



Review

Unconscious vision and executive control: How unconscious processing and conscious action control interact



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ABSTRACT

Research on unconscious or unaware vision has demonstrated that unconscious processing can be flexibly adapted to the current goals of human agents. The present review focuses on one area of research, masked visual priming. This method uses visual stimuli presented in a temporal sequence to lower the visibility of one of these stimuli. In this way, a stimulus can be masked and even rendered invisible. Despite its invisibility, a masked stimulus if used as a prime can influence a variety of executive functions, such as response activation, semantic processing, or attention shifting. There are also limitations on the processing of masked primes. While masked priming research demonstrates the top-down dependent usage of unconscious vision during task-set execution it also highlights that the set-up of a new task-set depends on conscious vision as its input. This basic distinction captures a major qualitative difference between conscious and unconscious vision.

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1. Introduction

Since long it has been argued that not all visual processing is conscious (Münsterberg, 1910), but especially the recent decades have seen a tremendous number of articles concerning the capabilities of unconscious vision (for topical reviews, see Ansorge, Horstmann, & Scharlau, 2011; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Dehaene & Naccache, 2001; Kiefer, Adams, & Zovko, 2012; Kunde, Reuss, & Kiesel, 2012; Lamme, 2003). The current article focuses on one very fruitful method in the area of unconscious vision, namely masked priming (Greenwald, Draine, & Abrams, 1996; Marcel, 1983). There are other methods to study unconscious vision, like investigating visual capabilities after brain lesions (Goodale, Milner, Jakobson, & Carey, 1991) or priming during continuous flash suppression (Almeida, Mahon, Nakayama, & Caramazza, 2008; Tsuchiya & Koch, 2005). In comparison to brain lesion studies, however, masked priming allows studying unconscious processing also in healthy participants, therefore avoiding interpretational difficulties due to neuro-plastic changes of processing after brain damage. Furthermore, masked priming has been applied in a greater variety of studies compared with the more recent method of continuous flash suppression. Finally, methods in which attention is directed away from a stimulus or in which binocular rivalry is used to lower conscious perception of a stimulus are not entirely convincing in terms of the claimed invisibility of the stimuli (Blake, 1998; Holender, 1986), and therefore are also only occasionally discussed in the present review. As masked priming research provides an important window on unconscious vision for several decades, our portrait therefore almost naturally relies mostly on research in this area, although we will sometimes refer to related findings with other methods as well.

The focus of the current review is on the connection between unconscious vision and executive functions. These functions encompass the setting up and representation of goals and the operations needed to achieve these goals (Baddeley & Hitch, 1974; Miller & Cohen, 2001; Miyake et al., 2000). In this context, task-control representations, sometimes simply called ‘task sets’, denote representations specifying preceding conditions that have to be met for the execution of an action (e.g., ‘It turns dark, so I should switch on the light.’) or an operation (e.g., ‘I have to get out of the airport, so I should search for an exit sign.’) the corresponding action (e.g., ‘Switch on the light.’) or operation (e.g., ‘Attend to the signs under the ceiling.’) itself, as well as optional intended consequences of these actions, such as outcomes (e.g., ‘Light is on.’, or ‘There is an exit sign.’). Finally, executive control includes the processes necessary for securing the success of the actions and operations. Among these supporting processes are the shielding of goal representations against conflicting goals, the monitoring of the outcomes of actions and operations, and the registration and correction of errors during the execution of the operations (Norman & Shallice, 1986). The latter are typically involved when an operation is repeatedly performed, as in a computer experiment consisting of many trials.

Intuitively, there seems to be a tight connection between the activity of executive functions and consciousness or awareness. For example, when I decide to buy an apartment because I do no longer want to pay the rent, I have the strong intuition that I am fully aware of setting up the task set representation of how I go about buying an apartment, including the visual information that I have taken into account while deciding. Accordingly, early theories equated conscious vision with top-down controlled processing and unconscious vision with so-called automatic processing (Norman & Shallice, 1986; Posner & Snyder, 1975). In this context, automatic processing means that unconscious vision would run off independently of an agent’s own intentions, being entirely stimulus triggered, and being even uncontrollable – that is, not modifiable by a currently opposing intention or task set. In fact, until today, many theories take this stance on unconscious vision (Mulckhuysse & Theeuwes, 2010).

As we will delineate, however, much research on masked priming supported a different view (Ansorge & Neumann, 2005; Dehaene & Naccache, 2001; Kiefer & Martens, 2010; Neumann, 1990). Specifically, our review has three aims. First, we look at the most important strands of research that led to the conclusion that unconscious vision depends on top-down control. This will be done in part 2. Second, we will review different theories of masked priming and point out some surprising commonalities between these theories (mostly in part 2), as well as the differences between them (in parts 2, 3, and 4). Finally, we will detail the limits of top-down control of unconscious vision in part 3, and the limits of unconscious vision in general in part 4. The latter concerns the very limited power of unconscious vision to modify or set up task sets in the first place.

1.1. Masked priming

In masked priming, a visual prime is presented followed by a visual mask at the same position or surrounding the same position. Typically, the interval between prime and mask is short (about a few tens of milliseconds). This procedure is called ‘backward masking’ because the mask follows the prime (Breitmeyer, 1984). Backward masking can lead to the complete

absence of the prime's visibility. Sometimes this subjective lack of awareness is additionally reflected in objective chance performance when the participant is asked to discriminate the prime stimulus (Dagenbach, Carr, & Wilhelmson, 1989; Hines, Czerwinski, Sawyer, & Dwyer, 1986; Klotz & Neumann, 1999; Marcel, 1983). Its invisibility notwithstanding, a masked prime influences overt behavior. For example, using visible boys and girls names as targets that had to be discriminated by their gender, with a masked gender-congruent prime presented before the target (e.g., a male prime before a male target) responses were facilitated as compared to a masked incongruent prime (e.g., a male prime before a female target) (Greenwald et al., 1996). This influence was found although the participants could not reliably discriminate between the prime's gender per se.

Clearly, such experimental tasks like to press one button for a girl's name and another button for a boy's name require setting up and execution of a task set. On the side of the participants, such a task requires connecting two arbitrary responses as the to-be-executed operations with the two different classes of inputs of boys' versus girls' names. Although the fact that such a task set needs to be implemented to get going is sometimes not considered important by researchers using masked priming to address questions of semantic memory, lexical access and so on, implementing the task set on the side of the participants means we have entered the realm of executive control. Masked priming must therefore have something to say about the interactions between unconscious vision and executive functions, which will be highlighted in the next sections of this article.

2. Unconscious vision and executive control

Theories on action control traditionally assume a strong link between cognitive control and consciousness. For example, Jack and Shallice (2001) make a clear distinction between conscious action where control is possible and automatic action where it is not. This distinction echoes the traditional dichotomy between unconscious automatic processing that is independent of executive control and controlled processing in the conscious domain (Posner & Snyder, 1975; Shiffrin & Schneider, 1977). Perhaps most clearly the control-consciousness link is expressed in the workspace model by Dehaene and Naccache (2001). Here the authors suggest that routine actions are possible without consciousness, whereas consciousness is required for cognitive control, such that "an unseen prime cannot be used as a source of control to modify the choice of processing steps" (Naccache, Blandin, & Dehaene, 2002, p. 423). The assumption of such a link between consciousness and control did not arise from nothing, but from empirical evidence that is sometimes overlooked in nowadays discussions of this topic. We want to remind of two studies. Marcel (1980) presented subjects with three words in row. The second word was a homonymous prime word such as "bank". The ambiguity of this prime was resolved by a preceding context word such as "park". The third word should be judged for lexicality and was either semantically related to the context-supported meaning of the prime (e.g., "sit") or it was not related (e.g., "save"). When the context word was masked the priming effect occurred with respect to both meanings of the homonymous prime. However, when it was visible, the priming effect was confined to the context-supported meaning of the prime. In other words, only a conscious context had the power to constrain the semantic processing of the homonym in one respect. In another study Merikle and Joordens (1997) used a variant of the Stoop task in which color words (e.g., 'red' and 'green') preceded to be named color patches. A common observation with this setting is that when the primes are more predictive of the opposite response category than of the same response category because more incongruent than congruent trials are realized, subjects respond faster in incongruent compared to congruent trials. This is considered as a strategic adaptation of the subjects who manage to prepare the response opposite to the one signalled by the prime. This strategy developed with visible but not with invisible primes, for which normal congruence effects were found despite the primes' predictiveness for the incongruent response. This and related findings formally demonstrated *dissociations* between visual awareness of the one hand and visual processing on the other hand. In this particular example, the influence of the frequency of incongruent trials selectively affected processing in the aware mode but not in the unaware mode. In other examples, the influences of one and the same variable on aware versus unaware modes can be dissociated from one another in other ways (Dixon, 1971; Schmidt & Vorberg, 2006). We will come back to this important observation at a later point in our review.

While studies like these prompted the assumption of a link between awareness and control, the picture has changed in recent years. The conclusion from this research is that it is possible to apply task-control representations to visual input of which the human observer remains unaware. At the same time unconscious stimuli also seem to be able to activate and influence task control representations, albeit in a very limited way. This conclusion has been reached with studies that can be classified along two major dimensions. One dimension concerns the particular process addressed with the indirect measure or the priming effect. For example, for the indirect measure visuo-motor priming, semantic priming, attentional priming, or task-set priming were used to probe the particular process under investigation. The other dimension concerns the particular method used for demonstrating an awareness-independence of the priming effect (direct measure). Awareness-independence can be established in different ways, such as zero discrimination ability in a direct measure of prime visibility, a regression method in which priming effects are regressed on prime visibility, or dissociations between direct and indirect measures in terms of different effects of one and the same manipulation on direct and indirect measures. In the following, we will develop our main conclusions with paragraphs roughly ordered along types of prime processing, whereas we will only occasionally refer to different types of prime awareness measures.

2.1. Masked visuo-motor priming

In line with the idea that vision can operate independently of consciousness, unconscious vision for action has been demonstrated in several ways. In masked visuo-motor priming, for example, several studies showed that masked shapes lead to a response activation (e.g., Fehrer & Raab, 1962; Klotz & Neumann, 1999; Klotz & Wolff, 1995; Neumann & Klotz, 1994; Tapia, Breitmeyer, & Shooner, 2010; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). In the meantime, congruence effects of masked primes have been independently found in numerous studies, with shapes (Breitmeyer, Ro, & Singhal, 2004; Jaśkowski, van der Lubbe, Schlotterbeck, & Verleger, 2002; Leuthold & Kopp, 1998; Wolbers et al., 2006), locations (Ansorge & Neumann, 2005; Neumann & Klotz, 1994), colors (Breitmeyer et al., 2004; Schmidt, 2002; Vath & Schmidt, 2007), pictures of movements (Güldenpenning, Kunde, Weigelt, & Schack, 2012), and even with illusory contours as masked primes (Seydell-Greenwald & Schmidt, 2012).

Importantly, there is only an arbitrary connection between, for example, a left-hand button press and a square, and a right-hand button press to a diamond (cf. Klotz & Wolff, 1995). Thus, a fitting task-control representation that specified the different shapes as the critical input for the execution of alternative motor responses seems to be necessary to account for some instances of the masked-priming effect in the first place.

However, in other instances of masked priming this was not so clear. For example, Neumann and Klotz (1994; Klotz & Neumann, 1999) asked their participants to respond to a target on the right with a right button press and to respond to a target on the left with a left button press. Also, in the congruent condition, the target-shaped prime was presented at the same position as the target, whereas in the incongruent condition, the target-shaped prime was presented at the opposite side to the target. In this situation, it is possible that the masked-priming effect reflected stimulus-driven activation of the responses of the Simon type – that is, an automatic response activation by the prime's position that occurred regardless of the actually pertaining task-control representation (cf. Kornblum, Hasbroucq, & Osman, 1990). However, Leuthold and Kopp (1998) found additive effects of prime-target congruence (i.e., the similarity of prime and target positions) and prime-response compatibility (i.e., the similarity of the prime and response positions) suggesting that task-control representations play a role in masked visuo-motor priming. The congruence effect was the same when the participants responded spatially compatibly to the targets (i.e., with a left button press to a left target) and when they responded spatially incompatibly to the targets (i.e., with a right button press to a left target), although a Simon effect of the masked primes should have undermined the congruence effect in the incompatible conditions. Along similar lines, several studies showed that the congruence effect (based on prime and target shape similarity or color similarity) was eliminated once the feature of the prime was task-irrelevant (Ansorge & Neumann, 2005). For example, when the participants were presented with masked primes, and with targets that varied with respect to the color-congruence and to the shape-congruence between prime and target, a masked priming effect based on prime-target color congruence was found if the task was to discriminate between target colors but not if the task was to discriminate between target shapes. The opposite pattern was found if the participants' task was to discriminate between target shapes (Ansorge, Becker, & Breitmeyer, 2009; Schmidt & Schmidt, 2010; Tapia, Breitmeyer, Jacob, & Broyles, 2013; see also Schlaghecken & Eimer, 2004). Clearly, this pattern of results also speaks against a bottom-up response activation of the Simon type because spatial prime-response compatibility relations in these studies were not altered. For example, when Ansorge et al.'s (2009) participants had to respond to the position of a target with a predefined task-relevant shape, the target's and prime's colors were irrelevant. Yet, a color-congruent prime (of the same color as the target and at the same position as the target) would have also had the potential to automatically activate the response required for the target, whereas a color-incongruent prime (of the same color as the target but at the opposite side of the target) would have also had the potential to automatically activate a response conflicting with that which was required for the targets. Yet, although the conditions for a Simon effect would have thus been met, the irrelevant color did not lead to a prime-target congruence effect.

Interestingly, van Opstal, Gevers, Osman, and Verguts (2010) found that the actually pertaining task set was also applied to stimuli that were outside the range of the instructed target stimuli. These authors asked their participants to judge, for example, whether two colored rectangles as targets that were presented side by side were of the same color (e.g., both red) or of different colors (e.g., one green and one blue). In this situation, they presented two masked numbers (also side by side) as primes. These primes were always black and clearly outside of the set of used targets. Despite the fact that the number primes were not part of the instructed task set, the primes created a congruence effect. If two identical numbers were used as primes (e.g., 3 and 3) congruent same-color judgments were facilitated as compared to incongruent different-color judgments. If two different numbers were used as primes (e.g., 2 and 6) congruent different-color judgments were facilitated as compared to incongruent same-color judgments. This is in contrast to studies like Ansorge and Neumann (2005) or Tapia et al. (2013) and means that more research is needed to characterize the content of the task set, which is applied to the unconscious prime. For instance, it is possible that in the van Opstal et al. (2010) study, in which participants' task was to decide about the identity of the target stimulus pair, stimulus identity irrespective of the specific stimulus dimension (color or numerical identity) constituted the task set. In any case a task set specifying which operation applying to which stimuli must exist for masked stimuli to bias behavior, at least in situations when there is only an arbitrary link between prime and target that is specified by task instructions.

2.2. Models of executive control of masked visuo-motor priming

The first model that explained the role of task sets for the selection of the relevant features during masked visuo-motor priming was Neumann's theory of direct parameter specification (1990). According to Neumann, humans set up action plans specifying the critical inputs that need to be met and the actions that are to be executed when the input is met. Critically, the theory of direct parameter specification requires that this task set is set up before a visual stimulus (e.g., a prime) so that the critical input resembling the relevant features can lead *directly* to the purported action – where the term '*direct*' means that the stimulus in question can activate a response directly, without a mediating conscious representation. In this way, the theory of direct parameter specification explained visuo-motor priming of to-be-executed actions on the basis of unconscious primes (Neumann & Klotz, 1994). This theory was subsequently spelled out by Kunde, Kiesel, and Hoffmann (2003) who suggested that the related principle of 'action triggering' accounted for visuo-motor priming. According to the action-triggering principle, a task-control representation includes templates for response-relevant target stimuli, the so-called 'action triggers'. In a task-control representation different action triggers are connected with their respective motor responses. These action triggers are defined in a top-down way and according to the actually pertaining instructions. This can be done without practising the trigger-response links. Once this has been done, a masked prime that is akin to an action trigger sets off the response that is specified in the task-control representation, although the prime can remain below the threshold of awareness. Both the concepts of direct parameter specification and the action-triggering account are reminiscent of related concepts such as 'Bezugsvorstellungen' (Ach, 1905), 'implementation intentions' (Gollwitzer, 1999), or 'start anticipations' (Hoffmann, 1993).

Given a task set has been implemented, several models explain how visuo-motor priming ensues. Vorberg et al. (2003) modelled the masked-priming effect with an accumulator model that was different from related models (Hanes & Schall, 1996; Ratcliff, 1978). In their model, prime and target (the latter also serving as mask) both elicit a respective increase of the accumulating evidence in favor of the response that they indicate, and a response would be initiated, once the threshold for a *difference between the responses* would be reached. According to the model, the prime's influence thus propels responding to the congruent target and delays responding to the incongruent target, and this congruence effect increases monotonically with the prime's head start relative to the target – that is, monotonically with the prime-target stimulus onset asynchrony (SOA). Early observations were well in line with this prediction and showed that the initial processing phase after prime presentation was entirely determined by prime activation until the target kicked in (Schmidt, Niehaus, & Nagel, 2006; Vath & Schmidt, 2007; Vorberg et al., 2003). This SOA-proportional masked visuo-motor priming effect also nicely contrasts with a deviating (e.g. non-linear) masking function (i.e., the prime's visibility as a function of the SOA). In fact, on the basis of the robust differences between the effects of SOAs on priming and prime visibility during metacontrast masking alone researchers have argued for a dissociation between awareness of the primes and awareness-independent forms of priming (Mattler, 2007; Schmidt & Vorberg, 2006).

However, additional factors have to be taken into consideration when one wants to account for the masked visuo-motor priming effect in full. These factors will be reviewed next. By now, there is good evidence that based on their prior experience with task performance in a masked priming experiment, the participants are able to adapt the thresholds for the responses towards their optimality points of trading speed against errors (Bodner & Dypvik, 2005; Bodner & Masson, 2001; Jaśkowski, Skalska, & Verleger, 2003; Kinoshita, Forster, & Mozer, 2008; Kinoshita, Mozer, & Forster, 2011; see also Norris & Kinoshita, 2008). The assumption of threshold-adaptation became necessary to account for the influence of the likelihood of incongruent conditions relative to congruent conditions on masked priming effects. These effects will be explained in more detail below.

Here it should suffice that this characteristic of the masked-priming effect inspired the ASE (adaptation-to-the-statistics of the environment) model of Kinoshita and colleagues. The ASE model is more flexible than the model of Vorberg et al. (2003) because it can also account for decisions based on masked primes other than response decisions, such as the decision about the execution of particular covert mental operations that are not identical with the execution of specific motor responses. In the next chapter, we will review evidence that demonstrated that this generalization of the task-control representation principle is necessary to account for those types of masked priming effects that are independent of visuo-motor processing alone.

A different modification of the model of Vorberg et al. (2003) was proposed by Schubert, Palazova, and Hutt (2013). These authors confirmed and modelled that the masked-priming effect also critically hinges on the allocation of temporal attention to the prime. Their experiments and model were prompted by findings, such as that of Naccache et al. (2002) that masked priming effects depended on the participants' ability to successfully allocate their attention to the primes. To account for the stronger response-activation effect of attended-to than not attended-to masked primes, Schubert et al. assumed an influence of attention on the drift rates with which information from the primes can be accumulated: With more attention being allocated to the prime, the slope of the drift rate would increase, the response criterion, thus, more swiftly reached, and a congruence effect increased.

A final adjustment of the models concerned the finding of an 'inverse priming effect' (Verleger, Jaśkowski, Aydemir, van der Lubbe, & Groen, 2004) or a 'negative compatibility effect' or 'NCE', as it was more often called (Eimer & Schlaghecken, 1998; Lleras & Enns, 2004; Schlaghecken & Eimer, 2002; Sumner, 2007). Eimer and Schlaghecken (1998) used the term 'compatibility' to refer to what we consistently called 'congruence' in the current review paper. The NCE, however, consists of faster responses in incongruent than congruent conditions. The NCE can be observed with longer prime-target SOAs (Boy

& Sumner, 2010). This pattern is the reverse of the straight or positive congruence effect that we have discussed so far and that is typical of shorter SOAs. The NCE can be reliably observed with a prime-target SOA exceeding about 150 ms (e.g., Boy, Husain, & Sumner, 2010), while it disappears with more than ca. 250 ms (Lingnau & Vorberg, 2005). Originally, the NCE was linked with the masking of the primes or with the participants' unawareness of the primes because it seemed as if the NCE was restricted to masked conditions and could not be found when the primes were clearly visible (Eimer & Schlaghecken, 2002). However, later research indicated that the NCE can also be found with clearly visible primes (Jaśkowski, 2007). Also, some authors attributed the negative compatibility effect partly or entirely to the mask (Kiesel, Berner, & Kunde, 2008; Lleras & Enns, 2004, 2006; Verleger et al., 2004).

Importantly in the present context, to account for the NCE, Bowman, Schlaghecken, and Eimer (2006) suggested a neural network model in which three processes interactively lead to the NCE: Feedforward inhibition that was responsible for masking, lateral inhibition that created response competition, and an opponent-processing principle which implemented the NCE. According to the opponent-processing principle, the absence of evidence in favor of one response amounts to evidence in favor of the opponent response. In this way, the authors modelled the NCE as a form of self-inhibition of a response tendency elicited by the prime. This alternative response is released from self-inhibition when the prime has been turned off. The model of Bowman et al. (2006) fits at least mean RT of the reactions in NCE conditions reasonably well.

In summary, masked-priming studies from the eighties of the last century on, clearly show that visual input of which humans are unaware can lead to response activation (e.g., Leuthold & Kopp, 1998) and that this response-activation effect critically depends on task-control representations (e.g., Ansorge & Neumann, 2005). Having said this, the question emerges whether other executive functions besides visuo-motor priming can be modulated by unconscious vision – that is, how general is the principle?

2.3. Masked semantic priming

Semantic priming denotes better performance when prime and target are semantically related than when they are not, sometimes even irrespective of the congruency of the motor responses associated with prime and target. An early example is the study of McCauley, Parmelee, Sperber, and Carr (1980). These authors presented a picture as a masked prime before a to-be-named visible picture as a target. The prime and target were either semantically congruent (e.g., the picture of a cat before the picture of dog) or incongruent (e.g., the picture of a knife before the picture of a dog). Under these conditions, a congruence effect was found. Related findings were reported in a number of studies (Dagenbach et al., 1989; Dehaene et al., 1998; Draine & Greenwald, 1998; Greenwald et al., 1996; Hines et al., 1986; Kiefer, 2002; Kiefer & Spitzer, 2000; Marcel, 1983), although in some of these studies semantic relatedness was confounded with response congruency (Dehaene et al., 1998; Draine & Greenwald, 1998; Greenwald et al., 1996). However, as we will show below, 'pure' masked semantic priming has been meanwhile reliably demonstrated.

However, first of all, after these original observations, a number of findings indicated that some priming effects in these studies could have reflected visuo-motor priming rather than semantic priming (Damian, 2001; Kunde et al., 2003). This was due to the fact that often small numbers of targets were used and that primes and targets were from the same set of stimuli. In this situation, it is questionable whether the masked priming effects reflected semantic priming or just action triggering. In an instructive example, Kunde and colleagues used the task of Dehaene et al. (1998). Instead of using all digits from '1' to '9' as targets in a number classification task (i.e., was the target larger or smaller than '5'), these authors only used a subset of the digits as targets and found that number primes outside of the set of targets failed to elicit a standard congruence effect although these numbers were either semantically congruent or incongruent with the meaning of the targets (that is with their size relative to the reference number of 5), too.

These findings were at least at odds with a form of purely stimulus-driven semantic priming, such as by spreading-activation of nodes in a network of interconnected concept representations (Collins & Loftus, 1975; Meyer & Schvaneveldt, 1971). However, these findings would possibly be in line with a top-down controlled form of awareness-independent semantic processing. This possibility was explicitly noted by Abrams and Greenwald (2000) and by Wentura (2000).

In fact, support of the notion of 'pure' unconscious semantic priming without the contribution of visuo-motor priming, was found with response-incongruent primes and targets in both semantically congruent and incongruent conditions (e.g., Hines et al., 1986; McCauley et al., 1980; Perea & Gotor, 1997; Perea & Rosa, 2002). For example, participants of McCauley et al. had to name the target and in each trial they saw a different prime than target. Yet, when the prime was semantically congruent to the target (e.g., the prime knife before the target gun) the participants' naming responses were faster than when the prime was semantically incongruent to the target (e.g., the prime cat before the target gun). Complementary to these findings, masked semantic priming effects have also been found in lexical-decision tasks in which both semantically congruent and incongruent conditions were response-congruent (e.g., Kiefer, 2002; Kiefer & Brendel, 2006; Kiefer & Martens, 2010; Kiefer, Martens, Weisbrod, Hermle, & Spitzer, 2009; Kiefer & Spitzer, 2000). In these tasks, semantically congruent and incongruent prime-target pairs required the same responses (i.e., word responses). Hence, facilitation in semantically congruent as compared to incongruent conditions was not confounded by more or less motor congruence (Abrams, Klinger, & Greenwald, 2002; Dell'Acqua and Grainger, 1999; Hirshman & Durante, 1992; Kiefer, 2002; Sereno, 1991; Wentura, 2000), although in lexical decision and naming tasks effect sizes were smaller compared with categorization tasks, in which visuo-motor priming additionally contributes (Van den Bussche, Van den Noortgate, & Reynvoet, 2009). In addition, if words are used as masked primes, a clear-cut event-related potential (ERP) effect of semantic origin can be observed: In comparison

to a semantically congruent prime, a semantically incongruent prime elicited a larger N400 (Kiefer, 2002), an ERP-component of known semantic origin (cf. Kutas & Hillyard, 1980).

The reliability of pure masked semantic priming is also supported by several studies, demonstrating that masked semantic priming does not depend on prior training with the particular stimuli that were used as primes (Hines et al., 1986) and that priming extends to novel prime words or novel prime pictures that are not used as targets in the same experiments (Naccache & Dehaene, 2001; Pohl, Kiesel, Kunde, & Hoffmann, 2010; Van den Bussche, Notebaert, & Reynvoet, 2010; Walter & Dassonville, 2005). Particularly, in the semantic priming studies using a lexical decision task, primes are typically not presented as targets, and the number of targets is huge (e.g., Kiefer, 2002; Kiefer & Spitzer, 2000). This means that the participants sometimes not only process the primes according to their task-specific experience with the actually relevant targets. Studies, such as that by Hines et al. and by Walter and Dassonville, were particularly convincing with respect to this interpretation because they used words as primes and pictures as targets, and thus ruled out that sensory priming or orthographic priming by repeated word parts (cf. Abrams & Greenwald, 2000) could have accounted for their masked semantic-priming effects.

In the context of masked category priming, an alternative or an instance of semantic priming – depending of how one conceives of it –, one further finding points to subtle differences between a word's priming effect and masked visuo-motor priming. If a congruent category-label prime is presented close to detection threshold, the participants' responses can be slower than if the prime denotes an incongruent category label that is different than the target exemplar (Carr & Dagenbach, 1990; Wentura & Frings, 2005). For example, the masked prime word 'flower' would delay responding to the category-congruent target word 'daisy' as compared to the category-incongruent target word 'beetle'. This inverse masked priming effect – with faster responses in semantically incongruent than congruent conditions – is observed in lexical decision and in pronunciation tasks meaning that the prime and target words indicated the same response in congruent and incongruent conditions. This means that direct parameter specification or visuo-motor priming cannot explain the congruence effect. Therefore, the inverse congruence effect in category-exemplar priming must be of a semantic origin (e.g., Wentura & Frings, 2005). However, the inverse congruence effect depends on the exact prime processing task: It is only observed if the participants are trained to semantically process the prime (Carr & Dagenbach, 1990). This is different from the NCE that does not require any particular task and training concerning the primes. What is more, this inverse semantic congruence effect has a time course that is different from the NCE that we have reviewed above (Lingnau & Vorberg, 2005). Above we have reviewed that the NCE of masked response priming is already over after 250 ms. However, this would be a typical interval for the observation of an inverse semantic category-priming effect. Therefore, this negative semantic congruence effect is one more subtle difference laying proof of the fact that not all word priming effects can be reinterpreted as visuo-motor effects.

2.4. Models of masked semantic priming

Originally, the semantic priming effect, whether obtained with visible or masked primes, has been taken as evidence that words can activate the representation of their semantic meaning in a purely stimulus-driven fashion, a process that is triggered by the prime word. According to the spreading activation account of semantic priming, presentation of a prime stimulus is thought to activate the corresponding conceptual node in a semantic network, and activation spreads through the links to related nodes as a function of associative strength, increasing their activation level. Hence, if a word denoting a related concept is presented, its recognition will be facilitated (Collins & Loftus, 1975; Meyer & Schvaneveldt, 1971).

However, spreading activation alone is not capable of explaining the results reviewed above because according to this explanation unconscious semantic priming should not depend on an appropriate task-control representation. Spreading activation is also unapt to deal with the finding of inverse semantic priming (Wentura & Frings, 2005). Researchers have therefore argued for some form of elaborated processing taking effect with unconscious input that constrains and orchestrates unconscious processes such as spreading activation (e.g., Carr & Dagenbach, 1990; Kiefer & Martens, 2010; Reynvoet, Gevers, & Caessens, 2005; Van Opstal, Reynvoet, & Verguts, 2005).

Above, we have seen that the ASE model of Kinoshita and colleagues is suited to address the control of covert mental operations, such as the top-down selectivity that is evident in masked semantic priming. The ASE model uses the flexibility of adjustments of decision thresholds to optimal speed-accuracy trade-off points as a means for exerting top-down selectivity (Norris & Kinoshita, 2008). The problem is that the ASE model explicitly addresses categorical priming only, although residual semantic priming beyond category priming would certainly be compatible with the ASE.

Equally three neurophysiological models are capable of explaining a top-down influence on unconscious vision in masked priming in general. First, extending prior work by Baars (1988); Dehaene and Naccache (2001) proposed in their global workspace model that masked primes could be processed in devoted physiological systems, once these systems are recruited for a particular task set (see also Dehaene & Changeux, 2011). Second, the possibility that unconscious vision can proceed in line with top-down sets has also been explicitly advocated in Lamme and Roelfsema's (2000) two-phase model of visual processing. According to the two-phase model, visual processing up to about 100 ms post stimulus, during the so-called 'feed-forward sweep', is independent of stimulus awareness. Only during a later phase, the re-entrant processing phase, an observer would also become aware of the visual input. Importantly, even during the consciousness-independent feed-forward sweep, top-down control settings can influence the way in which visual information is processed (Lamme, 2003). Third, recently, the possibility of executive control over unconscious cognition, such as semantic word processing, was also specified in the 'attentional sensitization model' by Kiefer (Kiefer, 2012; Kiefer & Martens, 2010).

Like the global work space and the two-phase model, the attentional-sensitization model assumes that task-control representations could be used for the control of unconscious processes, so that within one and the same masked priming stimulus different stimulus dimensions (Kiefer & Martens, 2010) or even different feature dimensions (Zovko & Kiefer, 2013) could be made task-relevant and subsequently extracted from unconscious input, too (Kiefer et al., 2012; Martens, Ansorge, & Kiefer, 2011). Pivotal to the model of unconscious processing of Kiefer and colleagues, for example, is an influence of attention as one form of top-down selection that would operate on unconscious input, too (see also Lamme, 2003). However, unlike in cognitive control of conscious cognition, which can operate reactively and intentionally in response to ongoing stimulus processing, cognitive control of unconscious cognition is assumed to be necessarily preemptive – that is, attentional control settings must be set up prior to unconscious stimulus presentation (Ansorge & Horstmann, 2007; Dehaene & Naccache, 2001; Kiefer, 2007; Martens & Kiefer, 2009). It is long known that humans have top-down control over their attentional control settings (Duncan & Humphreys, 1989; Folk, Remington, & Johnston, 1992). For instance, according to the top-down contingent capture theory, only stimuli with a feature matching to the top-down control settings will capture attention. For example, if participants in a computer experiment are searching for a red target, a red distractor will capture their attention but a green distractor does not capture their attention (Folk & Remington, 1998). This situation reverses where the participants are searching for a green target.

According to the attentional sensitization model, attention could be directed to a certain broader stimulus dimension or it could be directed to a specific sensory feature of the stimuli (e.g., Adams & Kiefer, 2012). Much as it has been shown in conscious vision, the model proposes that task representations held in prefrontal cortex generate a top-down signal that increases or decreases the sensitivity of specific processing pathways by modulating the likelihood that a neuron fires, even when the physical input is held constant. As a consequence, unconscious processing of the attended stimulus dimension is enhanced while unconscious processing of the unattended dimension is attenuated. The attentional-sensitization model is in line with a number of results.

Most importantly, masked visuo-motor priming (Naccache et al., 2002) and masked semantic priming was observed only when the prime was presented within an attended time window (Kiefer & Brendel, 2006) and when sufficient attentional capacity was available (Martens & Kiefer, 2009). Kiefer and Martens (2010; Kiefer, 2012) took these findings as a first cornerstone for their attentional sensitization model. In contrast to traditional theorizing that equates consciousness and attention (Posner & Snyder, 1975) but in line with newer findings demonstrating that attention and consciousness can be dissociated (Koch & Tsuchiya, 2007; Lamme, 2003), these authors argued that the allocation of attention to one or the other stimulus dimension prior to prime presentation would be required for a corresponding masked-priming effect of this dimension. Also, in many cases, the relevant dimension would be specified by the task instructions, thus, explaining that unconscious priming could be conditional on task sets that are set up for a processing of the targets (e.g., Ansorge, Kiefer, Khalid, Grassl, & König, 2010; Eckstein & Perrig, 2007; Klinger, Burton, & Pitts, 2000). In fact a recent study by Schmidt and Schmidt (2010) showed that task relevance of a feature boosted the priming effect already during the very first phase of prime processing (as indicated by stronger priming effects for relevant than irrelevant primes at the smallest prime-response intervals).

On top of instructions, stimulus dimensions might also be in an active state because of carryover from a preceding (induction) task to a subsequent priming task. For example, if an induction task required the discrimination of the meaning of a target (whether it was animate or inanimate), at least with a short interval between the induction task and the subsequent priming task a semantic congruence effect of the masked primes was found in the priming task (here: a lexical decision task). However, if the induction task required the discrimination of a perceptual dimension of a stimulus (whether a pictured object was elongated or round) or phonological features (e.g., whether a word started or ended with a vowel), the subsequent masked semantic priming effect was diminished or even abolished (Kiefer & Martens, 2010; Kiefer et al., 2012; Martens et al., 2011; for related results, see Spruyt, De Houwer, Everaert, & Hermans, 2012; Spruyt, De Houwer, & Hermans, 2009). In addition, perceptual induction focusing attention to visual form features boosted masked visuo-motor priming based on visual shapes, thereby establishing a double-dissociation between attention to semantics and attention to visual features (Martens et al., 2011).

Importantly, the behavioral RT congruence effects were accompanied by a characteristic shift of the scalp-distribution of the prime-elicited ERPs that was also predicted by the attentional-sensitization model (Kiefer & Martens, 2010; Martens et al., 2011). In line with the known cortical posterior origin of visual effects, the congruence effects of the masked primes in the ERPs indicated a more posterior scalp distribution after a perceptual induction task during visuo-motor priming than after a semantic induction task during semantic priming (Martens et al., 2011). Also, in agreement with prior studies on semantic effects, the semantic priming effect created an ERP difference with a later onset (relative to the sensory priming effect) at about 400 ms (N400) and with a more anterior maximum as compared to the electrophysiological correlate of the visuo-motor priming effect (Martens et al., 2011).

2.5. Shifting attention to masked stimuli

The so far reviewed studies motivated by the attentional sensitization model tested the assumption of preemptive top-down control of unconscious priming by specific task sets (e.g., Kiefer & Martens, 2010), but did not directly investigate whether attention could be directed to masked stimuli themselves.

That attention can be directed to masked stimuli in a top-down way was tested and confirmed in visual search and in cueing experiments. To start with visual search, Woodman and Luck (2003) used four-dot masking of shape singletons, such as one triangle and one square presented among several circles. These authors asked their participants to search for a particular shape, say a triangle, and to ignore the other shapes. In each trial of their experiment, Woodman and Luck presented one relevant, searched-for singleton shape – that is a stimulus standing out by its shape (e.g., a triangle) among more shape-similar non-singleton distractors (e.g., several circles). This singleton target was presented on one side of screen centre and an irrelevant distractor singleton was shown on the other side of the screen centre. As an index of attention, the authors recorded the N2pc, an ERP component occurring at about 200–300 ms post-stimulus at posterior scalp locations that has a stronger negativity at a site contralateral to an attended stimulus. In line with the assumption that the participants shifted their attention to masked stimuli in a top-down controlled way, Woodman and Luck found that the position of the relevant singleton determined the N2pc. For example, with a searched-for masked triangle on the left and an irrelevant masked square on the right, these authors found an N2pc with more negativity over the right than the left cortex, reflecting that participants shifted their attention in accordance with their task set towards the side of the relevant triangle. A similar N2pc effect has also been observed as reflection of top-down control of attention shifts towards differently masked (metacontrast-masked) prime stimuli (Jaśkowski et al., 2002).

The problem with this finding and a related result of Scharlau and Ansorge (2003), however, was that it was not entirely clear in as much response-activation by the primes could have fostered these attentional effects because the primes also led to RT congruence effects based on their response meaning. This was cleared in several subsequent studies in which metacontrast-masked color cues (Ansorge, Kiss, & Eimer, 2009), and color-singleton cues (Ansorge, Horstmann, & Worschech, 2010; Held, Ansorge, & Müller, 2010) captured attention in a top-down contingent way. Take the example of Ansorge et al. (2009). In that study, masked cues were used that were carefully crafted so as not to specify either of the required responses. A cue was presented before every target, either at the same position as the target or a different position than the target. Under such conditions, valid cues at the same position as the target facilitate responses because they direct attention to the upcoming target position, thereby curtailing target response times by the time of the attention shift to the target (Posner, 1980). This facilitation is found relative to conditions with an invalidly cued target, presented away from the cue, because in this condition, an attention shift to the target is only possible after the target's onset. Despite the fact that masked cues without any response-activating potential were used, an N2pc in response to the top-down matching cue was found. In a related study, when Ansorge et al. (2010) compared the effects on RT of color cues that all matched the top-down settings of searched-for target colors but that were either response-congruent to the target shapes or response-incongruent to the target shapes, they found only an attentional cueing effect but not a response activation (response priming) effect. This finding is interesting because it showed that attention shifts toward a masked cue could be a necessary but not a sufficient pre-condition for response activation by the masked stimulus. Presumably, in these studies the attention-capture effect of all cues was so strong that the tinier response activation difference between congruent and incongruent primes was drowned in their larger attention capture effect. Jointly, these data suggested that one fundamental premise of the attentional sensitization model holds true: A stimulus of which humans do not become aware, such as a masked cue, can capture attention depending on task-control representations. In these representations, the shifting of attention as a consequence of a fitting input is defined in a top-down way, much as it has been shown for motor responses and for semantic processing, too. Findings from a hybrid spatial cueing/priming task and the flanker task are in line with this conclusion (Schmidt & Seydell, 2008; Schwarz & Mecklinger, 1995; Tapia et al., 2010, 2013).

Finally, overlearned directional stimuli such as masked arrows (Reuss, Pohl, Kiesel, & Kunde, 2011) or masked eyes (Al-Janabi & Finkbeiner, 2012, 2013) are able to initiate an attention shift given that the prime has a predictive value for the participants. For instance, a cueing effect of masked arrows pointing to target positions was observed, with faster responses in valid than invalid conditions, but only if a context of visible arrow cues suggested the top-down usage of the arrows – that is, if valid cueing predicted the target position with an above-chance accuracy (Reuss et al., 2011).

Having said this, however, it is also noteworthy that an attention shift to the masked stimulus does not seem to be required in all cases of masked priming. Finkbeiner and Palermo (2009) and Khalid, Finkbeiner, König, and Ansorge (2013) showed that the masked-priming effect of a masked face prime during face-gender discrimination occurred regardless of whether spatial attention was shifted to the prime at one position or to the target at an alternative position (but see Shin, Stolte, & Chong, 2009). At the moment, it is unclear why some forms of masked priming occur independently of top-down attention and others ask for top-down attention. Possibly, masked faces or other evolutionary relevant stimuli capture attention and thus receive attentional amplification even when top-down attention is directed elsewhere. Of course, this interpretation is speculative and deserves future research.

3. Masked priming during task execution: Is it all top-down?

The review so far shows that masked priming effects contradict two of the three traditionally proposed hallmarks of automatic processing, namely (1) attention-independence, (2) intention-independence if not intention-resistance, and (3) awareness-independence (Posner & Snyder, 1975). According to this view, an effect that is independent of the participants' awareness about the stimulus being processed should at the same time not require the participant's deliberate control about the processing of the unconscious stimulus and it should also not require attention. However, our review has shown that

many forms of unconscious priming require that an appropriate top-down task set has been set up in advance of the displays (see, e.g., Kunde et al., 2003) and that attention has to be directed to the displays containing the unconscious primes at about the time of their presentation (see, e.g., Kiefer & Brendel, 2006; Naccache et al., 2002).

Yet, we do not want to rule out that there are instances of relatively pure bottom-up or stimulus-driven masked priming. The processing of particular masked features might show more convergence with the conception of Posner and Snyder (1975) than the processing of most of the masked features that we have discussed so far. For example, we have already pointed out that certain characteristics of faces, such as their gender status and their emotional expression, might be extracted by the visual system in an awareness-independent as well as in an attention-independent manner (e.g., Finkbeiner & Palermo, 2009; Smith, 2011; Vuilleumier, Armony, Driver, & Dolan, 2001; but see Holmes, Kiss, & Eimer, 2006).

Another very promising candidate feature for fulfilling all classical criteria of automatic processing remains attention-capture by visual abrupt onsets (Mulckhuysse & Theeuwes, 2010). Studies using methods other than masking have demonstrated that an abrupt onset that remains below the participants' threshold of aware perception can still capture the participants' attention (McCormick, 1997; Mulckhuysse, Talsma, & Theeuwes, 2007) and that this kind of attention-capture by an unconscious onset is not influenced by the participants' will to the same extent as attention-capture by a consciously perceived onset (Fuchs & Ansorge, 2012; Fuchs, Theeuwes, & Ansorge, 2013). For instance, Fuchs et al. (2013) observed that the processing of a supraliminal or conscious cue followed the rules of the top-down contingent-capture theory (cf. Folk et al., 1992) meaning that the cueing or capture effect was restricted to the conditions in which the visible cue resembled the searched-for target features (e.g., both, cue and target were white or both black). This was different in unconscious cueing conditions. With a cue of which the participants remained unaware, the cueing effect was found with both white and black cues, regardless of the searched-for target color (i.e., regardless of whether a black or a white target was used).

Most of these studies with abrupt onsets were conducted with methods different from masking because visibility of abrupt onsets cannot be so efficiently suppressed by masks. It is therefore difficult to investigate the role of abrupt onsets of which the participants remain unaware with the masked-priming procedure. Scharlau and Ansorge (2003), for example, directly compared their participants' ability to discriminate the abrupt onset and the colors of their masked primes under the very same conditions, and found that only the discrimination of the masked primes' colors was truly at chance level accuracy, whereas the participants were able to discriminate the masked primes' onsets.

Despite this complication, Scharlau and her colleagues have conducted a number of studies with backward-masked abrupt-onset cues to understand their attention-capture effect and the results are to a large extent at least in agreement with the conclusion that abrupt onsets could capture attention automatically in the sense of Posner and Snyder (1975) – that is, in an awareness-independent and attention- or intention-independent way. Scharlau used a temporal-order judgment (TOJ) task. In this task, two visual targets were presented close in time and with varying temporal intervals between the targets. Critically, one of the targets was primed by a masked prime, whereas the other target was not primed. In line with the assumption that attention decreases perceptual latency – a finding that has been termed 'prior entry' in consciousness psychology (Spence & Parise, 2010; Titchener, 1908; see also Wundt, 1896) – Scharlau and colleagues consistently find that the masked prime influences the TOJ: Participants tend to judge or perceive the primed target slightly earlier than the unprimed target (Scharlau, 2002; Scharlau, Ansorge, & Horstmann, 2006). This finding indicated that the prime acted like an attention-capturing cue and might have indeed curtailed the latency of a target at its position so that the uncued target had to be shown with a little head-start to compensate for this facilitation of the cued target (Weiß & Scharlau, 2011, 2012). Critically for the current argument, this attentional effect of the masked prime on the target might well reflect a stimulus-driven capture of attention because this priming effect is also of the same size whether the cue has a task-relevant feature or whether the cue has a task-irrelevant feature (Scharlau & Neumann, 2003a, 2003b). In this case, two criteria of automatic processing in the sense of Posner and Snyder (1975) would be fulfilled: awareness-independence and attention- or intention-independence. As a cautionary note, however, it is also possible that the task of judging the temporal onsets of two stimuli means that abrupt onsets were task-relevant features in all of the studies by Scharlau and colleagues. Therefore, it is possible that these findings might likewise reflect a form of top-down contingent capture: attention capture contingent on a match of the cue to a search template for abrupt onsets (cf. Folk et al., 1992).

A final very specific stimulus that might be processed independently of an intention to do so is the own name. Not only does the own name reach awareness despite being unattended, it also seems to bias behavior unconsciously in situations where other names do not (Pfister, Pohl, Kiesel, & Kunde, 2012).

In conclusion, some instances of masked priming could also reflect forms of stimulus-driven processing. The important point of the present review is not to deny that these forms of stimulus-driven processing of subliminal input might also exist. The critical point of the review is that classical theories of automatic processing, such as the theory of Posner and Snyder (1975), do not provide an explanation for the interaction between unaware vision and executive functions, which has been widely demonstrated.

4. Influences of unconscious stimuli during the setting up of task-control representations and goal selection

Although the setting up of a task-control representation and the representation of a goal both logically have to precede the execution of a task set and the pursuit of a goal, we have postponed the discussion of the influence of masked priming on these processes until the end. The reason for this is that we think that to select a goal and to set up task sets, awareness of the

reasons for doing so is much more relevant than during the execution of a task set. To understand this conclusion, we next review the evidence for influences of masked primes on the setting up and adjustment of task sets in particular and during goal selection in general.

4.1. Masked priming during task switching

We start with a relatively uncontroversial finding. Above, we have seen that once a task set has been set up, the different response alternatives represented within this task set can be retrieved according to the currently pertaining task at hand. In a very similar manner, participants are able to retrieve whole task sets from memory, once these task sets have been set up and stored.

By now, a number of studies demonstrated that task-switching is possible in response to masked primes, too (Lau & Passingham, 2007; Mattler, 2003, 2007; Reuss, Kiesel, Kunde, & Hommel, 2012). In his Experiment 5, for example, Mattler (2003) used two tasks. He instructed his participants to either judge the timbre or the pitch of a sound. Importantly, participants had to switch between the tasks. Which task had to be executed depended on the position of a visible task-cue, a diamond, on the screen. Critically, Mattler used perfectly masked primes that had a congruent or an incongruent shape to the subsequent task cue, and found that task execution was faster with congruently than with incongruently primed task cues. From this result Mattler concluded that it is possible to select the currently pertaining task set with the help of a visual stimulus of which the participants remained unaware (see also Mattler, 2005). This conclusion was supported by findings of Lau and Passingham (2007) who demonstrated that task cues activated task-specific brain areas under the conditions studied by Mattler.

The important implication of these findings is that masked priming and, thus, awareness-independent vision might also play a role during the changing of the task sets. Importantly, however, in these studies the respective task sets were already prepared so that they could be readily retrieved from memory and had not to be set up. In addition, it could be that the masked cue simply facilitated the sensory processing of the subsequent clearly visible task cue and that only the visible task cue could be used for the switching of the task – albeit a little earlier if it was congruently primed and thus easier to identify. Therefore, it is still open whether masked primes are able to establish new or to modify existing task sets.

4.2. Inhibition by masked nogo and by masked stop signals

A similar argument holds with respect to the priming of the stopping of a response with the help of a masked stop signal or a masked nogo stimulus. One important characteristic of the adaptation of the currently pertaining task set is its intended abortion on the fly – that is, during task-set execution. In everyday situations, this would occur, for example, when we realize that we are about to conduct an error. In this situation, humans might want to countermand and stop a currently executed response. The ability to stop a response has been tested in go–nogo tasks and in stop-signal tasks where either some targets do not require a go response or where a stop-signal is presented after some of the targets (Logan & Cowan, 1984). In line with the possibility that even visual information of which participants remain unaware could be used for halting or stopping a to-be-executed response, masked primes that are nogo stimuli can actually delay a response to the go targets (Ansorge, 2004) and masked primes which resemble stop signals can even lead to the abortion of the response execution (van Gaal, Ridderinkhof, van den Wildenberg, & Lamme, 2009).

Of course, this masked priming effect might be due to the adaptation of the currently executed task set. However, it is also possible that the stop signals are represented within the task-control representation that has been set up before the execution of the task. For example, even if a stop signal in an experiment is only rarely used, participants need to be informed about the stop signal in advance of the experiment, and they sometimes practised stopping responses to visible versions of the stop signals. These stop signals could thus be represented within the task-control representation, just as other mental operations which execution would be conditional on the presence of fitting stimuli (Ansorge, 2004). Again, our conclusion would be that the masked priming of stopping by stop-signal primes is equivocal with regard to the question whether a task set could be adapted in response to the presentation of a masked prime.

4.3. Masked priming and the adaptation of executive control settings

The best evidence that properties of masked primes can lead to an adaptation of the currently pertaining task sets comes from prime-validity effects (e.g., Bodner & Masson, 2001) and from conflict adaptation in response to masked incongruent primes (e.g., van Gaal, Lamme, & Ridderinkhof, 2010). These two sources of evidence will be discussed next. As we will highlight, although task set adaptation seems to occur in these situations, it remains controversial whether these effects can really be traced back to the masked primes themselves or whether some mediating effect of masked priming, such as the consciously perceived distribution of errors and response times (cf. Jaśkowski et al., 2003; Kinoshita et al., 2011) or meta-cognitive knowledge of conflict (Desender, Van Lierde, & Van den Bussche, 2014) accounts for the adaptations of task sets.

4.3.1. Conflict adaptation to prime validity

First of all a strategic adaptation of the task sets in response to the probability of congruent versus incongruent masked primes has been claimed to be possible. This claim is based on so-called ‘prime-validity effects’. Prime-validity effects show a

dependence of the size of the masked congruence effect on the validity or predictivity of the different prime types for the different target types (Bodner & Dypvik, 2005; Bodner & Masson, 2001). This effect is also called the compatibility ratio effect. For example, Jaśkowski et al. (2003) presented their participants with lowly or highly valid congruent conditions. In lowly valid blocks, congruent trials made up for 20% of all trials, whereas in highly valid blocks, congruent trials made up for 80% of all trials. In both cases the rest of the trials were incongruent. In a comparison of the performance between blocks, there was a stronger masked visuo-motor priming effect in highly than lowly valid blocks. This change of the size of the congruence effect probably reflected an adaptation of the task sets: Participants must have used a more liberal response-execution criterion – that is, their threshold to respond must have been lower in highly valid blocks than in lowly valid blocks.

The question is whether these task-set adaptations reflected a strategic processing of the primes or whether they reflected adaptations to the distribution of reaction times and/or error rates. To explain the prime-validity effect, Bodner and Masson (2001) assumed that the masked primes' predictive power for the finally required target responses in highly valid conditions was used for a strategic processing of the primes. This interpretation would mean that the visual input of which the participants' were not aware could have nonetheless figured as an origin of the adaptation of the task set and maybe even as the object of this adaptation. As an origin of the adjustments, participants would have registered the different probabilities of masked congruent and incongruent primes, so as to use these probabilities during the adjustment of the task sets. As an object of the adjustments, participants would have (additionally) targeted a more efficient processing of the congruent than of the incongruent primes by means of their task-set adjustments.

However, there are alternatives to this explanation that can equally well account for the prime-validity effect and without reference to a use of the masked primes as the origin or as the object of the task-set adjustments. This alternative explanation focuses on the changes of the error rates and of the response-time distributions as the origins and the objects of the task-set adjustments. These error and reaction-time effects are the consequences of the masked primes but similar effects of errors and reaction times on task-set adjustment could also be achieved by other factors that have nothing to do with masked priming. Participants might be aware of their higher error rate in the lowly than in the highly valid conditions, and respond more carefully – that is, wait longer until they give their responses (Jaśkowski et al., 2003). If participants respond more carefully, the balance of the respective response activations of primes versus targets might be tipped in the direction of the target-activated response, simply because more time would have passed since the prime has been presented and until a response is given in the lowly valid conditions. As a matter of fact, shifting the response times to an average higher value has a detrimental influence on the masked response-priming effect. This can be concluded from diminished masked response priming effects with overall higher reaction times (Ansorge et al., 2010; Kinoshita & Hunt, 2008).

In addition, even if the lowly valid condition does not increase the error rates, the lowly valid condition could lead to on average higher mean response time because the slower responses stem from the incongruent trials and there are more incongruent trials in the lowly than in the highly valid blocks. Slowing of the responses also typically slows the responses in a subsequent trial (Lupker, Brown, & Colombo, 1997). Again, this carry-over of response slowing from one trial to the next would lead to an average smaller masked congruence effect in lowly predictive than in highly predictive block without a mediating representation of the probabilities of congruent versus incongruent trials.

Whether these adaptation effects to the distributions of errors and/or response times are based on consciously perceived error-rate differences and/or response-speed differences or whether they reflect an implicit adaptation is currently not known. Critically, the corresponding adaptation could not be considered a strategic processing of the masked primes because the masked primes would neither figure as the origins for the adaptation of the task sets (here: the response thresholds), nor would they be the intended objects of the adapted task sets (Kinoshita et al., 2008, 2011). Some observations are better in line with the latter assumptions that the strategic adaptation does neither depend on the masked primes, nor concerns the use of these primes. In addition, prime-validity effects have not been found in all masked priming studies (Forster, 1998; Merikle & Cheesman, 1987).

4.3.2. Conflict adaptation on a trial-by-trial basis

A second way in which masked primes might alter the currently pertaining task sets is by modulating conflict control. Recent findings suggested that much as with other clearly visible conflict-eliciting stimuli (Gratton, Coles, & Donchin, 1992), a masked and incongruent prime in trial $n - 1$ might lead to a strategic down-regulation of the response threshold in a subsequent trial n . This has been concluded on the basis of a smaller masked response congruence effect after a preceding masked incongruent trial than after a preceding masked congruent prime trial (Desender et al., 2013; van Gaal et al., 2010). Again, this finding could be due to the strategic adaptation of the response threshold that critically depended on the masked primes as its input (van Gaal et al., 2010). However, as with the prime-validity effect, there are alternative interpretations possible.

To start with, as with the prime-validity effect, several studies have failed to find evidence for conflict adaptation with masked primes on a trial-by trial basis (Boy et al., 2010; Greenwald et al., 1996; Kunde, 2003) even if the prime-target SOA as a potentially confounding variable (Frings & Wentura, 2008) was exactly the same in masked and visible priming (Ansorge et al., 2011). Thus, the evidence for this highly flexible sort of adaptation of the task sets in response to conflict-eliciting masked primes is mixed at best. Also, on a more cautionary view, inter-trial variation of masked priming effects depending on the preceding trial's level of congruence (van Gaal et al., 2010) could again be due to a threshold adaptation based on the speed of the responses in a preceding trial rather than on the prime-elicited adaptation proper (cf. Lupker et al.,

1997). According to this interpretation, any response slowing would have this same effect on the congruence effect. Also, it is even possible that a reaction-time dependent adaptation of response speed in a subsequent trial, and its accompanying diminution of the masked congruence effect after masked incongruent trials depends entirely on instances of consciously registered slowing (of some) of the responses. So far, no study has tested this possibility. Related, even if the participants happen to be unable to discriminate their response speed as fast or slow, some other consciously available correlate of response speed, such as the experienced fluency (e.g., Bornstein & D'Agostino, 1994; Forster, Ansorge, & Leder, 2013; Kozlik, Neumann, & Kunde, 2013; Reber & Schwarz, 2002; Schwarz, 2001; Topolinski & Strack, 2009) might as well account for the strategic adaptation reflected in inter-trial contingencies of masked priming. In line with this assumption Desender et al. (2014) showed that conflict adaptation even with masked primes occurs when participants have a gut feeling that conflict had previously occurred independent of the actual congruence of the primes. Perhaps intuitions about fluency might also contribute to the striking observation that participants adapt prime processing to context features they cannot consciously discriminate (Reuss, Desender, Kiesel, & Kunde, 2014).

Finally, one should bear in mind that not all inter-trial adaptation effects reflected conflict regulation. Some of the inter-trial contingencies of congruence effects are due to context (Schlaghecken & Martini, 2012) rather than conflict and this issue has also not been considered in masked priming studies.

4.4. Masked priming of goals

Masked goal priming (Dijksterhuis & Aarts, 2010; Eitam, Hassin, & Schul, 2008; Fitzsimons & Bargh, 2003) might also have the potential to elicit a new task set or alter an existing task set because a goal implies a bundle of different instrumental actions and operations (Förster, Liberman, & Friedman, 2009). As an example, consider Experiment 3 in the study by Fitzsimons and Bargh. These authors used masked names of friends of the participants or of friends of yoked control participants as primes to respectively activate a situational or a dispositional attribution for the causes of the behavior of an unknown person that was narrated to the participants. Participants who were primed with the name of a friend gave more situational explanations for the behavior of the person in the narration than participants primed with the name of a friend of a yoked control participant. Fitzsimons and Bargh assumed that the masked name of a friend had primed a motivation to understand the causes of someone's behavior but that the names of a stranger would have failed to prime the same goal.

In this example, the meaning of the primes (names of friends versus names of strangers) was clearly not part of the instructions. Thus, these priming effects could not have been due to visuo-motor priming. Also, the primes had no obvious semantic bearings on the content of the responses of the participants (here: giving reasons for the behavior of a person in a narration). This rules out that the primes created a task-dependent semantic priming effect. The fact that the different types of masked primes systematically affected different behavior in a seemingly consistent way requires one to assume that the task sets in this situation were modified by the primes in a way that cannot be entirely due to the preceding set-up of task-control representations. Related research suggests that masked stimuli could prime decisions in favor of one or another product (Karremans, Stroebe, & Clauss, 2006; Winkielman, Berridge, & Wilbarger, 2005).

Of course, some forms of masked goal priming seem to reflect goal pursuit instead of goal selection. For example, in their study of masked priming of drink consumption Winkielman and colleagues found that the thirsty participants showed the strongest priming effects (see also Karremans et al., 2006, for a related conclusion). Related to this, masked primes that resembled the intended consequences of actions sometimes effectively facilitated responses (Kunde, 2004) or the feeling of being in control of an action (Linser & Goschke, 2007). If one construes the pre-existing drive of being thirsty in the studies of Winkielman et al. or the goal to create one particular sensory outcome in an experiment as a task-control representation that is set up in advance, one might therefore conceive that these masked-priming effects as facilitation of instrumental behavior rather than goal priming itself. In conclusion, however, masked goal priming and masked goal-pursuit priming seem to be the best evidence so far that masked priming can also activate task sets.

Whereas the explanation of goal priming has, thus, originally relied on the congruence between the semantic content of the prime and the meaning of a motif or goal, new evidence suggests that masked priming of a goal could also take effect via energizing a particular goal (Bijleveld, Custers, & Aarts, 2010; Pessiglione et al., 2007): Presenting the participants with a masked prime of higher monetary value, such as an image of a Euro coin rather than the image of a Cent coin, led participants to exert more force on a joystick movement (Pessiglione et al., 2007) or to respond faster at least in a demanding task (Bijleveld et al., 2010). The latter study was particularly interesting as it also highlighted that the influences on decisions could be qualitatively different in masked priming than unmasked priming conditions: Participants' risk aversion was lower in masked than unmasked priming conditions. These studies suggested that regardless of the semantic congruence between prime and goal, different behaviors could be similarly primed presumably by prime-elicited increases in movement force that was applied during task execution. To note, however, monetary gains in these studies were proportional to task performance (e.g., response speed) and feedback about the actually acquired reward was provided after each trial of these studies. Moreover, in these studies visible and invisible primes were mixed, so that it is likely that visible primes become associated with subsequent motor actions (e.g., pressing a response device forcefully after having seen a Euro coin). These motor responses might then simply be reactivated when the same prime is presented subliminally later in the experiment. Thus, it is not only possible that some form of semantic congruence between prime and feedback or expected reward is critical for masked monetary goal-priming effects, but that at least some of these studies reflect simple stimulus–response learning and do not require at all the concept of priming motivation or goals.

In conclusion, our review has shown that with the exception of masked goal priming, there is little unequivocal evidence for that masked priming leads to an adaptation or a change of a currently pertaining task set. Also, masked goal priming is special in so far as many forms of goal priming seem to be equally powerful in energizing the execution of very different task-control representations. In this sense, masked goal-priming might be regarded as an influence that is orthogonal to the selection of the input and the output criteria for a specific task-control representation.

5. Conclusion

Our review has revealed that unconscious or unaware visual processing serves particular, already intended actions and cognitive operations (Ansorge & Neumann, 2005; Dehaene & Naccache, 2001; Kiefer & Martens, 2010; Kunde et al., 2003). By contrast conscious or aware processing seems to be necessary for setting up a task set in the first place (Dehaene & Naccache, 2001; Kunde, 2003; Mayr, 2004; Neumann, 1990), and conscious vision seems to promote the global availability of mental representations for diverse potential goals (Baars, 1988; Dehaene & Naccache, 2001). According to this dichotomy, with a decision being based on conscious or aware vision humans can consider a huge number of potential alternatives. Furthermore, action plans and decisions can be intentionally modified on the grounds of consciously perceived stimuli. Because of this, actions or decisions based on conscious or aware vision can be labelled 'flexible'. However, consideration of many alternatives is also slower than a decision based on a single task-control representation. The latter would be characteristic of decisions based on unconscious or unaware vision. Actions or selections based on unconscious or unaware vision therefore offer the advantage of their swiftness because an action is selected from just a few alternatives fitting the pre-existing task-control representations.

The two types of decisions can be nicely illustrated by discerning the conscious/aware from the unconscious/unaware visual processing mode: On the left side of Fig. 1, a *conscious* visual signal affords a decision between many different task sets. This is reflected in the many white arrows in the inner ring, connecting the visual signal with the goals and further with many different decisions and actions. Eventually, the decision only realizes one of the intentions. This is illustrated by the single black arrow in the gray ring. Subsequently additional conscious decisions can follow the initial decision: In the case of decisions based on conscious vision, goals feedback on the representation of the visual signal. In this manner different goals can stimulate new interpretations of the visual signal in the conscious mode. By contrast, a decision based on unconscious visual signals is shown on the right of Fig. 1. According to our dichotomy, unconscious visual processing is fast and involuntary. Processing is triggered by the unconscious stimulus without the intention to do so, but depends on pre-emptive attentional control by currently active task representations.

In fact, we assume that any quick intuitive action based on visual signals is unconscious: Unconscious visual processing is the swift 'front end' of vision-based decisions. Unconscious vision trades off the number of potential options and intentions against a speed gain. With unconscious vision, most decision alternatives are not available. Even the combination of different visual feature dimensions, such as color and shape into one selection criterion seems to be difficult in unconscious vision (Tapia et al., 2010). The unconscious visual signal can thus only be used for the already existing intentions and goals for which there is a decision or action plan (e.g., Klinger et al., 2000). If there is a goal to process a particular stimulus or feature, it is possible to execute the action on the basis of an unconscious visual signal. This outcome might appear disappointing

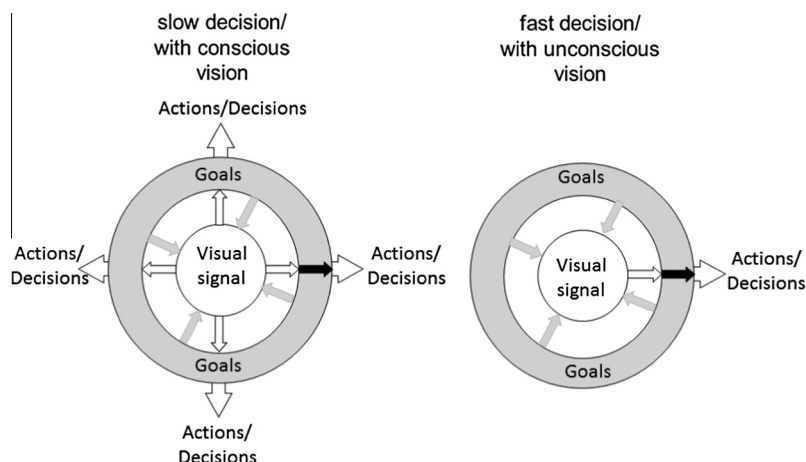


Fig. 1. Schematic depiction of the modes of functioning of conscious/aware and unconscious/unaware vision. According to Dehaene and Naccache's (2001) global neuronal work space model, with conscious/aware vision, the visual input could be used in many different ways, indicated by the reciprocal arrows from input to goals and onwards to different actions and decisions. With unconscious/unaware vision, the input could only be used for the specific purposes that are preconfigured in the currently pertaining task-control representation. As we detail in our Review, the large majority of findings in masked-priming research from the time predating the model as well as from the time since its publication adheres with these sketched principles.

given the preliminary evidence for apparent unconscious triggering of cognitive control settings that has accumulated recently. But we hope to console the reader by sharing our belief that finding cases where certain sorts of unconscious control failed are equally informative.

There might be additional qualitative differences between the conscious and unconscious visual processing mode. For example, unconscious vision might have advantages besides its swiftness: Masked priming studies have shown that unconscious vision might be driven by more veridical or more objective visual features and that it might be less prone to the ‘illusory’ appearance of visual stimuli than conscious vision (Breitmeyer et al., 2004; Bridgeman, Kirch, & Sperling, 1981; Bridgeman, Lewis, Heit, & Nagle, 1979). This characteristic of unconscious vision sheds a light on vision’s main evolutionary purpose: successful action control that is shielded against false or illusory input (Bridgeman et al., 1979; Haffenden & Goodale, 1998; Janczyk & Kunde, 2010, 2012; but see Franz, Gegenfurtner, Bühlhoff, & Fahle, 2000).

Likewise, there might be also advantages of conscious vision besides its flexibility. For example, some authors have argued that conscious vision could be necessary for veridical perception of combinations of color and shape (Tapia et al., 2010). The reason for this dependency of the veridical perception and even the successful processing of combinations of visual features on the participants’ awareness might reside in the fact that feature conjunctions of visual objects can only be established during the feedback or recurrent phase of visual processing (Bar et al., 2006; Di Lollo, 2012; but see Breitmeyer, Ogmen, Ramon, & Chen, 2005). [Some exceptions from this rule, where unconscious feature conjunctions apparently biased behavior can be attributed to the existence of templates in which feature conjunctions have been formed prior to the experiment as a consequence of expertise (Kiesel, Kunde, Pohl, Berner, & Hoffmann, 2009).] These limitations might be due to masking’s undermining of the successful processing of a visual stimulus until the feedback or recurrent phase (Lamme, 2003) and, therefore, only conscious vision might allow making use of visual feature combinations.

One general point concerns the categorical vs. gradual dependency on awareness for the setting up of action plans. As scientists we are forced to describe nature as parsimonious as possible. In this respect saying that setting up action plans requires awareness of the reasons for doing so, whereas the execution of such plans does not, is parsimonious. Yet, this description may of course turn out as overly simple. It might well be that awareness is not an indispensable ingredient for setting up control, but that it only facilitates control to a large extent (e.g., Reuss et al., 2014).

Another point we set aside is whether awareness of representations itself is functional for enabling some aspects of cognitive control or whether cognitive control and awareness arise from the same properties of representations, for instance, the consolidation and encoding of representations in working memory circuits (see below). This issue has also been discussed within the context of the relation between phenomenal consciousness (i.e. awareness) and access consciousness (i.e. intentional control; Block, 1995; Kouider, de Gardelle, Sackur, & Dupoux, 2011). For instance, awareness in the sense of reportability of a stimulus might require its encoding into working memory circuits, which at the same time might be a prerequisite for intentional cognitive control (Kiefer et al., 2011). This problem is obvious in masked priming, where masked and unmasked primes differ in respects other than explicit reportability, such as their respective signal strengths. It might be possible to approach this problem by comparing stimuli with equal strength but varying awareness (Lau, 2012). Yet, such comparisons are likely to come with other confounds, such as the deployment of attention that determines whether otherwise equal stimuli are reported or not. At present we find it most parsimonious to assume that awareness is one property of mental representations among several correlated others. This should not be underestimated, though. The ability to report a stimulus enables communication about that stimulus, including self-verbalization which is an important mediator of action control itself (Goschke, 2000). Conversely, verbal instructions received from other parties are much more efficiently applied to reportable than to unreportable stimuli.

One final important question remains before we want to conclude the present review. If it is true that vision-for-action is an awareness-independent legacy passed down from simpler organisms during, how would the priming of the execution of mental operations in general fit into the picture? One way to solve this puzzle is by looking at the similarities between mental representations in general and actions in particular. For instance, semantics might be grounded in perception and action (Barsalou, 1999; Kaschak & Glenberg, 2000; Kiefer & Barsalou, 2013; Kiefer & Pulvermüller, 2012; Kiefer, Sim, Liebich, Hauk, & Tanaka, 2007; Niedenthal, 2007; Niedenthal, Barsalou, Winkielman, Krauth-Gruber, & Ric, 2005; Zwaan, Stanfield, & Yaxley, 2002; Zwaan & Taylor, 2006). This is a fundamental assumption of the embodied cognition view of the human mind. According to this notion, there would be no understanding of meaning possible, without the retrieval of appropriate sensory and motor experiences grounded in the past that would form the basis of any meaning (Hoenig et al., 2011; Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008; Trumpp, Kliese, Hoenig, Haarmaier, & Kiefer, 2013). In line with this speculation, masked semantic priming seems to draw on motor activation (Ansorge et al., 2010), and on sensory representations, too (Ansorge, Khalid, & König, 2013; Trumpp et al., 2013). However, open questions remain before we can fully answer this question (Mahon & Caramazza, 2005). For the moment, it should suffice that the awareness-independent forms of vision during executive control are testimony of one principle underlying the division of labour between conscious and unconscious vision in many different domains, where unconscious vision is fast and maybe more error-resistant, and conscious vision increases the flexibility of executive functions by allowing the set-up of ever new task-control representations.

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