considerably reduced in a condition in which the primes excessively induced erroneous responses (Jaskowski, Skalska, & Verleger, 2003; Wolbers et al., 2006). Presumably, top-down control is reactively engaged in response to previous consciously perceived errors in order to suppress interfering subliminal information. (c) Masked response priming has been shown to depend on action intentions: Ansorge and colleagues (Ansorge, Heumann, & Scharlau, 2002; Ansorge & Neumann, 2005) found that unconsciously perceived masked primes trigger responses only if they are congruent with the current intentions of a person. Response priming effects were abolished when task instructions were changed in such a way that primes ceased to be task relevant. Similarly, masked stimuli primed responses only if they were expected and represented possible release conditions for prepared actions (Eckstein & Perrig, 2007; Kiesel, Kunde, Pohl, Berner, & Hoffmann, 2009; Kunde, Kiesel, & Hoffmann, 2003).

The Influence of Task Representations on Unconscious Processing During Task Set Switching

Previous studies have demonstrated that masked response priming crucially depends on the intention to act. The attentional sensitization model predicts, however, a more general influence of currently active task representations on automatic processes. For instance, previously performed tasks should differentially sensitize semantic processing pathways and correspondingly modulate subsequent subliminal semantic priming effects. Consider a scenario, in which the subject needs to perform two tasks in quick succession, the second task being a subliminally primed lexical decision task preceded by a semantic or a perceptual classification task. According to the attentional sensitization model, these previously performed tasks should differentially influence the masked priming effect. As this situation includes a switch from the first task to the primed lexical task, it is important to consult previous research on task switching in order to estimate how the reconfiguration of task representations during task switching unfolds over time and could influence subsequent priming. This top-down influence of previously performed tasks is assumed to be mediated by task representations activated in prefrontal cortex that constitute a task set (Bode & Haynes, 2008; Rogers et al., 1998). The concept of "task set" originates from the task-switching literature and has been defined as an adaptive configuration of the cognitive system as a prerequisite for efficient performance in a given task (Gilbert & Shallice, 2002; Rogers & Monsell, 1995). This task-dependent configuration persists for a while even when the task has already been completed and a reconfiguration for a new task is required. This reconfiguration process is behaviorally reflected by switch costs, that is, inferior performance in task switch compared with task repetition trials (Logan, 2003; Monsell, 2003). In the task-switching literature, the persistence of a task set has been referred to as *task set inertia* (Allport, Styles, & Hsieh, 1994). Results by Rogers and Monsell (1995) indicate that it takes approximately 600 ms after task completion to effectively reconfigure the cognitive system for the upcoming task when the nature of this new task can be predicted.

In the research on task switching, the mechanism involved in abandoning a task set during the course of the reconfiguration process is matter of a debate (Kiesel et al., in press). In particular, the existence of an inhibitory process that actively deactivates the irrelevant task set after task completion has been critically discussed. Task repetition costs on Trial n originating from Trial n − 2 support the notion of such an inhibitory process that aids transition from one task to another (Houghton, Pritchard, & Grange, 2009; Hübner, Dreisbach, Haider, & Kluwe, 2003; Mayr et al., 2006; Mayr & Keele, 2000): Performance was inferior when the same Task A was repeated after one intervening Trial B (task sequence ABA) in comparison to when the task switched after the intervening trial and a Task C was presented (task sequence ABC). These n − 2 task repetition costs have been taken as evidence for a backward inhibition process that actively suppresses a task set after the task has been abandoned. A neuropsychological study with brain-damaged patients demonstrated that right prefrontal cortex is crucial for the suppression of the old task set (Mayr et al., 2006). This observation is compatible with the more general involvement of right prefrontal cortex in inhibitory mechanisms underlying action control (de Zubicaray, Andrew, Zelaya, Williams, & Dumanoir, 2000; Rubia, Smith, Brammer, & Taylor, 2003). Please note that this task set suppression mechanism, which includes active inhibition processes, influences the activation level of task sets in accordance with dynamically changing action goals and therefore contributes to the reconfiguration of the cognitive system during task switching. This task set suppression mechanism has to be theoretically distinguished from the inhibition-free attentional sensitization mechanism proposed by our model, which mediates the influence of the currently activated task set on sensory or semantic processing. Mechanisms contributing to task set switching are beyond the scope of our model, but have to be considered from the task-switching literature in order to derive predictions about the temporal dynamics of task set activation and deactivation.

From previous findings in task switching described above, we derive tentative information about the reconfiguration processes when switching from the first task to the primed lexical decision task. In particular, they allow us to estimate how the influence of the first task on subsequent unconscious processing of a masked prime unfolds over time: A task set, which is induced by the task performed before masked prime presentation (induction task), should persist for about 600 ms after task completion. As the lexical decision task to the target is predictable in the masked priming paradigm, participants can prepare for this upcoming task. Therefore, a backward inhibition mechanism may be assumed to suppress the previously active but now irrelevant task set, and a new task set in preparation for the upcoming lexical decision task is activated. As the task-switching literature suggests a temporal dynamic of task set activation and suppression, a previously performed task should modulate automatic semantic priming differentially as a function of the time interval between the offset of task completion and the onset of the masked prime.

Overview of the Present Study

Although several lines of evidence support the attentional sensitization model, the specific nature of these attentional influences and the associated underlying mechanisms have as yet not been determined. In particular, it is unclear whether and how the specific configuration of the cognitive system induced by previously performed tasks constrains automatic processing of subliminal stimuli. According to the proposed attentional sensitization model, task representations enhance and attenuate processing streams in order to facilitate processing in congruency with higher level goals: Automatic processes that match task representations are assumed to be amplified, whereas other automatic processes should be attenuated.

In three experiments, we tested the assumptions of the attentional sensitization model and systematically investigated the influence of previously performed tasks on subsequent masked semantic priming. The first two experiments sought to empirically establish the proposed top-down influence of previously activated task representations on automatic processes. More specifically, we asked whether a semantic task set induced by a semantic word decision task immediately before masked prime presentation (induction task) sensitizes semantic processes pathways and enhances subliminal semantic priming. In contrast, a perceptual task set induced by a task that requires attention to local letter features of a word was assumed to desensitize semantic pathways and therefore to attenuate subsequent subliminal semantic priming.

The third experiment aimed at specifying the mechanism underlying this top-down modulation of unconscious cognition. The proposed attentional mechanism enhances processing in task-relevant pathways and attenuates processing in task-irrelevant pathways by differentially regulating the sensitivity of processing pathways to incoming stimulus information. This sensitization mechanism does not depend on the inhibition of task-irrelevant stimulus features. Alternatively, an active inhibitory mechanism is conceivable that is evoked by the induction task in order to resolve competition between stimulus features (letter form vs. semantic meaning) in favor of the target dimension (Hübner & Malinowski, 2002; Stroop, 1935). This mechanism inhibits task-irrelevant stimulus features in order to reduce the influence of interfering processes on behavior (Botvinick et al., 2001; Posner & DiGirolamo, 1998). The perceptual induction tasks of Experiments 1 and 2 required attention to a local, less salient stimulus dimension (letter form) and simultaneous inhibition of interfering processes originating from task-irrelevant, but more salient global stimulus dimensions (semantic meaning, word form). Hence, such verbal perceptual induction tasks might activate a task set that includes active inhibition of word form and meaning. This task set might in turn be implicitly applied to the unconsciously presented masked prime word, leading to attenuation of semantic analysis (Craik & Lockhart, 1972) and priming effects compared with the semantic induction task (Mari-Beffa, Houghton, Estevez, & Fuentes, 2000; Maxfield, 1997).

According to this active inhibition account, masked semantic priming would only be reduced subsequent to those types of perceptual induction tasks that afford the inhibition of word form processing in favor of letter processing, as in the letter detection tasks used in Experiments 1 and 2. However, for a nonverbal perceptual induction task with pictorial stimuli that does not require the inhibition of word form and meaning, the active inhibition account predicts comparable masked semantic priming for both the perceptual and semantic induction tasks. In contrast to this active inhibition hypothesis, the proposed attentional sensitization model assumes that for both verbal and nonverbal induction tasks, an attentional orientation toward perceptual stimulus information is sufficient to desensitize semantic pathways for several hundred milliseconds. Hence, the attentional sensitization model predicts reduced masked priming even with such a modified pictorial induction task that does not entail competition between local letter features and global word information. Please note that the inhibitory mechanism of the active inhibition account pertains to the task set evoked by the perceptual induction task. This form of inhibitory mechanism has to be distinguished theoretically from backward inhibition of task sets during task switching that has been described in the previous section. In the third experiment, we tested the contribution of the former mechanism and asked whether an inhibitory task set pertaining to the perceptual induction task is a prerequisite for modulating masked priming. A further clarification of the latter mechanism, that is backward inhibition during the course of task switching, was beyond the scope of the present study. In Experiment 3, we devised new nonverbal perceptual and semantic induction tasks with pictorial stimuli in order to differentiate between attentional sensitization and active inhibition. As the pictorial perceptual induction task does not require active inhibition of word form and meaning, a relative decrease in semantic priming following the perceptual induction task in comparison to the semantic induction task is predicted only by the attentional sensitization model and not by the active inhibition hypothesis.

Experiment 1

In Experiment 1, we used a novel experimental paradigm that exploited the temporal dynamics of task set activation to determine top-down influences of attentional sensitization on masked semantic priming. Prior to the masked semantic priming procedure, participants were engaged in a semantic or perceptual task (induction task) designed to induce either a semantic or a perceptual task set (see Figure 1). The semantic and perceptual induction tasks were presented in separate blocks in order to avoid task-switching effects between trials with different induction tasks, which could have induced unwanted task set reconfiguration processes. In both cases, the induction tasks were followed immediately by the primed lexical decision task. In order to activate a perceptual task set, the induction task required attention to perceptual letter features: Participants had to decide whether either the first or the last letter of a word had a closed shape (e.g., *d* in *doctor* or *p* in *tulip*) or whether both the first and last letter had an open shape (e.g., *c* and *t* in *cat* or *h* and *r* in *hammer*). The task for inducing a semantic task set required participants to classify words according to their semantic meaning. They had to decide whether words referred to a living (e.g., cat, tulip) or a nonliving object (e.g., hammer, chair).

Subsequent to the response in the induction task, a masked prime word that was not consciously perceived was displayed and followed by a visible target that formed a real word or a pseudoword. The target required a lexical decision (word vs. pseudoword). Masked priming effects in response to target words were measured by means of reaction times (RTs) and ERPs. We recorded ERPs in addition to behavioral measures in order to track the time course of semantic priming continuously within the range of milliseconds. As the N400 is susceptible to semantic priming (e.g., Kiefer, 2002) and has been shown to be highly sensitive to top-down modulation of unconscious priming (Kiefer & Brendel, 2006), inferences were specifically drawn from this ERP component.

In order to gain information about how the influence of a previously performed induction task on masked semantic priming unfolds over time, we varied the time interval between the response to the induction task and the onset of the masked prime (response prime interval [RPI]) in all experiments. When participants prepare for a new upcoming task, research on task switching suggests a persistent activation of the irrelevant task set for approximately 600 ms after task completion (Rogers & Monsell, 1995). Thereafter, a backward inhibition process presumably suppresses the irrelevant task set and a new task set is activated (Mayr & Keele, 2000). Given this information from the task-switching literature, we selected an interval of 200 ms as the short RPI and an interval of 800 ms as the long RPI.

For the short RPI, the predictions are straightforward: A masked prime immediately following a semantic induction task (i.e., during conditions of an increased sensitization of semantic pathways) should elicit larger semantic priming effects than when following a perceptual induction task (i.e., during conditions of a decreased sensitization of semantic pathways).

However, for the long RPI, the above-described reconfiguration processes during task switching suggest that the effects on the sensitization of semantic pathways associated with both the preceding task set of the induction task and the new task set, which supports the lexical decision task, occur concurrently and jointly influence semantic processing. The task set of the lexical decision task increases the sensitivity of semantic pathways equally subsequent to both the perceptual and semantic induction tasks and thus cannot contribute to possible differential effects of the induction tasks. However, the suppression of the task sets associated with the induction tasks at the long RPI may lead to a differential sensitization of semantic pathways and thus to a modulation of priming effects. After completion of the semantic induction task, the semantic task set is suppressed, and this results in a strong desensitization of semantic pathways. The upcoming lexical decision task is a more implicit semantic task in contrast to explicit semantic tasks like category verifications that require retrieval of specific semantic information (Simmons, Hamann, Harenski, Hu, & Barsalou, 2008; Stone & Van Orden, 1993; Yap, Balota, Cortese, & Watson, 2006). Although the activation of the task set for the lexical decision task may therefore increase the sensitivity of semantic pathways to some extent, the conflicting desensitizing influence of the suppressed semantic task set is expected to produce a net decrease of the sensitivity of semantic pathways. These considerations about task set inhibition lead to the somewhat counterintuitive prediction that masked semantic priming is decreased following a semantic induction task at the long RPI. Following a perceptual induction task at the long RPI, both the suppression of the perceptual task set and the activation of the task set for the upcoming lexical decision task are assumed to conjointly increase the sensitivity of semantic pathways and to enhance masked semantic priming.

On the basis of these assumptions about the conjoint influence of the abandoned and the new task set on the sensitivity of semantic pathways, we expected larger semantic priming at a long RPI following a perceptual induction task (i.e., during conditions of a net sensitization of semantic pathways) than following a semantic induction task (i.e., during conditions of a net desensiti-

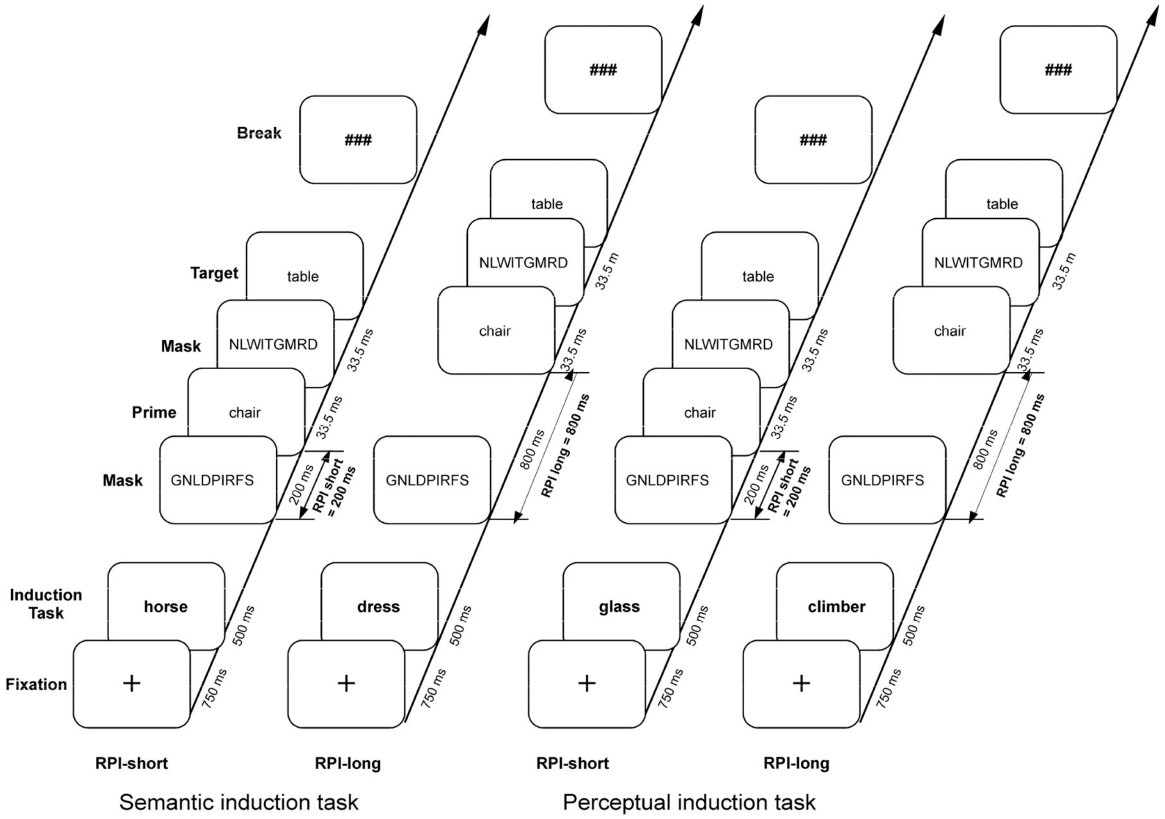

Figure 1. Temporal sequence of one trial in the semantic and perceptual induction task conditions of Experiment 1. The masked prime word was presented either 200 ms or 800 ms following the response to the induction task (response stimulus interval [RPI]) that is intended to elicit the corresponding task set. The semantic induction task required semantic classification (forced-choice living/nonliving decision), whereas the perceptual induction task required a forced-choice perceptual classification decision of the first and last letter (open/closed shape). The "plus" sign indicates the fixation cross; the hash marks indicate the breaks between the trials.

zation of semantic pathways). In view of the discussed temporal dynamics of task set activation and suppression, we expected a triple interaction between the factors induction task, RPI, and semantic priming.

Method

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 had to be discarded from analysis, one due to technical problems in data acquisition and the other because the identification rate of this participant exceeded the confidence interval of chance performance in the masked prime identification test (more than 65% correct responses). The remaining 22 participants (10 men and 12 women) were in the age range of 20–38 years, with a mean of 24.8 years. In this and the subsequent experiments, all participants gave informed, written consent after the experimental task and the EEG recording procedure had been explained. Participants were naïve to the purpose of the experiment. All experiments were conducted in accordance with the Declaration of Helsinki.

Material.

Tasks for inducing task sets. For the perceptual induction task, the stimuli were 200 German words. Half the words had an initial or final letter with a closed shape (e.g., *d* in *doctor*) and the other half an initial or final letter with an open shape (e.g., *h* and *r* in *hammer*). A different set of 200 German words were used as stimuli for the semantic task, 100 of these words described living objects (e.g., pilot, apple, dog), and the other 100 referred to nonliving objects (e.g., castle, pencil, bottle). Word length of all words ranged from five to six letters. Words of the different tasks were equated for word length and frequency. This stimulus set was tested in a pilot experiment. Fifteen participants (on average 22.4 years old, nine men) were asked to perform the two induction tasks, which were presented in blocks. Task order was counterbalanced across participants. In the perceptual task, participants decided whether the letter at either the first or the last position of the presented word had a closed shape or whether letters at both positions had an open shape. In the semantic task, participants decided whether the presented word described a living or a nonliving object. Responses were given by pressing one of the two assigned response buttons with the index or middle finger, as fast and as accurately as possible. Response times of correct answers and error rates (ERs) did not show a significant difference between the perceptual and the semantic task (720 vs. 754 ms, $p > .23$, and 3.6% vs. 6.9%, $p > .13$, respectively).

Masked priming paradigm. Primes and targets were the same as in earlier priming studies (Kiefer, 2002; Kiefer & Brendel, 2006; Kiefer & Spitzer, 2000). 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 at visual angle of about 2.58° in width and .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). For the filler trials, 160 new prime–target combinations were selected (the rationale for including filler trials is given below in the Procedure section). Half the filler trials consisted of word–word pairs (40 related, 40 unrelated), and the other half of word–pseudoword pairs. Prime–target combinations were divided into four lists. The assignment of a list to a given experimental condition (combinations of induction tasks/task sets and RPI) was counterbalanced across participants. It was ensured that the word 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 on the modulation of masked priming by previously performed induction tasks, we were only interested in interactions between semantic relatedness and induction tasks, 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.

Procedure. The total number of 800 trials (640 experimental and 160 filler trials) was divided into eight blocks of 100 trials each. The trials of the induction tasks and the masked priming paradigm were combined such that all conditions of the induction task 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 carryover effects. Four subsequent blocks were assigned to each induction task (semantic vs. perceptual). Block order was counterbalanced across participants. Trial order within each block was randomized (semantic relatedness and RPI conditions). Breaks were provided between the blocks. In each trial (see Figure 1), participants were first presented with a fixation cross for 750 ms, which was followed by a word for 500 ms. Participants had to decide as fast and as accurately as possible (a) in the perceptual task, whether or not either the first or the last letter of the word contained a closed shape, and (b) in the semantic task, whether the word referred to a living or nonliving object. As soon as the response was given by pressing one of the designated buttons, a random letter string (forward mask) consisting of 10 capital letters was presented for 200 ms in one condition (RPI, short) or for 800 ms in the other condition (RPI long). Filler trials with an intermediate RPI of 500 ms were included, in order to render the transitions between the different RPI conditions smoother and somewhat more continuously. In either case, the random letter string was followed by the prime word, which was shown for 33.5 ms. After prime presentation, another random letter string was presented for 33.5 ms, which served as backward mask. Thereafter, the target stimulus was displayed that formed either 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. Participants were not informed of the presence of the prime between the forward and backward masks. They were instructed to passively view the masking random letters strings and to concentrate on the target task. The target remained on the screen until a response was given. Thereafter, three hash marks were presented, which prompted the participant to initiate the next trial by a button press. All stimuli were displayed in white font against a black background on a computer monitor synchronously with the screen refresh (refresh rate = 16.67 ms). Before the two blocks of a given induction task, participants first received task instructions and practiced the induction task assigned to this block and the lexical decision task 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 prime between the masks and were asked whether they had recognized that prime words had been presented. None of the participants reported awareness of the primes. An objective measure of prime identification was obtained thereafter within a simple visual discrimination task (see also Kiefer, 2002). Sequence of events and stimulation parameters were identical with the main experiment. After the perceptual or semantic induction tasks, a visual discrimination task on masked stimuli consisting of 80 words and 80 letter strings had to be performed. Each letter string comprised nine repetitions of the identical capital letter (e.g., AAAAAAAAA), which was randomly selected in each trial. Masked words were either semantically related or unrelated to a subsequently presented unmasked context word (40 trials of each condition). This context word corresponds to the lexical decision target in the main experiment and 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). The only difference to the main experiment was that only the long-RPI condition (interval between the response to the induction task and masked stimulus presentation) was realized. This condition should provide a liberal estimation of masked prime identification for the short RPI because at the long RPI, the masking influence of the word of the induction task is reduced. The participants' task was to decide whether the masked stimulus was a word or a letter string. Instructions stressed accuracy over response speed. Participants were also requested to make the best guess when they did not feel confident about the correct response.

Electroencephalography (EEG) recording, signal extraction, and statistical analysis. Scalp voltages were recorded using an equidistant montage of 64 sintered Ag/AgCl electrodes mounted in an electrode cap (Easy Cap, Herrsching, Germany). An electrode between Fpz and Fz was connected to the ground, and an electrode between Cz and FCz served as recording reference. Eye movements were monitored with supra- and infraorbital electrodes and with electrodes on the external canthi. Electrode impedance was kept below 5 kΩ. Electrical signals were amplified with Synamps amplifiers (low-pass filter = 70 Hz, 24 dB/octave attenuation; 50 Hz notch filter) and continuously recorded (digitization rate = 250 Hz), digitally bandpass filtered (high cutoff: 16 Hz, 24 dB/octave attenuation; low cutoff: .1 Hz, 12 dB/octave attenuation), and segmented (420 ms before to 800 ms after target onset of the lexical decision task). EEG data were corrected to a 152-ms baseline that started 352 ms prior to the offset of the forward mask (offset of the mask was at 68 ms before target onset) in order to avoid distortion of the baseline by visually evoked potentials to the mask. In all RPI conditions, the baseline lasted from 420 to 268 ms before target onset. In the short-RPI condition (onset of the mask at −268 ms), the baseline was directly set prior to the onset of the forward mask, whereas in the long-RPI condition (onset of the mask at −868 ms), the baseline started 448 ms after mask onset. Trials with nonocular artifacts and with saccades were discarded. Subsequently, the EEG was corrected for ocular blink contributions using independent components analysis (Makeig, Bell, Jung, Ghahremani, & Sejnowski, 1997). Artifact-free EEG segments to trials with correct behavioral responses were averaged separately for each experimental condition and for each of the 64 electrodes. Analyses of ERPs and those of the RT data (see below in the Results section) were based on the same set of trials. In order to obtain a reference-independent estimation of scalp voltages, the ERP data was recalculated to average reference (Kiefer et al., 1998). EEG analysis was performed with BrainVision analyzer (Brain Products, Gilching, Germany). N400 amplitude was analyzed statistically in the time window of 500–700 ms after target onset, which covered the N400 peak at about 600 ms. Similar to our previous masked priming studies (e.g., Kiefer, 2002; Kiefer & Brendel, 2006), the N400 peaked relatively late in comparison to unmasked priming. As the N400 ERP component typically has the largest amplitudes over the posterior portions of the scalp (Kutas & Hillyard, 1980), ERPs were statistically analyzed at the following electrodes within a region of interest comprising central, parietal, and occipital sites, comparable to our previous studies (Kiefer, 2002; Kiefer & Brendel, 2006): O1/O2, PO1/PO2, PO3/PO4, P1/2, P3/4, CP1/CP2. At each selected electrode site, N400 amplitude was quantified as the mean voltage within the 500- to 700-ms time window.

Repeated measures analyses of variance (ANOVAs) were performed on N400 amplitude at each selected electrode site, with induction task (perceptual vs. semantic), RPI (short vs. long), semantic relatedness (related vs. unrelated), hemisphere (left vs. right), and electrode site (six positions within the region of interest) as within-subjects factors ($p < .05$). In this and the following experiments, statistical analyses were always based on voltages at the individual electrodes within the region of interest. Only for display purposes, ERPs were collapsed across electrode sites if topographical factors (hemisphere or electrode site) did not show significant influences. In order to account for possible violations of the sphericity assumption of the repeated measures ANOVA model, degrees of freedom were adjusted according to the method of Huynh-Feldt (Huynh & Feldt, 1970), and the Huynh-Feldt ε and the corrected significance levels are reported when appropriate.

Results

Behavioral results.

Masked word identification test. We assessed the visibility of the masked primes in an identification test following the priming phase. Identification performance was distributed around the chance level of 50% (mean perceptual = 51.5%, mean semantic = 52.2%), which is to be expected when merely guessing. In order to assess whether the context word facilitated identification of related masked primes (backward priming), d' sensitivity measures for semantically related and for unrelated conditions were calculated from each participant's hit rates (correct responses to words) and false-alarm rates (erroneous responses to letter strings) according to Green and Swets (1966). Backward priming would have produced a higher d' for the related than for the unrelated condition. A repeated measures ANOVA on d' measures with the within-subject factors semantic relatedness and induction task revealed no significant differences between conditions (Fs < 1.82, ps $> .19$). Consequently, it can be excluded that backward priming rendered the masked prime words partially recognizable. Furthermore and most importantly, as the main effect of induction task was not significant (see above in this paragraph), masked prime identification was comparable for the perceptual ($d' = .05$) and semantic ($d' = .18$) induction tasks.

Induction tasks. For RT analysis, mean RT of the correct responses was calculated for each induction task condition. Responses faster or slower than two standard deviations of the individual's means were defined as outliers and not entered into data analysis. In total, 583 trials of all participants (i.e., 4.1% of the entire data set) were excluded from analysis. Separate repeated measures ANOVAs on mean RT and ER with the within-subject factor induction task were performed. Responses in the semantic induction task were significantly faster than responses in the perceptual induction task (887.81 vs. 974.04 ms), $F(1, 21) = 11.25$, $p < .003$. An identical analysis of ER revealed a reversed pattern. Participants committed significantly more errors in the semantic induction task than in the perceptual task (8.8 % vs. 5.3 %), $F(1, 21) = 4.72$, $p < .041$.

Masked priming. Analysis of RT data in the masked priming paradigm was based on mean RT of the correct responses in each experimental condition. Criteria for outlier rejection were the same as for the induction task data. Two hundred ninety-one trials of all participants (i.e., 2.1% of the entire data set) were discarded. Repeated measures ANOVAs on mean RT and ER, with the within-subject factors induction task, RPI, and semantic relatedness, were performed. For the RT data, the main effects for RPI, $F(1, 21) = 5.8$, $p < .026$, and semantic relatedness, $F(1, 21) = 16.54$, $p < .001$, were significant. Most importantly, the expected three-way interaction between the factors induction task, RPI, and semantic relatedness, $F(1, 21) = 5.16$, $p < .034$, was also significant. This interaction was due to a differential modulation of masked semantic priming by the induction tasks as a function of the RPI (see Figure 2): At a short RPI, priming (i.e., the RT difference between the unrelated and related condition) was numerically larger following the semantic (38 ms) than following the perceptual induction task (17 ms), although planned contrasts comparing RTss with semantically related and unrelated prime–target pairs revealed significant priming effects for both the semantic, $F(1, 21) = 14.54$, $p < .001$, and the perceptual induction

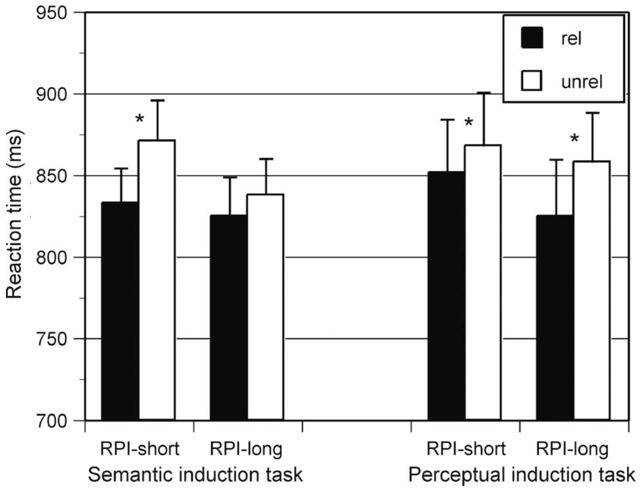

Figure 2. Experiment 1. Lexical decision mean latencies as a function of semantic relatedness, induction task, and response prime interval (RPI). The vertical lines depict the standard error of the means of each condition, and the asterisks indicate significant masked priming effects within each induction task/RPI combination. rel = semantically related prime target pairs; unrel = semantically unrelated prime target pairs.

tasks, $F(1, 21) = 5.01$, $p < .036$. At a long RPI, priming was numerically larger following the perceptual (33 ms) than following the semantic induction task (13 ms). According to planned contrasts, priming was only reliable for the perceptual, $F(1, 21) = 5.07$, $p < .035$, but not for the semantic induction task, $F(1, 21) = 0.68$, $p < .42$. An equivalent ANOVA performed on the ERss did not show significant effects of any factor or combination of these factors—5.5% (perceptual induction task) versus 8.8% (semantic induction task) (Fs < 1.52, ps $> .231$).

Electrophysiological results. Semantically unrelated targets elicited a more negative potential than related targets at central, parietal, and occipital electrodes. This negativity to unrelated targets peaked at about 600 ms (see Figure 3). According to its sensitivity to semantic relatedness, polarity, and topography, this potential was identified as the N400 ERP component (Curran, Tucker, Kutas, & Posner, 1993; Kutas & Hillyard, 1980). In masked priming with short prime durations, the N400 typically reaches its maximum somewhat later than in unmasked priming (e.g., Kiefer, 2002; Kiefer & Brendel, 2006). Note that the N400 ERP component partially overlapped with a positive wave (late-positive complex), as it is typical for experimental paradigms involving an explicit decision (Kutas & Van Petten, 1994). Therefore, the N400 only appears as negative deflection in the waveforms rather than as a negative potential in absolute terms (Holcomb & Neville, 1990; Kiefer, 2001): A less positive potential in one experimental condition compared with a different condition indexes a greater N400. However, for reasons of clarity, the term *more negative* is used hereafter to indicate a greater N400. It was statistically assessed whether the N400 priming effect (relatively more negative potentials to unrelated than to related targets) was modulated by the induction task. Thus, only effects involving the factor semantic relatedness will be reported. For our investigation purposes, the three-way interaction involving the factors semantic relatedness, induction task, and RPI was of central theoretical importance.

We performed a repeated measures ANOVA on mean voltages in the time window of 500–700 ms, with the within-subject factors induction task, RPI, semantic relatedness, hemisphere, and electrode site. The main effect semantic relatedness was significant, $F(1, 21) = 19.32$, $p < .001$, which reflects more negative ERPs to unrelated than to related targets (N400 priming effect). Most importantly, this main effect was further qualified by the three-way interaction of semantic relatedness with induction task and RPI, $F(1, 21) = 5.05$, $p < .035$. This interaction shows that the task sets differentially modulated masked N400 priming effects at the short and long RPIs, similar to the behavioral priming effects (see Figure 3B). At the short RPI, N400 priming effects were larger when preceded by the semantic induction task than when preceded by the perceptual induction task. Planned contrasts that compared N400 amplitude between the related and unrelated conditions demonstrated significant N400 priming only for the semantic, $F(1, 21) = 17.07$, $p < .001$, but not for the perceptual induction task, $F(1, 21) = 0.53$, $p > .474$. At the long RPI, in contrast, priming was larger when preceded by the perceptual than by the semantic induction task. According to planned contrasts, N400 priming effects were only reliable when preceded by the perceptual, $F(1, 21) = 7.56$, $p < .012$, but not when preceded by the semantic induction task, $F(1, 21) = 0.17$, $p > .687$.

Discussion

Behavioral and electrophysiological data revealed differential modulation of the masked semantic priming effect by the induced task set. We obtained an expected triple interaction between semantic relatedness, induction task, and RPI: For short RPIs, masked semantic priming was observed when a semantic task set was activated. In contrast, an induced perceptual task set reduced (in RT data) or even entirely abolished (in ERP data) masked semantic priming. As predicted by our attentional sensitization model, an activated semantic task set thus enhances automatic semantic processing of the subliminal prime, whereas an activated perceptual task set attenuates automatic semantic processing.

The priming effects in the long-RPI conditions suggest that a reconfiguration of the cognitive system in preparation of the upcoming lexical task took place at longer intervals after task completion (800 ms): Masked semantic priming effects were significant following a perceptual induction task, but were absent following a semantic induction task. This priming pattern at the long RPI indicates a relative sensitization of semantic pathways when the perceptual induction task had been completed for several hundred milliseconds. In contrast, when the semantic induction task had been abandoned for a longer time, this condition resulted in a relative desensitization of semantic pathways. The present findings are therefore compatible with the notion of a backward inhibition mechanism that suppresses an irrelevant task set after a task has been abandoned. As outlined in detail in the introductory section, observations of $n - 2$ task repetition costs suggest that such an inhibitory mechanism helps to reconfigure the cognitive system during task switching (Houghton et al., 2009; Hübner et al., 2003; Mayr & Keele, 2000).

In order to estimate the direction in which the preceding induction tasks influenced the magnitude of masked priming, we took as baseline the size of masked priming effects (27 ms) obtained within a previous experiment (Kiefer, 2002) with the same priming procedure and material, but without a preceding induction task.

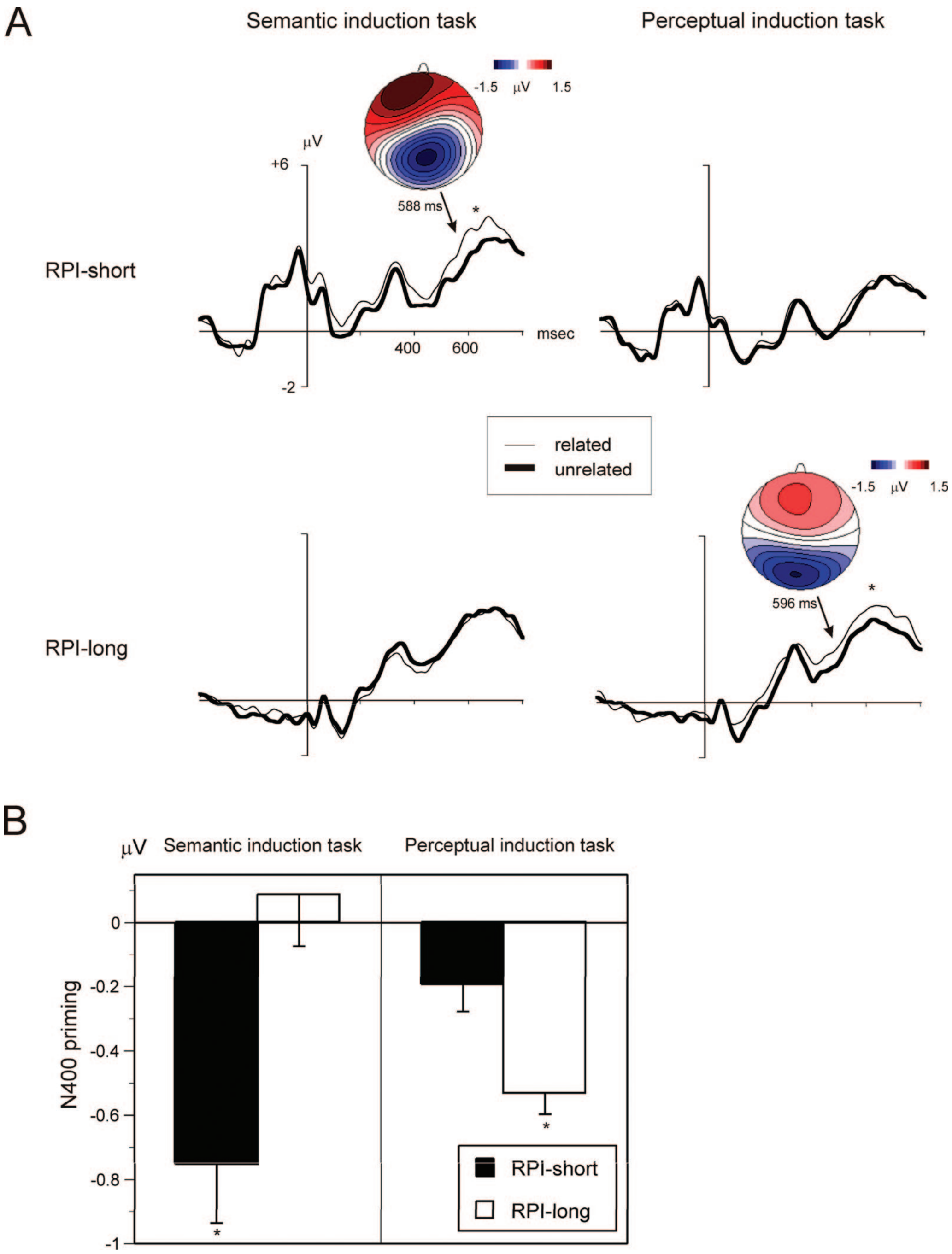

Figure 3. Experiment 1. A: Average-referenced, grand-averaged voltage data from centro-parietal and occipital electrodes as a function of semantic relatedness, induction task, and response prime interval (RPI). As statistical analyses did not yield significant effects of the factors hemisphere or electrode sites, voltages were collapsed across electrode sites within this scalp region of interest. The analyzed electroencephalography epoch lasted from 420 ms before the onset of the target of the lexical decision task to 800 ms after target onset. The long vertical line indicates target onset. Negative potentials are plotted downwards. Color maps display the potential distribution of significant N400 priming effects (unrelated minus related condition) at the respective maximum of global field power (maximum of neural activity) in each condition. The nose indicates the anterior parts of the head. Note the widely distributed negative potential (N400) over the posterior scalp. B: Magnitude of the N400 event-related potential priming effects (unrelated minus related condition) as a function of induction task and response prime interval (RPI). Due to a lack of topographic differences, voltages were collapsed across electrode sites. The asterisks indicate significant masked N400 priming effects in this and the upcoming figures.

The experimental factor RPI could not be realized in this earlier experiment, because participants did not perform an induction task prior to masked prime presentation. When we compare this baseline priming effect with the priming effects in the present experiment, the following picture emerges: At the short RPI in the present experiment, the semantic induction task numerically enhanced priming (38 ms), whereas the perceptual induction task attenuated priming (17 ms). At the long RPI, the opposite pattern was observed. Here, the perceptual induction task numerically enhanced priming (33 ms), whereas the semantic induction task reduced priming (13 ms). However, it should be noted that these comparisons provide only rough measures of the relative sensitization and desensitization of semantic pathways due to semantic and perceptual task sets, respectively. This is because the induction tasks did not only activate task sets, but they also reduced the availability of attentional resources required for amplifying subliminal prime processing in general (Kiefer & Brendel, 2006; Martens & Kiefer, 2009; Naccache et al., 2002). We discuss this issue in the next paragraph.

Overall, behavioral and ERP data provided convergent findings of a top-down modulation of unconscious semantic processing by previously activated task sets. However, interpretation of the data of this experiment is limited by performance differences between the semantic and perceptual induction tasks, although a pilot study assessing the induction tasks in isolation did not reveal significant task differences. In the main experiment, the perceptual task required more processing time than the semantic task when followed by the lexical decision task, indicating increased difficulty of the perceptual induction task. As the semantic induction task was simultaneously associated with a higher ER, the relation between RT and ER in this task resembles a speed–accuracy trade-off rather than a difficulty effect. A speed–accuracy trade-off is, however, unlikely for two reasons. First, we observed in the pilot study the same higher ER for the semantic than for the perceptual task within the context of an opposite RT pattern. Second, semantic judgments of word meaning are more fuzzy and error prone than perceptual judgments of letter shapes, which are based on the well-defined decision criterion whether a letter contains an open or a closed shape.

In support of refined theories of automaticity, masked semantic priming depends on the allocation of attention in time (Kiefer & Brendel, 2006; Naccache et al., 2002) and on the availability of attentional resources (Martens & Kiefer, 2009). One could therefore argue that the differential pattern of the priming effects was not caused by the different task sets activated by the induction tasks, but was due to the higher cognitive load in the perceptual induction task. A simple attentional capacity account does not explain the reduction of priming following the semantic induction task at the long RPI. However, it cannot be excluded with certainty that the reduced availability of attentional resources under the more demanding perceptual induction task abolished masked priming effects at the short RPI. In order to address this possibility, we conducted a second experiment with a novel semantic and perceptual induction task, in which task difficulty was reversed.

Experiment 2

This second experiment aimed at substantiating the differential modulatory effects of the semantic and perceptual induction tasks on masked semantic priming. To assess the relative influences of task sets and attentional resources on masked priming, the processing load in the respective tasks was reversed in Experiment 2 so that the perceptual induction task was now considerably easier than the semantic task: In the perceptual induction task, participants had simply to decide whether the word starts or ends with the letter *t*. The semantic task required the participants to make the demanding decision of whether words refer to objects typically associated with a wet ("bottle") or a dry context ("desert"). If the attenuation of unconscious semantic processing in Experiment 1 immediately after a perceptual induction task at the short RPI was also due to the induced perceptual task set rather than exclusively reflecting reduced attentional resources, this effect should also be observed for the much easier letter decision task. Conversely, if the attenuation of masked priming was caused by reduced attentional resources, we should expect to observe the largest semantic priming effects following the perceptual induction task at the short RPI and smaller or absent priming effects following the semantic induction task.

Method

Participants. Twenty-five healthy, right-handed (Oldfield, 1971), native German speakers with normal or corrected-to-normal vision contributed data to this experiment. The data of three participants had to be excluded from analysis, two due to technical problems in data acquisition and one because the identification rate of this participant exceeded the confidence interval of chance performance in the masked prime identification test (more than 65% correct responses). The remaining 22 participants (eight men and 14 women) were in the age range of 21–32 years, with a mean of 25.7 years.

Material and procedure. The stimulus sets for primes and targets, the timing of all events, and ERP recordings and analysis were identical to Experiment 1. The only difference was in the induction tasks: In the perceptual task, participants had to decide whether or not the first or last letter of the word was the letter *t*. In the semantic task, participants had to categorize the presented word as to whether it refers to an object typically occurring within a wet or dry context. For the perceptual task, 200 German words served as stimuli. One hundred of these words started or finished with the letter *t*, whereas the other 100 did not. Another 200 German words were used as stimuli for the semantic task. One half referred to something wet (e.g., milk, ocean, rain) or to something used within a wet context (e.g., bottle, soap). The other half referred to something dry (e.g., desert, radio). Word length ranged from four to seven letters. Words of the different tasks were equated for word length and frequency. This stimulus set was tested on seven pilot participants for task difficulty. Results showed that responses in the perceptual task were significantly faster than in the semantic task (663 vs. 749 ms), $t(6) = 5.14$, $p < .01$. ERs confirmed also that the perceptual task was significantly easier than the semantic task (3.4 % vs. 6.8 %), $t(6) = 3.51$, $p < .01$. In contrast to Experiment 1, the perceptual task was thus less demanding than the semantic task. All the other experimental parameters, including the recognition test, were identical with those of Experiment 1.

Results

Behavioral results.

Masked word identification test. As in Experiment 1, we assessed the visibility of the masked primes in an identification test following the priming phase. Identification performance was distributed around the chance level of 50% (mean perceptual = 51.9%, mean semantic = 53.0%), which is expected by mere guessing. A repeated measures ANOVA on d' measures (for details see Experiment 1) with the within-subject factors semantic relatedness and induction task revealed no significant differences between conditions (all Fs < 0.43, all ps $> .518$). The possibility can therefore be excluded that masked primes were differentially visible following the perceptual ($d' = .11$) and semantic ($d' = .0$) induction task and that backward priming rendered the masked prime words partially recognizable.

Induction tasks. Analysis of the data of the induction task was identical to Experiment 1. Five hundred seventy-five trials (4.1%) from the whole data set were rejected as outliers. An ANOVA with repeated measures was calculated on mean RT and ER that included the factor induction task. RT in the perceptual induction task was significantly shorter compared with RT in the semantic induction task (744.97 vs. 850.94 ms), $F(1, 21) = 19.53$, $p < .001$. ER revealed in an identical analysis a similar pattern. Performance was significantly less error prone in the perceptual task than in the semantic one (2.6% vs. 9.9%), $F(1, 21) = 11.87$, $p < .002$.

Masked priming. Analysis of the behavioral data of the masked priming task was identical to Experiment 1. Two hundred eighty-six trials (2%) from the entire data set were rejected as outliers. A repeated measures ANOVA, with the within-subject factors induction task, RPI, and semantic relatedness, was performed on mean RT as a dependent variable. All three main effects were significant, all Fs$(1, 21) > 4.38$, all ps $< .048$, as well as the Induction Task × RPI interaction, $F(1, 21) = 8.03$, $p < .01$. The latter reflected longer response times in the lexical decision task following a semantic task set in comparison to the perceptual task set, particularly at the short RPI. Similar to Experiment 1, masked priming after a perceptual induction task was reduced at a short RPI and recovered in the long-RPI condition (see Figure 4). However, this result pattern was only obtained qualitatively because the Semantic Relatedness × Induction Task × RPI interaction did not reach statistical significance, $F(1, 21) = 0.46$, $p > .502$. This was due to the fact that behavioral priming effects following the semantic induction task at the short RPI were small, presumably due to the demanding semantic induction task. When performing an identical ANOVA on ER, a main effect for induction task was obtained, $F(1, 21) = 25.51$, $p < .001$: Following a perceptual task, participant's ERs in the lexical decision task were higher compared with lexical decisions following the semantic task (8% vs. 1.56%). No other factor or combination of factors yielded a significant effect.

Electrophysiological data. As in Experiment 1, we assessed N400 priming effects at central, parietal, and occipital electrodes. We performed a repeated measures ANOVA on mean voltages within the time window of 500–700 ms, with induction task, RPI, semantic relatedness, hemisphere, and electrode site as within-subject factors. The significant main effect of semantic relatedness, $F(1, 21) = 12.89$, $p < .002$, reflected more negative ERPs to unrelated than to related targets demonstrating an N400 priming effect (see Figure 5). Most importantly, this main effect was further qualified by the three-way interaction involving the factors induction task and RPI, indicating that the N400 priming effect was differentially modulated by the induction tasks as in Experiment 1, $F(1, 21) = 8.00$, $p < .01$: At the short RPI, small but significant N400 priming effects were obtained following the semantic induction task, $F(1, 21) = 5.79$, $p < .025$, but not following the perceptual induction task, $F(1, 21) = 0.032$, $p > .859$. At the long RPI, the opposite pattern was found: Significant N400 priming effects were obtained subsequent to the perceptual induction task, $F(1, 21) = 12.39$, $p < .002$. Following the semantic induction task, N400 priming effects were not reliable, $F(1, 21) = 0.95$, $p > .340$ (see Figure 5B).

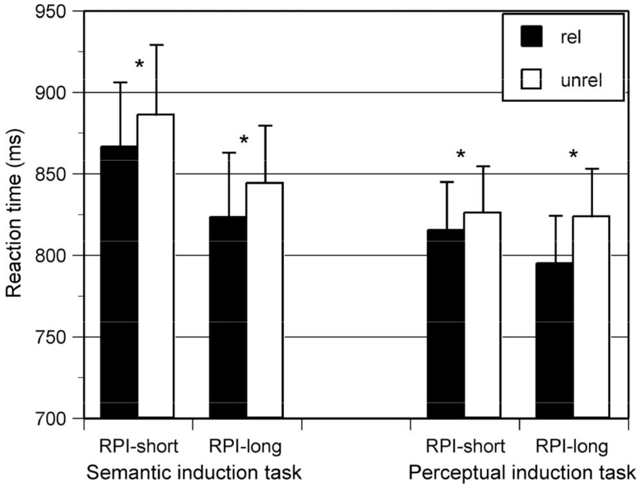

Figure 4. Experiment 2. Lexical decision mean latencies as a function of semantic relatedness, induction task, and response prime interval (RPI). As only the main effect of semantic relatedness, but not the interaction between semantic relatedness, induction task, and RPI, was significant. Priming effects in all induction task–RPI combinations were highlighted as significant with an asterisk. The vertical lines depict the standard error of means of each condition. rel = semantically related prime target pairs; unrel = semantically unrelated prime target pairs.

Discussion

Experiment 2 was designed to assess the contributions of task sets and attentional resources to the modulation of masked semantic priming. In particular, we wanted to substantiate whether the attenuation of masked priming following the perceptual induction task at the short RPI, as obtained in Experiment 1, reflected also the effect of the activated perceptual task set and was not exclusively due to the greater difficulty level of the perceptual induction task. We tested this possibility because masked semantic priming has been shown to depend on available attentional resources (Kiefer & Brendel, 2006; Martens & Kiefer, 2009). In Experiment 2, we therefore developed new versions of semantic and perceptual induction tasks that exhibited the opposite level of difficulty. Data from the pilot experiment and the main experiment showed, as expected, that the perceptual induction task was significantly easier than the semantic task. Hence, the difficulty manipulation of the induction tasks was successful. Despite these differences in the

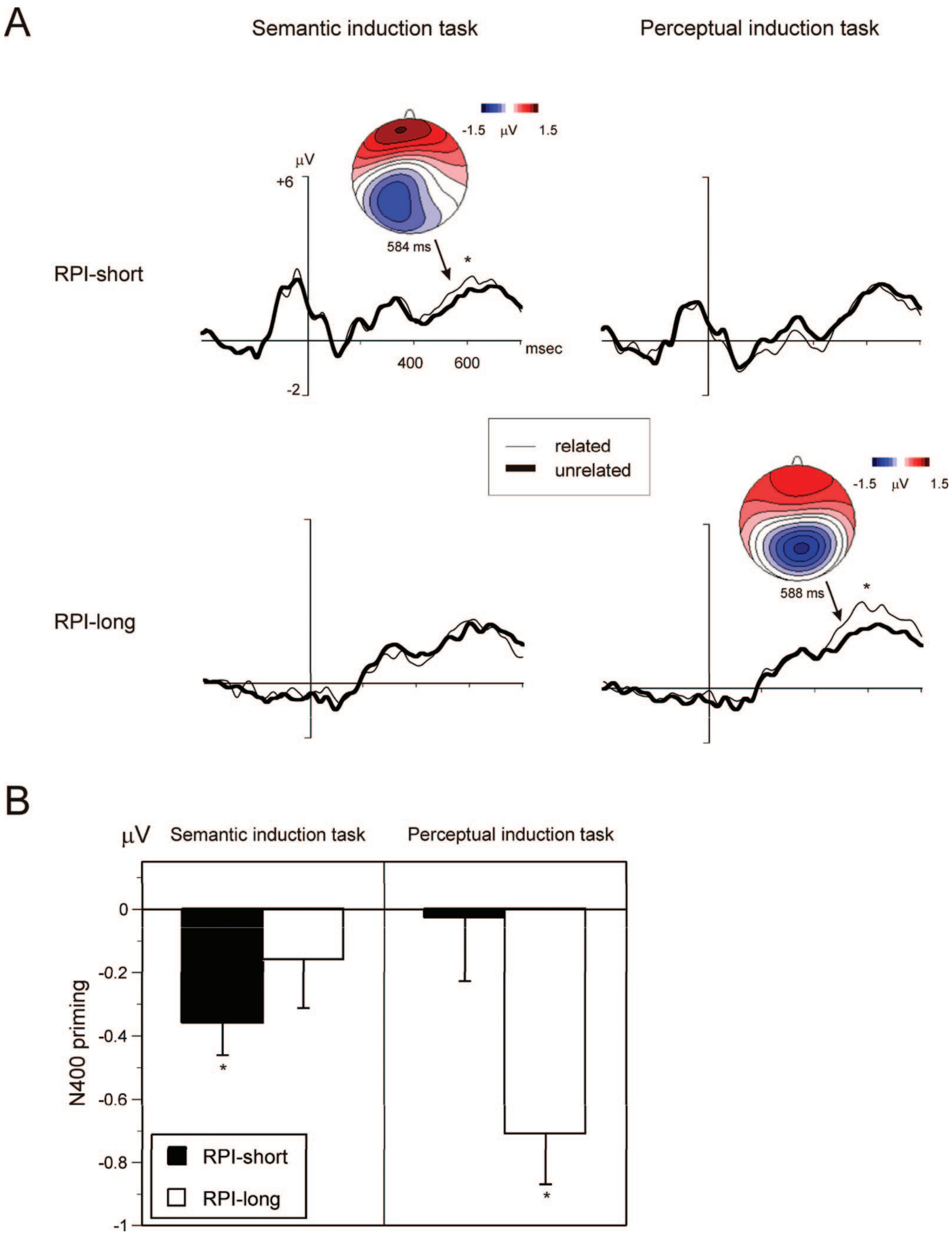

Figure 5. Experiment 2. A: Average-referenced, grand-averaged voltage data from centro-parietal and occipital electrodes as a function of semantic relatedness, induction task, and response prime interval (RPI). As statistical analyses did not yield significant effects of the factors hemisphere or electrode sites, voltages were collapsed across electrode sites within this scalp region of interest. Color maps display the potential distribution of significant N400 priming effects (unrelated minus related condition) at the respective maximum of global field power (maximum of neural activity) in each condition. The nose indicates the anterior parts of the head. B: Magnitude of the N400 ERP priming effects (unrelated minus related condition) as a function of induction task and RPI. Voltages were collapsed across electrode sites. The long vertical line indicates target onset.

difficulty of the induction tasks, the pattern of the N400 priming effects were strikingly comparable across experiments. At a short RPI, N400 priming effects were only obtained after the semantic but not after the perceptual induction task. At a long RPI, in contrast, N400 priming recovered after the perceptual induction task, whereas priming was abolished following the semantic induction task. Experiment 2 therefore substantiates the notion of an attentional sensitizing mechanism that orchestrates the unconscious processing stream in congruency with the current task representations. Similar to Experiment 1, the modulatory effects of the induction task on masked semantic priming varied as a function of the RPI, suggesting a reconfiguration of processing pathways at about 800 ms that reflects a suppression of the irrelevant task set after the task had been completed (Mayr & Keele, 2000).

In contrast to Experiment 1, only N400 priming effects but not behavioral priming effects were significantly modulated by the induction tasks. Nevertheless, following the perceptual induction task, the behavioral priming effect pattern across RPI conditions was qualitatively similar to Experiment 1: There was only little priming at the short RPI (11 ms), whereas priming at the long RPI was numerically stronger (29 ms). In line with the electrophysiological data, these results suggest that an activated perceptual task set dampens unconscious semantic processing of a masked prime.

In addition to the influences of the task sets induced by the induction tasks, there were also signs that masked priming depends on available attentional resources. The relatively difficult semantic induction task appears to have reduced the amount of semantic priming in both the behavioral and ERP data, when the magnitude of priming is compared between Experiments 1 and 2: The behavioral priming effect at the short RPI was numerically quite small (20 ms) compared with the large priming effect in Experiment 1 (38 ms). Similarly, in comparison with Experiment 1, N400 priming in Experiment 2 was numerically reduced at the short RPI following the more difficult semantic induction task, whereas it was numerically enhanced at the long RPI following the easier perceptual induction task. These observations fit in well with the findings of a recent study, in which a reduction of available attentional resources significantly reduced masked semantic priming (Martens & Kiefer, 2009). Hence, in support of the proposed attentional sensitization model, automatic semantic processing of masked words depends on attentional processing capacity that amplifies subliminal stimulus representations (see also Dehaene & Naccache, 2001; Kiefer, 2007; Naccache et al., 2002; Neumann, 1984).

However and highly important for the central goal of our study, the qualitative pattern of the electrophysiological priming effects varied as a function of induction task in a quite comparable manner in Experiments 1 and 2: Independent of the difficulty level of the induction tasks, a perceptual task set activated immediately before masked prime presentation resulted in a relative decrease of semantic priming, whereas a semantic task set led to an increase of priming. Hence, task representations configure the cognitive system in such a way that task-relevant pathways are sensitized. As a result, automatic processing of task-relevant features of subliminal stimuli is enhanced, whereas automatic processing of task-irrelevant features is dampened.

Experiment 3

The third experiment served to substantiate the assumption that top-down modulation of unconscious cognition is accomplished by a differential sensitization of processing pathways. This sensitizing mechanism is assumed to enhance processing in task-relevant pathways and attenuates processing in task-irrelevant pathways without the involvement of an inhibitory mechanism. However, as outlined in the introduction, top-down modulation could alternatively be accomplished by an active inhibition mechanism evoked by the particular type of verbal perceptual induction tasks that were used in the previous experiments: These perceptual induction tasks afforded identification of letter features within a word while the more salient global word form and word meaning had to be inhibited (Hübner & Malinowski, 2002; Stroop, 1935). It is possible that this inhibitory task set activated by such verbal perceptual induction tasks had been implicitly applied to the unconsciously presented masked prime word. As a consequence of this inhibitory mechanism, semantic analysis of the masked word (Craik & Lockhart, 1972) and priming effects were attenuated in comparison to the semantic induction task (Mari-Beffa et al., 2000; Maxfield, 1997). It should be noted at this point that the possible inhibitory mechanism discussed here is associated with the task set evoked by the perceptual induction task and has to be theoretically distinguished from the backward inhibition mechanism during task switching that serves to suppress an irrelevant task set (Mayr & Keele, 2000). As already mentioned in the introductory section, a further elucidation of backward inhibition of task sets is beyond the scope of Experiment 3.

In Experiment 3, we tested the assumption that an inhibitory task set that originates from a conflict between stimulus dimensions in the induction task is a prerequisite for the modulation of masked priming by previously performed tasks. In order to decide between the attentional sensitization and the active inhibition accounts, we developed two different nonverbal induction tasks with pictorial stimuli, which required attentional orientation to semantic and to perceptual features, respectively. In contrast to Experiments 1 and 2, the perceptual induction task did not require inhibition of task-irrelevant global word features in favor of local letter features. In the new perceptual induction task, participants had to decide whether the object's shape was round or elongated. In the new semantic induction task, participants were requested to decide whether the picture displayed a living or nonliving object. As the perceptual induction task of this experiment did not require inhibition of global word form and meaning, the active inhibition account predicts comparable priming following the perceptual and the semantic induction tasks. If, however, top-down modulation of masked priming is accomplished by the proposed attentional sensitization mechanism, semantic priming should be decreased following the perceptual induction task compared with the semantic induction task, because an attentional orientation toward semantic versus toward perceptual stimulus features is sufficient to differentially sensitize semantic processing pathways. Hence, we expect that the nonverbal induction tasks of Experiment 3 modulate masked priming in a similar way as in the previous experiments with verbal induction tasks.

Method

Participants. Twenty-five healthy, right-handed (Oldfield, 1971), native German speakers with normal or corrected-to-normal vision contributed data to this experiment. The data of one participant had to be excluded from analysis due to technical problems in data acquisition, data of another participant due to too many artifacts in the EEG data, and data of an additional participant because the identification rate exceeded the confidence interval of chance performance in the masked prime identification test (more than 65% correct responses). The remaining 22 participants (10 men and 12 women) were in the age range of 20–33 years, with a mean of 25.0 years.

Materials and procedure. The stimulus sets for primes and targets, the timing of all events, and ERP recordings and analysis were identical to the previous experiments, with the exception that object pictures instead of words were used in this experiment as stimuli for the induction tasks. A set of 400 grey-scale pictures of living and nonliving objects was selected from an initial set of 706 pictures according to a pilot study. Pictures showed a common object against a black background and were adjusted to comparable levels of brightness and contrast. The horizontal and vertical size of each image frame was 170 × 216 pixels (72 pixels/inch resolution), resulting in a visual angle of 3.2 × 3.8° at a viewing distance of 90 cm. For the perceptual induction task, 200 of these pictures were used as stimuli. Half of these displayed an object with a round shape and the other half an object with a long shape (living and nonliving objects were equally distributed across the shapes). Unlike the pictures in this perceptual induction task, another 200 pictures were used as stimuli for the semantic task, of which 100 displayed living objects and 100 nonliving objects (shape was balanced across conditions). These stimuli were tested in the following pilot experiment: Eight participants (eight women, on average 24.4 years old) were asked to perform the two induction tasks, which were presented in blocks. Task order was counterbalanced across participants. In the perceptual task, participants were instructed to decide whether the displayed object had a round or a long shape. In the semantic task, they had to decide whether the presented object was a living or a nonliving object. Responses were given by pressing as fast and as accurately as possible one of the two assigned keys with the index or middle finger. For the final stimulus set of 400 objects, only those pictures were chosen for which none of the eight participants committed an error. Moreover, they were matched for response times, so that RTs did not significantly differ between the perceptual and the semantic task (547.4 vs. 551.0 ms, $p > .82$).

Results

Behavioral results.

Masked word identification test. We assessed the visibility of the masked primes in an identification test following the priming phase. Identification performance was distributed around the chance level of 50% (mean perceptual = 51.6%, mean semantic = 49.9%), which is expected by mere guessing. A repeated measures ANOVA on d' measures, with the within-subject factors semantic relatedness and induction task, revealed a significant main effect for semantic relatedness, $F(1, 21) = 6.95$, $p < .016$. This effect was due to a slightly better recognition of primes that were semantically related to the target than when not ($d' = .11$ vs. $-.06$, respectively). However, note that the overall recognition rate was at chance level, suggesting that this difference between semantic relatedness conditions reflects traces of unconscious semantic processing. Furthermore, there was no effect of induction task or an interaction between induction task and semantic relatedness (all Fs < 1.82, all ps $> .19$), demonstrating comparable masked prime identification following the perceptual ($d' = .08$) and the semantic ($d' = -.03$) induction tasks.

Induction tasks. Analysis of the data of the induction task was identical to the previous Experiments. In total, 363 trials from all participants (i.e., 2.6% of the entire data set) had to be excluded from analysis as outliers. Separate repeated measures ANOVAs on mean RT and ER, with the within-subject factor induction task, were performed. RT differences between the induction tasks were not significant, but responses to the perceptual task tended to be slightly faster than to the semantic task (544.39 vs. 570.57 ms), $F(1, 21) = 3.63$, $p < .071$. An identical analysis of ER revealed no differences between both tasks. ER was on average 13.8% in both tasks, $F(1, 21) < .02$, $p > .90$.

Masked priming. Analysis of the data of the masked priming task was identical to the previous experiment. Across all participants, 185 trials (i.e., 1.3% of the entire data set) were rejected as outliers. Repeated -measures ANOVAs on mean RT and ER, with the within-subject factors induction task, RPI, and semantic relatedness, were performed. In the RT analysis, the main effects for RPI, $F(1, 21) = 13.5$, $p < .0014$, and semantic relatedness, $F(1, 21) = 33.78$, $p < .0001$, were significant. Most importantly, the predicted three-way interaction between the factors induction task, RPI, and semantic relatedness, $F(1, 21) = 12.00$, $p < .003$, was also significant (see Figure 6). As expected, this interaction was due to a differential modulation of masked semantic priming by induction task and RPI: At the short RPI, priming was numerically larger subsequent to the semantic induction task (29 ms) than subsequent to the perceptual induction task (12 ms), but planned contrasts demonstrated reliable priming effects for both the semantic, $F(1, 21) = 20.46$, $p < .001$, and the perceptual induction tasks, $F(1, 21) = 4.99$, $p < .037$. At the long RPI, in contrast, priming was numerically larger for the perceptual (30 ms) than for the semantic induction task (10 ms). Planned contrasts yielded reliable priming effects only for the perceptual, $F(1, 21) = 17.79$, $p < .001$, but not for the semantic induction task, $F(1, 21) = 2.05$, $p > .16$. An equivalent ANOVA performed on ER showed only a significant main effect of semantic relatedness, 1.9% (related) vs. 3.5% (unrelated), $F(1, 21) = 17.19$, $p < .001$.

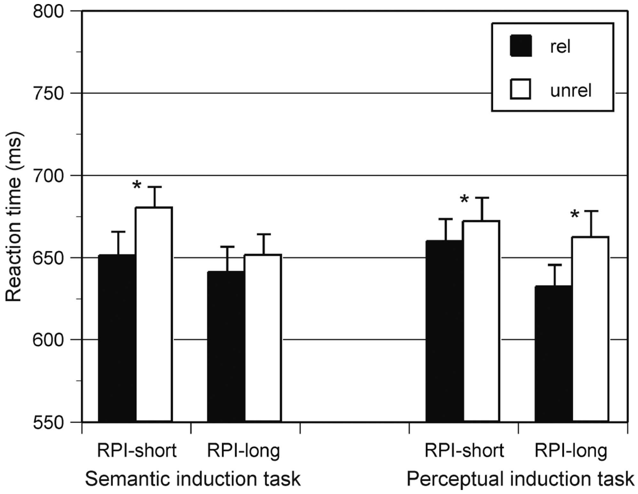

Figure 6. Experiment 3. Lexical decision mean latencies as a function of semantic relatedness, induction task, and response prime interval (RPI). The vertical lines depict the standard error of means of each condition. rel = semantically related prime target pairs; unrel = semantically unrelated prime target pairs.

Electrophysiological results. We performed a repeated measures ANOVA on mean voltages in the N400 time window of 500–700 ms with the within-subject factors induction task, RPI, semantic relatedness, hemisphere, and electrode site. Only effects involving the factor semantic relatedness are reported. The main effect semantic relatedness was significant, $F(1, 21) = 12.55$, $p < .002$, which reflected more negative ERPs to unrelated than to related targets (N400 priming effect). Most importantly, N400 priming was significantly modulated by the factors induction task and RPI, as shown by the four-way Semantic Relatedness × Induction Task × RPI × Electrode Site interaction, $F(5, 105) = 2.39$, $p < .043$. This interaction indicates that the induction tasks differentially modulated masked N400 priming effects (see Figure 7). Although the inclusion of the factor electrode site in this interaction could be indicative of a difference of N400 priming across electrodes, separate follow-up repeated measures ANOVAs for each RPI with the factors induction task, semantic relatedness, hemisphere, and electrode site did not reveal any variations in scalp distribution: For the short RPI, the Induction Task × Semantic Relatedness interaction was significant, $F(1, 21) = 5.58$, $p < .027$, reflecting a reliable N400 priming effect for a semantic induction task, $F(1, 21) = 6.82$, $p < .016$, but not for a perceptual induction task, $F(1, 21) = 0.45$, $p > .51$. For the long RPI, only the main effect semantic relatedness was significant, $F(1, 21) < 9.43$, $p < .01$, but semantic relatedness did not interact with the factor induction task ($F < 1$) (see also Figure 7B).

Conjoint analysis of Experiments 1–3. In order to test whether the observed modulation of masked priming significantly differed across experiments as a function of induction task and RPI, we performed a conjoint analysis of the data from all three experiments and calculated separate ANOVAs with repeated measures for behavioral priming (RT data) and N400 priming. This analysis included the additional between-subject factor experiment. Most importantly, for both the RT and the electrophysiological data, the three-way Induction Task × RPI × Semantic Relatedness interaction was significant: RT data, $F(1, 63) = 8.78$, $p < .004$; electrophysiological data, $F(1, 63) = 12.07$, $p < .001$. In contrast, the corresponding four-way interaction, including the additional between-subject factor experiment, was far from reaching conventional significance levels: RT data, $F(2, 63) = 0.53$, $p > .59$; electrophysiological data, $F(2, 63) = 0.61$, $p > .55$. Hence, the pattern of priming effects was comparable across experiments and did not significantly depend on the precise quality of the perceptual and semantic induction tasks (verbal and nonverbal, easy and difficult).

Discussion

Experiment 3 was set up to assess the specific nature of the mechanism underlying the modulatory effects of task sets on masked semantic priming. In particular, we wanted to determine which of the two potential mechanisms could account for the observed pattern of results: The proposed attentional sensitization model assumes that top-down modulation is achieved by a differential sensitization of processing pathways depending on the activated task set. Alternatively, top-down modulation could be the result of an active inhibition mechanism evoked by the induction task in order to resolve competition between less salient letter features and more dominant global word features (word form and meaning) in favor of the less salient target dimension (Hübner & Malinowski, 2002; Stroop, 1935).

In order to distinguish between these alternative accounts, we developed for this experiment new, nonverbal induction tasks that required the perceptual and semantic classification of object pictures. As the nonverbal perceptual induction task (shape classification) required suppression of neither the word form nor the global shape in general, which was in fact task relevant, this task cannot induce an inhibitory task set toward word processing that could have been implicitly applied to the subsequently presented subliminal prime. Accordingly, only the attentional sensitization model but not the active inhibition account predicts attenuation of semantic priming following the nonverbal perceptual induction task.

Behavioral and ERP results of Experiment 3 are straightforward and clearly support the attentional sensitization model. As in the previous experiments with verbal stimuli, this nonverbal perceptual induction task attenuated masked semantic priming compared with the semantic induction task when the subliminal prime was presented at a short RPI. As predicted by our model, attention to perceptual stimulus features, whether pertaining to verbal or nonverbal stimuli, suffices to attenuate unconscious semantic priming. In contrast, the observed interaction between induction task and priming with nonverbal stimuli is clearly inconsistent with an active inhibition account.

This demonstration of attentional top-down control on unconscious cognition therefore agrees nicely with results from previous neurophysiological studies on the neuronal correlates of attention on conscious stimulus processing (Pessoa et al., 2003). These earlier studies provided converging evidence for an attentional enhancement of processing pathways through the increase of sensitivity in sensory areas to incoming information following an attentional cue (Chawla et al., 1999). Our present findings suggest that a similar attentional sensitization mechanism could be controlling not only conscious but also unconscious cognition. It should be noted, however, that in the present experiments, we could measure only the computational consequences of the differential attentional sensitizing of semantic pathways via behavioral and electrophysiological masked semantic priming effects, but not the sensitization process itself. In contrast to single-cell recordings or functional magnetic resonance imaging, the spatial resolution of ERPs is too low to neuroanatomically differentiate between a sensitization of perceptual and semantic processes, respectively, because both types of processes involve areas within the temporal lobe (inferior temporal cortex) in close neuroanatomical vicinity (L. Cohen & Dehaene, 2004; Hoenig, Sim, Bochev, Herrnberger, & Kiefer, 2008; Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996).

At the long RPI, when the onset delay of the masked prime was longer after the induction task, we again found evidence of a reconfiguration of the cognitive system that includes a deactivation of the irrelevant task set: Priming following the perceptual induction task recovered (behavioral and ERP data), whereas priming following the semantic induction task was abolished (behavioral data only). Unexpectedly, following the semantic induction task at the long RPI, only behavioral, but not N400, priming was attenuated. We attribute the divergence between behavioral and electrophysiological priming in this occasion to the fact that behavioral measures reflect the output of the entire processing chain, includ-

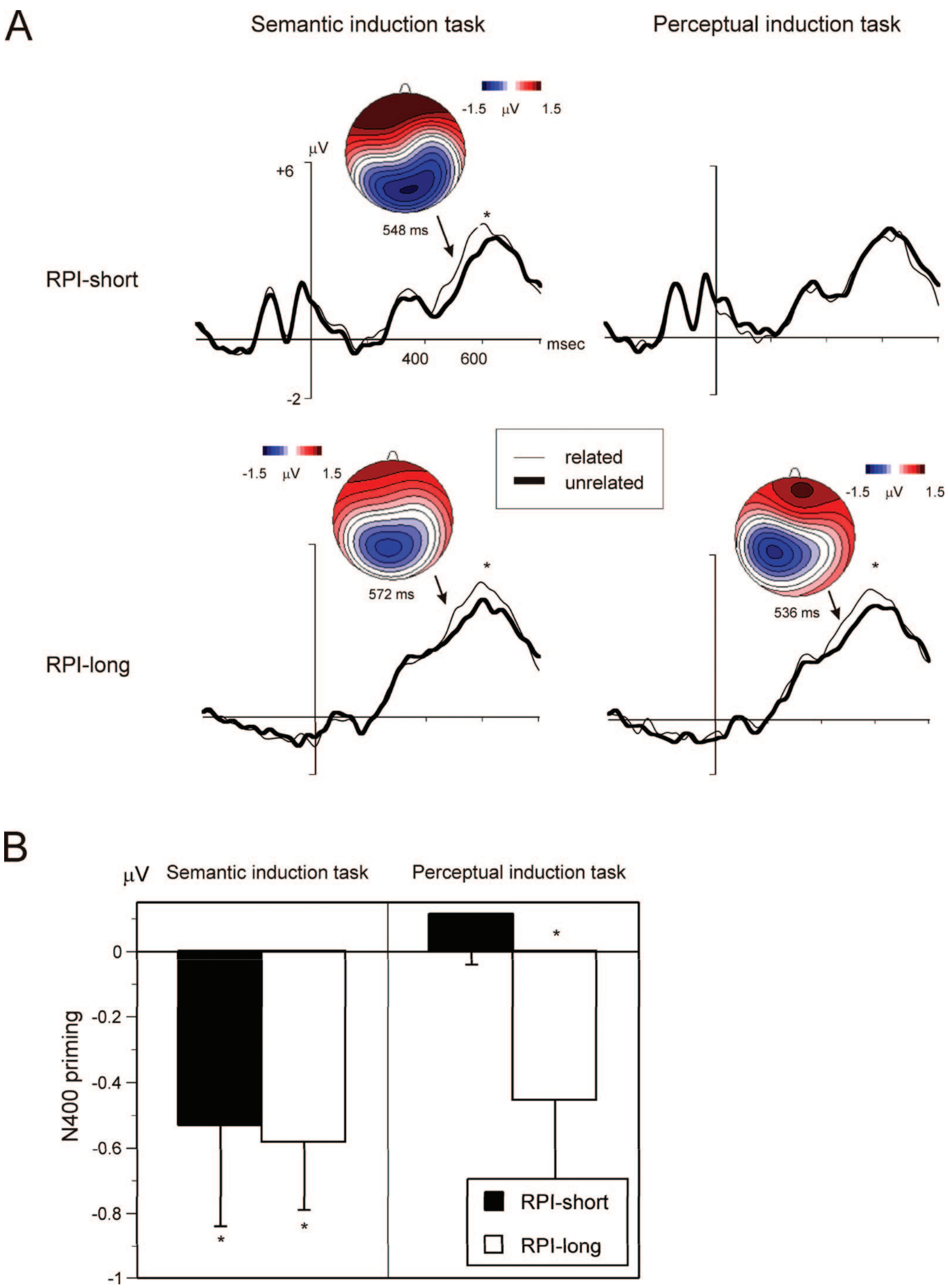

Figure 7. Experiment 3. A: Average-referenced, grand-averaged voltage data from centro-parietal and occipital electrodes as a function of semantic relatedness, induction task, and response prime interval (RPI). As N400 priming effects did not significantly differ between electrode sites, voltages were collapsed across electrode sites within this scalp region of interest. Color maps display the potential distribution of significant N400 priming effects (unrelated minus related condition) at the respective maximum of global field power (maximum of neural activity) in each condition. The nose indicates the anterior parts of the head. B: Magnitude of the N400 event-related potential priming effects (unrelated minus related condition) as a function of induction task and RPI. Voltages were collapsed across electrode sites. The long vertical line indicates target onset.

ing decision and response execution processes, whereas N400 data index semantic integration processes within a specific time window (see also the General Discussion section). Most importantly, the predicted reduction of priming effects following a perceptual induction task at the short RPI, which was of main theoretical interest, was obtained for both behavioral and N400 priming data.

It is noteworthy that in this experiment, perceptual and semantic induction tasks exhibited a quite comparable level of task difficulty. If anything, the perceptual task was slightly, but nonsignificantly easier than the semantic task. Nevertheless, the perceptual induction task attenuated semantic priming at the short RPI similarly to the previous experiments. The results of the present experiment therefore confirm the main finding of Experiments 1 and 2: They show that the modulatory influences of the induction tasks on unconscious semantic priming also reflect the specific effects of task sets and cannot be reduced to the availability of unspecific attentional resources. In fact, a conjoint analysis of the RT and electrophysiological data across all three experiments yielded significant interactions between the factors induction task, RPI, and semantic relatedness, whereas the between-subject factor experiment was far from significant.

In conclusion, Experiment 3 shows that top-down modulation of masked semantic priming generalizes to nonverbal induction tasks that do not require an active suppression of the word form and that exhibit a comparable level of task difficulty. Hence, these results further substantiate our proposal of a differential sensitization of processing pathways in congruency with task sets and higher level goals.

General Discussion

We investigated for the first time the nature of implicit top-down control of unconscious semantic priming in the present study. In particular, we tested the assumption of the attentional sensitization model that task representations configure the cognitive system in such a way that processing streams are sensitized in congruency with an active task set, whereas task-incongruent processing streams are desensitized. To investigate this proposed modulation of unconscious automatic processes by task sets, we developed a novel experimental paradigm, in which participants were engaged in a semantic or perceptual induction task before undergoing masked semantic priming within a lexical decision task. The induction task was expected to activate a corresponding task set (semantic or perceptual) and to modulate the sensitivity of semantic and perceptual processing pathways. The rationale of this approach was that when a masked prime word is presented after the induction task, depending on the semantic or perceptual nature of the activated task set, semantic processing of the unconsciously perceived word is enhanced or attenuated. Consequently, within a few hundred milliseconds after the induction task, a semantic induction task should enhance unconscious semantic priming, whereas a perceptual induction task should attenuate semantic priming.

In line with the attentional sensitization model, all three experiments showed that the induction tasks strongly modulated unconscious semantic processing, irrespective of their form (verbal or nonverbal) and level of difficulty. At a short RPI, subliminal semantic priming was consistently large when the masked prime was presented immediately after a semantic induction task. In contrast, when the masked prime was presented subsequent to a perceptual induction task, semantic priming was consistently attenuated. Hence, within an interval of several hundred milliseconds after task completion, a persistently active semantic task set sensitizes semantic processing pathways compared with a perceptual task set, which induces a relative desensitization of semantic processing.

At a long RPI, when the induction tasks had already concluded 800 ms earlier, we found indications for a reconfiguration of the cognitive system that presumably reflects active suppression of an abandoned irrelevant task set: Following a perceptual induction task, the masked prime word elicited strong semantic priming effects, whereas priming was attenuated following a semantic induction task. In line with evidence from studies on task switching, the present results are compatible with the notion that a task set is suppressed once the old task has been completed and preparation for a new, predictable task has started (Houghton et al., 2009; Hübner et al., 2003; Mayr et al., 2006; Mayr & Keele, 2000). Following a perceptual induction task at the long RPI, both the suppression of the perceptual task set and the activation of the task set for the upcoming lexical decision task are assumed to conjointly increase the sensitivity of semantic pathways and to enhance masked semantic priming. However, following a semantic induction task at a long RPI, the suppression of the semantic task set results in a strong desensitization of semantic pathways. The task set associated with the upcoming lexical decision task is not able to considerably increase the sensitivity of semantic pathways due to the counteracting influence of the suppressed task set of the semantic induction task. As the net sensitivity of semantic pathways is decreased, at the long RPI, masked semantic priming is reduced following a semantic induction task compared with priming following a perceptual induction task. The differential modulatory effects of induction tasks on masked priming as a function of RPI provide a window to the dynamic nature of cognitive reorganization that takes place during task set switching that in turn influences top-down control of unconscious cognition.

The novel paradigm presented here, combining a task for inducing task sets with a subsequent priming paradigm, could therefore serve as an important tool for elucidating the reconfiguration processes in future task-switching studies. In particular, the somewhat counterintuitive modulatory effects of the induction tasks on masked priming at the long RPI, which are assumed to originate from the suppression of the task set of the induction task, could represent a potentially interesting direction of future research. For instance, it would be theoretically relevant to investigate whether this phenomenon indeed reflects suppression of the task set of the induction task by systematically varying the type of induction task (e.g., semantic classification vs. perceptual letter shape classification) and the form of priming (e.g., orthographic priming vs. semantic priming). If task set suppression is the relevant mechanism underlying the modulation of masked priming at the long RPI, an induction task requiring letter shape classification should suppress orthographic letter priming (for orthographic priming, see Lupker & Davis, 2009), but should permit semantic priming after long delays.

The present experiments cannot determine whether the induction task influences masked priming by speeding up responses to related prime target pairs and/or by slowing down responses to unrelated pairs. The differential difficulty of the induction tasks and the cognitive reconfiguration process elicited by the switch from the induction task to the lexical decision task influences lexical decision latencies in a complex manner as a function of the RPI. As a consequence, absolute RTs (or ERPs) to the related and unrelated prime target pairs in the lexical decision task cannot be interpreted unequivocally across induction task and RPI conditions. For this reason, we focus on the magnitude of priming, calculated as RT (or ERP) difference between related and unrelated prime target pairs. Perhaps, the inclusion of a putatively "neutral" prime condition, such as a meaningless letter string, could provide more information in future studies on the issue of how the induction tasks influence priming. However, even such neutral priming condition would deliver only tentative information because there are doubts as to whether a "neutral" prime condition is really neutral and unbiased (de Groot, Thomassen, & Hudson, 1982; den Heyer, Taylor, & Abate, 1986).

Although the recovery of semantic priming following a perceptual induction task at a long RPI was found for both ERP and behavioral data in all experiments and very consistently, the attenuation of priming following a semantic induction task was somewhat less robust. In Experiment 2, an attenuation following the semantic induction task at a long RPI was observed only for the ERP data, and in Experiment 3 only for the behavioral data. As we elaborated above, we assume that in the long-RPI condition, the concurrent influence of suppressing the old irrelevant task set induced by the induction task and activating the new task set for the upcoming lexical decision task conjointly modulate the attentional sensitization of semantic pathways and consequently affect masked semantic priming. In the perceptual induction task, both influences increase the sensitivity of semantic pathways resulting in robust priming effects. In the semantic induction task condition, in contrast, influences from the suppression of the irrelevant semantic task set and the activation of the task set for the upcoming lexical decision task are conflictive regarding the sensitization of semantic pathways. Hence, at the long RPI, depending on the precise state of the reorganization process, these diverging influences result in a net (de-)sensitization of semantic pathways of varying magnitude that translates into a less robust attenuation of behavioral and ERP priming effects.

It should be noted, though, that a divergence between behavioral and N400 measures has also been observed in several earlier studies on semantic processing (e.g., Bentin, Kutas, & Hillyard, 1995; Heil, Rolke, & Pecchinenda, 2004; Kiefer & Brendel, 2006). This divergence between dependent measures of behavioral and physiological origin is most likely due to the fact that RT priming and N400 priming capture semantic processing in different ways. RT measures are always influenced by the entire processing chain required for task performance from perceptual stimulus processing over the different semantic processing stages to decision and motor execution. The N400, in contrast, specifically reflects semantic integration processes within a well-defined time window predominantly originating from a relatively circumscribed neuroanatomical structure in the anterior-ventral temporal lobe (Kiefer et al., 2007; Nobre & McCarthy, 1995). Other semantic processes like initial access to conceptual features, which also contribute to RT priming effects, are indicated by other, earlier ERP components (Hinojosa et al., 2001; Hoenig et al., 2008; Kiefer et al., 2008), which could not be recorded in the present paradigm. Given these inherent differences in indexing semantic information processing, it is likely that behavioral and N400 measures occasionally diverge because experimental manipulations may differentially influence various stages of semantic processing. As a result, a divergence between these measures is most likely apparent in conditions as for the semantic induction task at the long RPI, in which cognitive influences are heterogeneous and more variable.

Mechanisms Underlying the Modulation of Subliminal Priming by Previously Performed Tasks

In this study, the perceptual induction task consistently reduced subliminal semantic priming in comparison with the semantic induction task when the masked prime was immediately presented after the induction task. In terms of the attentional sensitization model, this effect was interpreted as reflecting a differential sensitization of processing pathways in congruency with higher level task representations without the contribution of inhibitory processes. In Experiment 3, we were able to rule out the influence of an active inhibitory mechanism involved in suppressing dominant irrelevant stimulus features in order to overcome interfering processes (Craik & Lockhart, 1972; Maxfield, 1997; Stroop, 1935). As we outlined in detail in the introductory section, this possible inhibitory mechanism pertains to the task set evoked by the perceptual induction task if it includes a competition between stimulus features. This form of inhibitory mechanism has to be theoretically distinguished from backward inhibition of task sets during task switching that is thought to be responsible for task set suppression at the long RPI. The task set suppression mechanism, which also involves active inhibition processes, influences the activation level of task sets in accordance with dynamically changing action goals and contributes to the reconfiguration of the cognitive system during task switching. A further elucidation of this mechanism is beyond the scope of the present study.

In order to find evidence in favor of either the attentional sensitization or active inhibition accounts, we used a nonverbal induction task with pictorial stimuli in Experiment 3. This task required attention to object shape without there being any need to suppress conflicting influences from word form and word meaning in favor of less salient local features, as could have been the case in Experiments 1 and 2. Even this nonverbal perceptual induction task attenuated priming in comparison with the semantic task (semantic classification of pictures) when presented before the masked prime at a short RPI. The present study therefore specifies the mechanism underlying top-down modulation of unconscious priming. It demonstrates that previously performed tasks induce an attentional sensitization of task-relevant processing pathways (perceptual vs. semantic) that enhance or attenuate subliminal priming. This notion of an inhibition-free mechanism of attentional sensitization of unconscious processing parallels earlier suggestions that active inhibition is only applied to controlled, but not to automatic processes (Merikle et al., 1995; Neely, 1977; Posner & Snyder, 1975).

Although the results of Experiment 3 clearly support the attentional sensitization model, a further alternative explanation is conceivable. It could be argued that the observed modulation of masked priming by previously performed induction tasks reflects a competition between the simultaneously activated semantic representations of the word (or picture) presented in the induction task, on the one hand, and of the masked prime word, on the other (e.g., Schriefers, 1992). This would result in a weaker semantic prime activation. It is further conceivable that the semantic representation of the stimulus in the induction task is strengthened at the long RPI, because participants had more time to process its meaning. It thus interferes more strongly with the meaning of the masked prime at the long than at the short RPI, thereby reducing priming. However, this semantic competition account cannot explain the data for several reasons: First, the word or picture in the induction task was not semantically related to the masked prime. However, semantic competition typically occurs only for close associates, but not for unrelated concepts (Carr & Dagenbach, 1990; Humphreys, Riddoch, & Quinlan, 1988). Second, it only explains the reduction of semantic priming following a semantic induction task at a long RPI, but does not account for the priming pattern following the perceptual induction task at either RPI. Third, the stimulus of the induction task was only presented for 500 ms. Within the RPI, the forward mask was seen that prompted participants to get ready for the lexical decision task. Thus, there is no reason to believe that the semantic representation of this word should gain in strength when the task had been abandoned and participants prepared for the upcoming lexical decision task. Typically, semantic representations decay as a function of time unless they are actively maintained (Greenwald, Draine, & Abrams, 1996; Kiefer & Spitzer, 2000; Neely, 1991). As a strengthened semantic representation of the word from the induction task would highly interfere with the lexical decision to the target word, the semantic competition account predicts slower responses to the lexical task in the long- than in the short-RPI conditions. Exactly the opposite pattern was observed, however: Lexical decisions were consistently faster at the long than at the short RPI, indicating a more efficient reconfiguration of the cognitive system when participants had more time to get ready for the lexical decision task. Hence, semantic competition can neither explain the priming pattern following the perceptual induction task nor the overall lexical decision latencies as a function of the RPI.

In conclusion, the priming pattern across the three experiments confirms the predictions of the attentional sensitization model: Irrespective of the type of the induction task, masked priming was reduced when the prime was presented within the time window of an active perceptual task set in comparison to a semantic task set. Hence, the present data strongly supports the notion of an attentional sensitization of processing pathways that enhances and attenuates automatic processing of unconsciously perceived stimuli in congruency with task representations. Alternative theoretical accounts that include active inhibition of task-irrelevant stimulus features or a competition between semantic representations are inconsistent with the present data. The generality of the attentional sensitization model could be tested in future studies by investigating the modulatory influence of perceptual and semantic induction tasks on other forms of priming such as orthographic (Lupker & Davis, 2009), perceptual (Tulving & Schacter, 1990), or response priming (Neumann, 1990). As these forms of priming strongly depend on visual or visuomotor representations, our model makes the strong prediction that a perceptual induction task enhances perceptual-based priming at a short RPI, whereas a semantic induction tasks reduces priming.

Attentional Sensitization and the Automaticity of Semantic Processing

The present work not only has important implications for the field of unconscious cognition but also helps to resolve the fierce debate regarding the automaticity of semantic processing. Researchers have argued that semantic processing is not automatic, but requires controlled access to conceptual meaning (Duscherer & Holender, 2002; Henik et al., 1994). This is because semantic priming with consciously perceived stimuli strongly depends on attentional orientation toward the prime word (for a review, see Deacon & Shelley-Tremblay, 2000; Maxfield, 1997). Several studies found reduced or absent semantic priming when the prime word was presented outside the focus of attention (Kellenbach & Michie, 1996; McCarthy & Nobre, 1993) or when participants were required to attend to perceptual letter features of the prime (e.g., a letter search task) and not to its meaning (Chiappe, Smith, & Besner, 1996; Mari-Beffa, Valdes, Cullen, Catena, & Houghton, 2005). These findings are taken as evidence that access to conceptual meaning is confined to a controlled processing mode. However, several other studies favor the view that semantic processing can also occur in an automatic fashion: That unconsciously perceived prime words can elicit semantic priming effects has been demonstrated reliably (Carr & Dagenbach, 1990; Draine & Greenwald, 1998; Kiefer, 2002; Kiefer & Spitzer, 2000; Rolke, Heil, Streb, & Henninghausen, 2001). As priming by unconsciously perceived words cannot be caused by controlled processes, these data provide support for automatic semantic processing.

At first glance, these preceding findings regarding the automaticity of semantic processing appear highly contradictory. However, the proposed attentional sensitization model and the present demonstration of top-down modulatory effects on subliminal semantic priming help to resolve this discrepancy. Our research suggests that automatic semantic processing and the notion of attentional top-down control is not necessarily a contradiction as has been previously thought. Semantic processing can occur automatically in the sense that it does not depend on conscious awareness and that it is initiated without deliberate intention. However, automatic semantic processing is susceptible to attentional top-down control and is only elicited if the cognitive system is configured accordingly. In classical masked priming experiments without a preceding induction task, this configuration may be achieved by the task set, which is induced by the preparation for the target task (e.g., lexical decision or naming task). This attentional orientation toward word reading and recognition could be sufficient for sensitizing pathways for unconscious semantic prime processing (see also Valdes, Catena, & Mari-Beffa, 2005).

The earlier findings of attentional effects on visible priming do not necessarily question the possibility of automatic semantic processing, because they can be easily explained by the attentional sensitization model of automatic processing outlined here. As we have shown, the classical defining criteria for automaticity, such as independence of attentional top-down control and cognitive autonomy (Posner & Snyder, 1975; Schneider & Shiffrin, 1977), do not provide a theoretically reasonable distinction between automatic and controlled semantic processes, because an interaction between attentional orientation and semantic priming can be obtained even under subliminal and therefore clearly automatic processing conditions.

Attentional Sensitization of Automatic Processes in Cognition and Emotion

The present study provides evidence for an attentional top-down modulation of masked semantic priming by task sets. If the dependence of automatic processes on attentional sensitization is a general computational principle and does not represent a peculiarity of the semantic system, similar phenomena of top-down control on automatic processing should be observed in other domains. In this section, we discuss results from previous research on sensorimotor preparation, emotion, and on cognitive deficits in psychiatric patients, which are highly relevant in this respect. In particular, we show that seemingly paradoxical, hitherto unexplained findings regarding the automaticity of the underlying processes can be easily accommodated within the attentional sensitization model.

As already mentioned in the introduction section, automatic sensorimotor response preparation within the masked response priming paradigm presumably depends on action intentions: Only unconsciously perceived masked primes that are congruent with the current action plan elicited response priming effects (Ansorge & Neumann, 2005; Eckstein & Perrig, 2007; Kunde et al., 2003). Similarly, a goal-dependent action congruency effect was obtained during the processing of visible, manipulable objects. Several behavioral and neurophysiological studies showed that the mere observation of manipulable objects like tools is sufficient to activate action representations (Chao & Martin, 2000; Hoenig et al., 2008). In this context, an action congruency effect was described, which reflected faster responses in a decision task when motor responses were compatible with the action affordances of an object even though its action affordances were task irrelevant (Bub, Masson, & Cree, 2008; Helbig, Graf, & Kiefer, 2006; Tucker & Ellis, 1998). This action congruency effect has been interpreted to reflect automatic activation of sensorimotor representations, because this effect depends on an involuntary and task-irrelevant process. However, this action congruency effect was abolished when the goal state for the target task did not involve a reach-and-grasp response (Bub & Masson, 2010). Does this task dependency of action congruency and masked response priming effects indicate that sensorimotor processes exclusively proceed in a controlled and strategic fashion? And how do such top-down effects, implicating strategic control, match with reports of unconscious, putatively automatic sensorimotor effects in healthy participants (Neumann, 1990) as well as in brain-damaged patients with visual agnosia (Milner & Goodale, 1995)? As we have already argued in the discussion of the automaticity of semantic processing, these seemingly conflicting results in sensorimotor processing can be easily resolved if one assumes that automatic processes are susceptible to top-down control: According to the attentional sensitization model, unconscious or conscious stimuli can only automatically trigger those sensorimotor processes that match the sensitized processing pathways.

In the research on emotion, findings of the automaticity of emotional processing are likewise contradictory. Several studies suggest that emotional stimulus information is processed outside conscious awareness in an automatic fashion (Gaillard et al., 2006; Kemp-Wheeler & Hill, 1992; Morris, Öhman, & Dolan, 1998; Öhman & Soares, 1998), whereas other results suggest that emotional information is only accessed within a strategic processing mode: For instance, the typical increase of neural activity to emotional faces in the amygdala, a subcortical structure essentially relevant for assigning emotional arousal to a stimulus, was abolished when a demanding secondary task strongly depleted attentional resources (Pessoa et al., 2002). As emotional brain activity depends on attention, it has been concluded that emotional processing is not automatic (Pessoa et al., 2003). Again, these seemingly discrepant findings of the automaticity of emotional processing can be accommodated in the attentional sensitization model. Our framework assumes that automatic processes, similar to controlled processes, depend on an attentional amplification that sensitizes processing pathways. If a secondary task depletes attentional resources, the potential of an affective stimulus to automatically trigger an emotional response is reduced or abolished.

These examples from sensorimotor and emotional processing demonstrate that the proposed attentional sensitization model generalizes to domains other than semantic processing and has the explanatory power to account for, to date, conflicting empirical phenomena in the healthy subject population. However, this framework also helps to better understand heterogeneous cognitive and emotional deficits in psychiatric disorders by conceptualizing them as a partial breakdown of the attentional sensitization mechanism. Patients with schizophrenia suffer from deficits in attentional control, as demonstrated in tasks affording executive function and controlled semantic retrieval (Nestor et al., 2001). However, these patients also exhibit exaggerated automatic processing, reflected particularly by increased conscious and unconscious semantic priming (Kiefer, Martens, Weisbrod, Hermle, & Spitzer, 2009; Spitzer, Braun, Hermle, & Maier, 1993).

Although the attentional dysfunction hypothesis and the exaggerated automatic processing hypothesis of cognitive deficits in schizophrenia have been previously considered to be mutually exclusive (e.g., Barch et al., 1996), the impairment in controlled processing and the simultaneous enhancement of automatic processing could have a common origin: According to the attentional sensitization model, both peculiarities in patients with schizophrenia could result from deficits in the attentional sensitization mechanism that affects both controlled and automatic processing, presumably because of dysfunctional prefrontal neural circuits (Weinberger et al., 2001). As a result, the loss of a modulating prefrontal top-down signal leaves automatic processes in posterior brain areas unfocused and enhanced, with controlled processes being likewise impaired (Kiefer et al., 2009; Spitzer, 1997). In support of this assumption, patients with schizophrenia exhibited reduced functional connectivity between prefrontal and temporal areas during a word recognition task compared with a group of healthy controls (Griego, Cortes, Nune, Fisher, & Tagamets, 2008). This suggests a diminished prefrontal top-down influence on sensory and semantic processing. A similar explanation could also apply to cognitive and emotional deficits in major depression, which also affect both controlled (Fossati, Amar, Raoux, Ergis, & Allilaire, 1999; Fresco, Heimberg, Abramowitz, & Bertram, 2006) and automatic processing (Dannlowski et al., 2006; Watkins, Vache, Verney, Muller, & Mathews, 1996). In future studies, impairments of attentional sensitization in psychiatric patients could be directly tested by using our modified masked priming paradigm: Unlike healthy controls, these psychiatric patient groups should be less susceptible to attentional sensitization and should exhibit comparable subliminal semantic priming irrespective of the induction tasks. The examples in this section show that the proposed attentional sensitization model accommodates, to date, unexplained, apparently paradoxical findings in many research areas and generates novel, empirically testable predictions.

Top-Down Control of Unconscious Cognition and the Flexibility of the Mind

The implicit top-down control of unconscious processing by attentional sensitization demonstrated here evidences the adaptability of the cognitive system in optimizing ongoing processing toward the pursuit of an intended goal: Task-relevant information is prioritized and task-irrelevant, possibly interfering influences are attenuated, both at a conscious and an unconscious level. The unconscious processing streams are thus under the control of higher level attention to some extent. The proposed attentional sensitization mechanism operates in such a fashion as to considerably reduce the risk that unintended and not goal-related unconscious processes determine cognition and eventually influence behavior. If automatic processes were entirely autonomous, as claimed by classical theories of automaticity, a major part of the cognitive processing stream would be beyond higher level control. Goal-directed information processing would thus be massively influenced by interfering processes stemming from unconscious cognition. This would have a tremendous impact on the amount of effort required by the cognitive control system to produce the intended behavioral output, because control would mainly be exerted reactively and late in the processing stream at the stage of response selection. In contrast, preemptive top-down control of unconscious processes as postulated by the attentional sensitization model allows for coordinating the processing streams in congruency with higher level goals at the earlier perceptual and semantic stages of processing. This considerably reduces the effort of the cognitive control system in response monitoring (Botvinick et al., 2001) because conflicting processes are dampened at relatively early stages. Hence, attentional sensitization of automatic processing pathways ensures a high degree of flexibility and adaptability of our cognitive system in the interaction with the dynamically changing challenges of the environment.

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