Interferences of Visual Masks with Semantic and Perceptual Priming Effects

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Summary

Many studies demonstrate that visual stimuli can be processed even if they are not consciously perceived. These studies show that unconscious stimuli can be processed – amongst other things – in terms of their shape, color, and even semantic content. To prevent stimulus awareness, researchers present additional stimuli, visual masks, in close temporal and spatial proximity. Although different types of visual masks successfully reduce stimulus visibility it is not entirely clear in what way these masks interfere with information processing. Recent studies show that masks not only prevent stimulus awareness, but also reduce the extent of processing that occurs in the absence of consciousness. At the same time, priming studies that investigate the extent of processing in the absence of consciousness report that priming of low-level perceptual features is unaffected by masking, whereas priming of high-level semantic features is reduced under masking. This has often been interpreted as evidence that non-conscious processes are limited in depth. Here, we investigate an alternative explanation: Since different masks are used in semantic and perceptual studies, it is possible that the reduced effects in semantic studies are due to a confounding mask interference that is not present in perceptual studies. To clarify the role of visual masking for priming effects we examine the effects of conventional forward and backward masking techniques. To that end, we also introduce novel metacontrast masks for words. We find that different types of backward masks reduce stimulus visibility, but do not affect priming effects. Crucially, this was true for both priming of perceptual and semantic features. Forward masks, however, severely reduced perceptual priming effects. This suggests that reduced priming effects in semantic studies may be an artifact of the visual masking technique, since semantic priming studies typically involve forward masks, whereas priming studies on perceptual features often use only backward masks. When forward masks are avoided, semantic priming effects can be successfully dissociated from visibility. Our

results bridge theories stating that priming effects are related to an early part of the neuronal response and neurophysiological masking studies stating that early neuronal responses are disrupted by forward masks, but not backward masks.

Contents

1. Introduction

Driving on a misty evening in December, I suddenly realized that (1) I was hitting the brakes, (2) checking the mirror, and (3) had noticed a movement at the roadside. The order of this narrative gives the impression that certain reactions occur even before we become aware of their causes. Only in hindsight do we recognize, with a sense of bewildered respect, the cause of our actions. This contradicts the common intuition that we consciously perceive our environment and only afterwards initialize reactions according to this conscious percept. It appears that many processes, from stimulus processing up to reactions, can operate without consciousness.

The question whether consciousness is required for stimulus processing and actions has a long history in psychology: In a set of reaction time experiments, Ludwig Lange, who was a member of the research group of Wilhelm Wundt, demonstrated that fast reactions can precede a conscious perception of stimuli, as indicated by introspective reports (Lange, 1888; reviewed in Neumann, 1990). Lange concluded that these fast reactions, which he labeled “muscular reactions”, neither rely on conscious awareness (“apperception”) of a stimulus, nor on a voluntary initiation of the reaction. Instead, he compared these reactions to an automated *brain reflex*:

> Die musculäre Reaction schließt überhaupt keine Apperception und ebensowenig einen Willensact ein; sie stellt vielmehr eine unwillkürliche, reflectorische Bewegung dar, allerdings eine solche, die unter dem nachwirkenden Einflusse eines vorangegangenen Willensimpulses erfolgt. (Lange, 1888, p. 510)
>
> The muscular reaction involves neither conscious awareness nor a voluntary decision; it is rather an involuntary, reflexive movement, even though one that occurs under the lasting influence of a previous impulse to react. (my translation)

Lange suggested that this brain reflex involves a different cortical route than reactions following a conscious perception of the stimulus because it bypasses brain areas that are needed for conscious control. This interpretation suggests that stimuli can be processed on a nonconscious route of processing that is functionally different from a conscious route of processing. Lange noted that muscular reactions were less specific than reactions that subjectively follow a conscious perception, suggesting that the nonconscious processing route underlying muscular reactions has certain limitations.

Versions of this idea are discussed to this day and researchers are still trying to understand what makes the processing of conscious stimuli functionally different from nonconscious processing. One way to answer this question is to determine whether the processing of unconscious stimuli is limited compared to the processing of conscious stimuli (e.g., Kouider & Dehaene, 2007; Lamme, 2015). In a branch of this research field, visual processing is investigated by reducing stimulus visibility with the help of visual masks. Visual masks, for example in the form of overlapping patterns, surrounding rings (Schiller & Smith, 1965) or uniform fields of light (Eriksen, 1966) have been shown to reduce the visibility of stimuli such as letters when presented in close temporal proximity. These experimental manipulations allow controlling stimulus visibility to investigate processing at different levels of awareness. In the most severe case, so-called *subliminal* presentation conditions, visual masks completely prevent conscious access to the masked stimuli and subjects are no longer able to identify task relevant features (e.g., Klotz & Neumann, 1999; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). Interestingly, it has been shown that various stimulus features can be processed even in the absence of consciousness. This includes perceptual features such as color (Schmidt, 2000, 2002) or shape (Klotz & Neumann, 1999), and more complex features such as orthography (Kouider, Dehaene, Jobert, & Le Bihan, 2007) and semantic content of words (Kiefer, 2002; Marcel, 1983). These studies show that subliminal stimuli can be processed in surprising depth and indicate that consciousness is not essential for many aspects of visual processing.

While the role of consciousness for stimulus processing is being debated (Kouider & Dehaene, 2007; Lamme, 2015), increasingly extreme positions emerge stating that "Unconscious processes can carry out every fundamental high-level function that conscious processes can perform" (Hassin, 2013, p. 195) and "the 'zombie within' […], that is, the unconscious processes underlying perception, behavior, and cognition, may be much more sophisticated than was previously thought" (Mudrik, Breska, Lamy, & Deouell, 2011, p. 6). According to these positions, stimuli can be efficiently processed in a "zombie mode" that operates independent from consciousness (Crick & Koch, 2003, p. 120).

Even though findings of high-level processing of subliminal stimuli are largely acknowledged in the literature, and have been implemented into current theories of consciousness (e.g., Dehaene & Changeux, 2011), these studies are elsewhere met with skepticism (e.g., de Wit & Kinoshita, 2015). Claims of subliminal processing alternate with refutations and methodological criticism of these studies, which makes it difficult to define the extent to which stimuli can be processed without consciousness (Kouider & Dehaene, 2007). According to critics, the capacities of this "zombie within" may have been overestimated, either because the visibility of critical stimulus features was not really null (Kouider & Dupoux, 2004), or because apparently complex processes like the activation of semantic categories can be explained by the processing of less complex perceptual features. For example, semantic categories (e.g., tools versus animals) may be confounded with low-level perceptual features (e.g., elongated versus round shapes; Hesselmann, Darcy, Ludwig, & Sterzer, 2016). Alternatively, stimuli may have been processed with respect to acquired stimulus-response rules with no need for an in-depth semantic processing (Kouider & Dupoux, 2007; Kunde, Kiesel, & Hoffmann, 2003). These studies illustrate that some experimental setups promote an overestimation of subliminal processing. In this thesis, we show that the reverse is also true, and some experimental setups may also lead to an underestimation of subliminal processing. Such detrimental effects may contribute to weak effects and failed replications of subliminal processing in the literature. The primary goal of this thesis is to examine how specific methodological variables – more specifically the type of visual mask that is used to suppress stimulus visibility – determine the outcome of semantic and perceptual studies of stimulus processing.

In this thesis, the processing limits of masked stimuli will be examined by analyzing *priming effects*. Priming paradigms allow measuring how reactions to a target stimulus are influenced by another stimulus, the *prime*. For example, if subjects have to make speeded decisions about the directions of target arrows, their reaction times will be faster if a previous prime arrow points to the same direction. Because the prime is not required to complete the task, priming effects can be used to measure *indirect effects* of stimuli on behavior even if these stimuli cannot be consciously reported as indicated by *direct measures* of prime awareness (e.g., Klotz & Neumann, 1999; Marcel, 1983; Mattler, 2003; Vorberg et al., 2003). In this thesis, three versions of this priming paradigm will be applied: First, a semantic priming task that is suited to investigate semantic access to lexical stimuli. Second, priming of color and shape will be used to index processing of perceptual stimulus features. These tasks will be introduced in more detail in Chapter 1.2. Together, these tasks provide a comprehensive insight into stimulus processing at varying degrees of complexity. After looking in more detail into the methodological details of these tools, especially the masking techniques that are commonly used to suppress stimulus visibility in certain priming tasks (Chapter 1.3), the last chapter of this introduction will follow up by discussing how these masking techniques by themselves influence the outcome of priming experiments (Chapter 1.4).

1.1. Searching for a function of consciousness

Why is it interesting to explore stimulus processing in the absence of awareness? One superordinate goal of studies on the processing of unconscious stimuli is to uncover how stimulus awareness is related to cognitive functions (Kouider & Dehaene, 2007; Lamme, 2015). According to a functionalist view on consciousness, consciousness evolved because it is evolutionary adaptive, that is, serves a function. The causality implied in this statement can be misleading, because it may suggest that consciousness causes some sort of efficient processing. Instead, consciousness may also arise as a direct consequence of this efficient processing. In this case, consciousness exerts no function by itself but arises as a by-product, i.e., an epi-phenomenon of a complex functional system (see Blackmore, 2010, chapter 1, for an overview about philosophical theories of consciousness). In either case, learning which cognitive functions are linked to conscious experience is an essential step to gain insight into the nature of consciousness. As Cohen and Dennett put it, “a true scientific theory [of consciousness] will say how functions such as attention, working memory and decision making interact and come together to form a conscious experience” (2011, p. 362). In principal, a theory that equates consciousness with a certain mode of information processing need not be restricted to mechanisms in the brain. Advocates of the *Information Integration Theory* (IIT) propose that consciousness is a property that can in principle be determined for every – organic or non-organic – system:

> IIT was not developed with panpsychism in mind (sic). However, in line with the central intuitions of panpsychism, IIT treats consciousness as an intrinsic, fundamental property of reality. IIT also implies that consciousness is graded, that it is likely widespread among animals, and that it can be found in small amounts even in certain simple systems. (Tononi & Koch, 2014, p. 6)

According to IIT, consciousness is directly related to the amount of integrated information in a system, which can be loosely described as the degree to which the elements of a system interact with each other, producing dynamic states of a system that allow inferences about future states while reserving a certain degree of freedom (Tononi & Edelman, 1998). Integration of information is a key aspect of consciousness in many theories of consciousness. This idea comes in many manifestations, likening consciousness to “fame in the brain” (Dennett, 2001, abstract), “coalitions of neurons” (Crick & Koch, 2003, p. 121), or a global workspace formed by widespread recurrent activation (Lamme, 2010; Lamme & Roelfsema, 2000) or by an ignition state of reverberating neural activity in a fronto-parietal network (Baars, 2005; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Dehaene & Naccache, 2001). The bottom line of these theories is that consciousness is related to brain states that serve to integrate and sustain information.

However, in each of these theories, integration of information is not limited to conscious processing but can also take place in the absence of consciousness, albeit to a lesser extent. Identifying the processing limits of subliminal stimuli may thus help to narrow down how much information integration is possible without awareness (Kouider & Dehaene, 2007; Lamme, 2015). Processing of subliminal stimuli has been a central issue of many studies to date and brought forth a variety of experimental paradigms. In the next chapter, some these paradigms will be described that have been used to investigate the processing of unconscious stimuli according to perceptual and high-level semantic features.

1.2. Using priming effects to probe stimulus processing

A number of different priming tasks has been used to study the processing of unconscious stimuli at different levels of complexity, or, as Kouider and Dehaene put it, “levels of processing” (2007, their title). Throughout this thesis, a selection of three of these priming tasks will be used. These tasks are designed to probe the processing of shape, color, and semantic features of a stimulus when its visibility is reduced by masking. The comparison of priming effects across different tasks could be advantageous because these tasks measure processing on different processing levels and it is conceivable that priming of low level features such as shape or color may be possible in conditions when priming of high level features such as semantic content is not.

1.2.1. Priming of shapes using arrows

In this section, priming effects of shapes will be explained in further detail in the context of a masked priming paradigm that uses arrows as stimuli (Vorberg et al., 2003). After introducing the paradigm, I will present key findings and outline neurophysiological processes that may contribute to priming effects.

In priming of shapes using arrows, the subject has to respond to the direction of a large target arrow pointing to the left or right that is preceded by a smaller prime arrow. The special feature of this paradigm is that the target stimulus is presented at the same location as the prime, and thereby also serves as a visual mask that reduces the prime visibility. The role of the masks will be discussed in more detail in the subsequent chapter (Chapter 1.3). When the target and prime arrow point in the same direction (*congruent* trials) subjects respond to the target direction faster and with fewer arrows than when target and prime point in different directions (*incongruent* trials). The difference between reaction times or response errors in incongruent minus congruent trials constitutes the *priming effect*. Because the prime arrows could by themselves trigger left and right responses, priming in this paradigm is referred to as *response priming*.

According to Vorberg et al. (2003), priming effects with arrow stimuli rise with unit slope when the *stimulus-onset asynchrony* (SOA) between prime and target increases. This means that when the SOA between prime and target is about 50 ms, roughly 50 ms priming effects can be expected in a speeded reaction task. However, the authors point out that this rule need not extent to SOAs beyond 100 ms that were not covered in their study. In the data of Vorberg et al. (2003), the slope of priming effects across SOAs was independent of factors such as the duration of prime and target, and, more importantly, the visibility of the prime. In their study, robust priming was found even when prime directions could not be discriminated above chance level (Experiment 1). Furthermore, priming effects were independent of prime visibility that was varied by manipulating the duration of the prime and target, demonstrating a simple dissociation between prime visibility and priming effects (Experiment 2). Additionally, this experiment provides evidence for a double dissociation between priming effects and prime visibility: Prime visibility decreased with longer SOAs whereas priming effects increased. Double dissociations provide strong evidence for independent mechanisms underlying priming effects and prime visibility (Schmidt & Vorberg, 2006; Vorberg et al., 2003). The results of Vorberg and colleagues have been replicated and extended in different variants of this priming paradigm (Francken, van Gaal, & de Lange, 2011; Mattler, 2003; Mattler & Palmer, 2012). The robust nature of priming with arrows makes it a rewarding paradigm to study unconscious priming of basic visual features such as orientation of shapes.

There are different ideas about neurophysiological mechanisms underlying priming of arrow stimuli. Vorberg et al. (2003) suggest that priming and visibility reflect information in two different systems which they refer to as the action and perception system, respectively. In reference to Grossberg and Mingolla (1985), they propose that perception of stimuli requires boundary contours to be computed and filled in. Whereas the processing of contours is sufficient to trigger reactions, resulting in priming effects, the filling-in process is disrupted by the target arrow, which explains reduced visibility. Other theories of shape priming follow a similar logic by attributing priming effects to levels of object processing that can operate independently of consciousness. It has been suggested that basic stimulus features are extracted during a feedforward sweep from V1 to higher cortical areas (DiCarlo, Zoccolan, & Rust, 2012; Lamme & Roelfsema, 2000; VanRullen, 2007), thereby enabling priming of these features (Breitmeyer, 2014; Dehaene et al., 2006; Schmidt, 2002; Schmidt, Niehaus, & Nagel, 2006; van Gaal & Lamme, 2012). When TMS pulses were applied to human V1 and V2 with a short delay after the prime, these pulses completely eliminated shape priming effects whereby having only small effects on prime visibility, supporting the view that priming effects of shape correlate with an early feedforward sweep originating in V1 and V2 (Koivisto, Henriksson, Revonsuo, & Railo, 2012). The view that priming of basic features is caused by very early neuronal activity is also consistent with an accumulator account of response priming effects. According to one version of an accumulator model, information in favor of one response alternative is continuously sampled beginning with the onset of the prime (Mattler & Palmer, 2012; Vorberg et al., 2003). The accumulation of prime information is disrupted when the target is presented. This idea was further developed by Schmidt et al. (2006), proposing that prime and mask/target processing proceeds as being engaged in a *rapid chase*, whereby the initial prime activation is completely independent of the subsequent mask, because the activity of the mask cannot catch up with that of the prime. Indeed, it has been shown that initial reactions in speeded discrimination tasks are exclusively driven by the masked stimulus, and do not depend on features of the mask (Schmidt, 2002; Schmidt et al., 2006; VanRullen & Koch, 2003). As a consequence, this account can also explain why priming effects in the arrow paradigm are independent of prime perception: Whereas the backward mask can disrupt ongoing processes that are required for conscious visibility, it cannot catch up with the early stimulus activity of the prime. However, this early stimulus activity is sufficient to engage motor preparation in accordance with the prime identity. Schmidt et al. (2006) point out that it is less important whether such early neuronal activity does or does not allow for local recurrence beyond a pure feedforward sweep as long as the strict sequentiality of prime and target/mask processing is preserved. In summary, these theories suggest that shape priming relies on an early stage of processing that is not vulnerable to subsequent masking.

The scope of this thesis will be limited to experimental designs that either present the mask simultaneously with the target or combine mask and target into a single stimulus as in the study of Vorberg et al. (2003). Such paradigms are also referred to as *two-stimulus paradigm*s, and differ from *three-stimulus paradigms* which present masks as a separate event between prime and target. In three-stimulus paradigms, negative priming effects have frequently been reported (Eimer & Schlaghecken, 2003; Sumner, 2007). Because the origins of negative priming are still discussed and three-stimulus paradigms add more factors that would need to be controlled when investigating priming effects, this thesis focusses on the investigation of priming effects in two-stimulus paradigms.

1.2.2. Priming of color

Priming of color shares many characteristics with priming of shape. In a color priming paradigm presented by Schmidt (2000, 2002), colored annuli (target rings) were preceded by smaller colored disks (primes). Again, the target ring also served as a mask that prevented identification of the prime color. If prime and target color were identical, subjects responded faster to the color of the target annulus. As for arrow stimuli, the magnitude of these color priming effects was roughly equal to or even larger than the SOA between prime and target (Breitmeyer, Ro, & Singhal, 2004; Schmidt, 2000, 2002). As a downside of the disk-ring paradigm to study color priming effects, the visibility of the prime depends on the color of the mask (Breitmeyer, Ro, et al., 2004) and the color congruency between mask and prime (Maeda et al., 2010; Ro, Singhal, Breitmeyer, & Garcia, 2009; Schmidt, 2000, 2002; Yellott

& Wandell, 1976), creating confounded variables. To reduce the influence of the mask color, visual masks can be constructed that contain equal amounts of both target colors (Wernicke, 2014). In this paradigm, the target is separate from the mask and is presented simultaneously above and below the masking stimulus. However, the color priming effects were somewhat smaller in the studies by Wernicke (2014) when compared to the studies reported above.

Neurophysiological findings suggest that color processing rests mainly on color-opponent parvocellular geniculate neurons projecting to the ventral pathway (Livingstone & Hubel, 1988), and it has been argued that color priming is related to activation in areas of the ventral pathways (Schmidt, 2002). Breitmeyer et al. (2004) exploited the versatility of the color priming paradigm to explore the processes underlying color priming. When they analyzed the effects of white primes on reactions to blue and green targets, they found that the white primes facilitated responses to blue targets, but not or only little to green targets. Because the wavelength of the white primes is more similar to that of the blue targets, but the white primes were perceptually more similar to green targets as indicated by subjective color confusions, Breitmeyer and colleagues (2004) concluded that the color priming effects are wavelength- rather than percept-dependent, linking color priming with early visual areas V1 and V2 rather than activations in later areas such as V4 that show increased color constancy in spite of changes in wavelength. Early visual areas V1 and V2 have previously been assigned a central role in color processing as neurons in monkey V1 and even more in V2 start to exhibit sharp color selectivity, being tuned to specific directions in color space (Gegenfurtner, 2003; Komatsu, 1998).

A comparison with priming of shape reveals that both priming paradigms share a number of important properties: Both priming by arrows and color are affected by the temporal interval between prime and target onset (SOA) in such a way that they increase with SOA. These priming effects can be predicted with an accumulator model which assumes programmable accumulator units that continuously collect evidence in favor of one response alternative (Vorberg et al., 2003). Because prime stimuli could by themselves activate motor responses of subjects, priming of color and shape in the tasks introduced above can both be classified as instances of response priming that allow for a direct activation of motor pathways. According to the *direct parameter specification theory* (Klotz & Neumann, 1999), subjects develop specific stimulus-response rules to achieve an efficient processing of the task. If stimulus-response rules can be prepared, sensory stimuli can trigger motor responses without mediation by a conscious stage of information processing. In accordance with this view, Schmidt et al. (2006) proposed that initial reactions in a priming task are triggered by the prime alone, independent of the effectiveness of a subsequent mask. Furthermore, color and shape both reflect basic visual properties of the stimulus. In the course of this thesis, these two priming paradigms will be treated as different ways to probe the processing of basic perceptual stimulus features.

1.2.3. Semantic priming in the Lexical Decision Task (LDT)

So far I discussed priming paradigms in which either color or form of visual stimuli constitute the response relevant criterion. These tasks are applied to investigate processing of unconscious stimuli with regard to perceptual features. As I pointed out earlier there is reliable evidence that these features, although not consciously registered, can influence behavior. However, when striving to uncover the processing limits of unconscious stimuli, researchers focus on tasks that require a higher level of processing (Kouider & Dehaene, 2007; Lamme, 2015; Mudrik, Faivre, & Koch, 2014). For this purpose semantic tasks are particularly suitable.

In this subchapter, I will introduce the lexical decision task as a tool to investigate semantic priming, and give an overview of possible mechanisms that contribute to semantic priming effects. To give an insight into the complex processes that underlie semantic processing, I would like to conclude the chapter with a few recent papers that deal with the question of how semantic concepts might be represented in the brain.

Resting on a definition by Mudrik et al. (2014), semantic processing refers to processes underlying access to associative and conceptual knowledge that is stored in long-term memory. A popular example for semantic tasks is the *lexical decision task* (LDT, Meyer & Schvaneveldt, 1971; Meyer, Schvaneveldt, & Ruddy, 1972; Neely, 1976). In the LDT, subjects indicate whether a presented string is either a word (e.g., *lion*) or a pronounceable pseudoword (e.g., *bion*). When a target word like *lion* is preceded by a semantically related prime word (e.g., *tiger*) reactions to the target word will be faster than when preceded by an unrelated word (e.g., *car*).

Semantic priming effects in the LDT are remarkable because they cannot be explained by response priming: Since primes in congruent and incongruent trials are both words, semantic priming effects cannot be explained by responses to the primes but only by the semantic relation between prime and target. In the perceptual priming tasks reviewed above, on the other hand, a congruent prime triggers the same reaction as the target, whereas an incongruent prime triggers the alternative reaction, so priming effects could either be explained by responses to the prime, or by the perceptual relation between prime and target (Klotz & Neumann, 1999; Mattler, 2003, for discussions). This distinguishes semantic priming effects in the LDT from other paradigms that are designed to probe semantic processing of subliminal stimuli, such as categorical priming. In categorical priming, subjects classify stimuli according to arbitrary semantic categories, like numbers versus letters (Naccache & Dehaene, 2001; Wernicke, 2014), animals versus body parts (Ortells, Kiefer, Castillo, Megías, & Morillas, 2016), positive versus negative affective valence (Draine & Greenwald, 1998; Klinger, Burton, & Pitts, 2000), or male versus female names (Draine &

Greenwald, 1998). Although categorical priming effects are generally more robust than semantic priming effects in the LDT (de Wit & Kinoshita, 2015; Klinger et al., 2000; Van den Bussche, Van den Noortgate, & Reynvoet, 2009), it has been argued that categorical priming tasks may be explained by response priming rather than semantic priming. Specifically, priming effects may be explained by stimulus-response rules that are acquired during the experiment, rather than by a deep semantic processing of the prime (Ansorge, Kunde, & Kiefer, 2014, for a review). As a possible mechanism, subjects may construct sets of expected stimuli that can trigger certain reactions to subliminal stimuli without having to encode this stimulus on a semantic level (Kiesel, Kunde, & Hoffmann, 2007). Alternatively, subword fragments like syllables may suffice to reactivate practiced responses to the words independent of the whole-word meaning (Abrams & Grinspan, 2007a, 2007b; Abrams, Klinger, & Greenwald, 2002; Klinger et al., 2000). As a consequence, it is not clear what constitutes ‘semantic’ processing in this context, and thus whether categorical priming tasks can be used to test the access of meaning in long term memory (Kouider & Dupoux, 2007; Ortells et al., 2016). Investigating semantic priming in the LDT avoids such sources of non-semantic influence and can unambiguously be attributed to the semantic relation of prime and target.

A number of mechanisms have been proposed that can account for semantic priming effects. Regarding these mechanisms, a general distinction between automatic and consciously controlled, strategic processes can be made. Traditionally, automatic processes have been defined as fast processes that do not require attention or stimulus awareness, whereas strategic processes refer to a slow, consciously controlled use of the prime (Neely, 1991; Posner & Snyder, 1975). The criteria for this taxonomy are under constant discussion (e.g., de Wit & Kinoshita, 2015; Kouider & Dehaene, 2007), and a strict separation of these processes may not be tenable in the future (McNamara, 2005). Since strategic processes require conscious processing, it has been argued that masks prevent strategic processing (e.g., Kiefer, 2002; Neely, 1991). As masked priming is the primary concern in this thesis, the focus of this chapter is on automatic semantic processing and strategic processes will be discussed only briefly.

What are possible processes underlying automatic semantic prime processing? The most popular theory for automatic semantic processing is spreading activation (Anderson, 1983; Collins & Loftus, 1975). Localist theories of spreading activation propose that semantic concepts can be represented as nodes. When a node is activated, activation automatically spreads to neighboring nodes. The strength of the link between two nodes is governed by the degree of semantic overlap. In the model of Collins and Loftus (1975) the strength of the links corresponds to the number of shared properties between the connected nodes. According to multistage activation models, after prime representations have been activated in the semantic network and activation spreads to related concepts, activation of the related concepts will feed back to lexical and orthographic layers and thereby boost semantic priming effects (see McNamara, 2005, chapter 6, for an overview).

More recently, alternatives for localist accounts of spreading activation between specific concept nodes have been provided by the more biologically oriented distributed memory accounts of semantic processing (Kiefer & Pulvermüller, 2012; Lerner, Bentin, & Shriki, 2012; Masson, 1995; Plaut, 1995; Plaut & Booth, 2000). According to distributed memory accounts, concepts are not represented by a single node but by a pattern of activation of neuron-like processing units. Each of these processing units can be part of any number of concepts, and the co-activation of a specific set of units constitutes a particular concept. Semantic relations are expressed by the overlap of these activation patterns. Semantic priming in distributed memory model arises not as a consequence of activation spread from one concept to another, but because the prime partly activates the correlated memory pattern of the target. In some models (see Kiefer & Pulvermüller, 2012, for a disambiguation), this overlap between activation patterns can be understood as overlap between semantic features: Because the prime word *tiger* shares a majority of the features of *lion* it will by itself activate features of the *lion* concept. Distributed memory models have been implemented in neuronal attractor models (e.g., Lerner et al., 2012; Plaut, 1995). In these models, due to the strong connections between some units but not others, one activated processing unit will tend to activate all other processing units of a concept. Such self-maintaining, semi-stable states in distributed networks are termed *attractor states*. If a word is processed, the system will stabilize in an attractor state corresponding to the associated concept. This attractor state will remain stable until either new input arrives or depleted activity due to adaptation mechanisms of some of the units causes the system to settle to a correlated attractor, resembling an association-like process (Lerner et al., 2012). It should be noted that although neuronal attractor models can exert spreading-activation-like characteristics, fundamental differences remain. One important difference is that only one attractor is active at a time in neuronal attractor models, whereas in localist models activation spreads to all neighboring nodes at the same time (Lerner et al., 2012).

The portrayed models of automatic semantic prime processing do not include predictions for the role of consciousness in semantic access, or, as in the case of Lerner et al. (2012) explicitly refrain from commenting on the relation between attractor states in the semantic network and the contents of conscious thought. In the original model of Collins and Loftus (1975), a concept can be consciously accessed if the activation of the associated node exceeds a threshold. The fact that nodes can pass activation on to their neighbors even when they did not exceed this threshold may imply that spreading activation per se does not require full activation of nodes, and therefore, conscious awareness of the stimuli. However, this is clearly a post-hoc interpretation and their theory does not make a clear statement how semantic priming effects relate to the conscious awareness of stimuli (see McNamara, 2005).

Strategic mechanisms of semantic priming on the other hand are by definition linked to conscious control, and have been argued to benefit from conscious prime presentations (Neely, 1991). Two well-known strategic mechanisms that contribute to semantic priming are expectancy generation and retrospective semantic matching (for reviews see Hutchison, 2003; Neely, 1991). When the expectancy generation strategy is invoked, conscious processing of the prime allows the subject to generate a set of likely targets. When the target is anticipated correctly, its processing is facilitated in a top-down fashion. In general, prospective use of primes is thought to require a minimum processing time to be effective and should thus increase with SOA (de Groot, 1984; Neely, Keefe, & Ross, 1989). However, retrospective use of the prime may also occur at short SOAs (de Wit & Kinoshita, 2015). According to one retrospective strategy, semantic matching, subjects assess the relatedness of prime and target once their semantic representations have been activated (de Groot, 1984; Neely et al., 1989). If a semantic relation is identified, subjects will be more inclined to rate the target as word. Such a strategy should be more useful when the proportion of related word trials is high, and predicts increased semantic priming effects that have been found in such conditions (de Groot, 1984; Neely et al., 1989). This is an advantage over spreading activation models because an effect of relatedness proportion would not be expected from spreading activation accounts alone.

Although spreading activation, expectancy generation and semantic matching give a good impression about possible mechanisms that may contribute to semantic priming effects in the LDT (Neely, 1991), the theories reviewed above were almost exclusively based on findings with supraliminal primes. Interestingly, semantic priming effects have been reported even in cases where the visibility of the primes is limited by masks (Marcel, 1983; Neely, 1991). According to the traditional distinction between automatic and strategic mechanisms, strategic use of the prime requires its conscious awareness (Neely, 1991), suggesting that masked priming effects should be explained by automatic processes (e.g., Kiefer, 2002). However, it can be difficult to define which mechanisms are restricted to supraliminal prime processing. For example, Bodner and Masson (2003) found that the relatedness proportion effect that is commonly used to index strategic mechanisms like expectancy generation and retrospective semantic matching can also be observed in masked semantic priming. Thus, Bodner and Masson (2003) concluded that some retrospective processes are also possible when primes are subliminal. However, later attempts to replicate their findings using the LDT (Grossi, 2006) or a priming task with number words (Van den Bussche, Segers, & Reynvoet, 2008) were not successful. In categorical tasks, it has been suggested that, rather than due to purely automatic prime processing, masked priming occurs because task instructions are strategically applied to the prime (Dehaene et al., 1998; Kouider & Dehaene, 2007). According to this logic, stimuli do not have to be conscious to be processed strategically. Thus, the line between automatic and strategic mechanisms can be blurry, and it is a matter of ongoing debate whether strategic processes also occur in the absence of conscious awareness of the primes. However, classical strategic mechanisms like expectancy generation and retrospective matching should be more likely when primes can be consciously identified. In the absence of prime awareness, spreading activation or correlated activations in distributed memory accounts remain favored explanations for semantic priming effects in the LDT (Grossi, 2006; Kiefer, 2002; Kiefer & Spitzer, 2000; Ulrich, Hoenig, Grön, & Kiefer, 2013).

When discussing semantic priming effects in the absence of stimulus awareness it should be noted that the existence of such subliminal semantic priming effects is no general consensus. In a nutshell, the literature of masked semantic priming effects is challenged by methodological concerns on the one hand, and small effects which are difficult to replicate on the other (for a review, see Kouider & Dehaene, 2007). Early studies showing semantic priming effects with supposedly unconscious prime words (e.g., Marcel, 1983) have been criticized due to methodological flaws that lead to underestimated visibility estimates, such as low trial numbers or differences between light adaption between priming and visibility trials. When these studies were repeated with more methodological rigor, their results could not be replicated (reviewed in Holender, 1986). Together, these results called for maximum comparability between priming and visibility trials in subsequent studies to prevent a systematic underestimation of prime visibility. Following this period, a number of studies claimed to have found semantic priming effects of unconscious stimuli even when visibility was carefully controlled for (Kouider & Dehaene, 2007; Van den Bussche et al., 2009). However, methodological objections continue to be raised until the present day. Some authors point out that partial awareness of prime features may account for previous findings of priming by words (Gelbard-Sagiv, Faivre, Mudrik, & Koch, 2016; Kouider & Dupoux, 2004, 2007; Lähteenmäki, Hyönä, Koivisto, & Nummenmaa, 2015). Influences of partial awareness on priming effects may go unnoticed due to inadequate visibility tasks or insensitive data analyses (Abrams & Grinspan, 2007b; Dienes, 2015; Lähteenmäki et al., 2015; Rothkirch & Hesselmann, 2017; Shanks, 2017). For instance, Shanks (2017) recently pointed out that the common practice of excluding visible trials or subjects with high visibility scores promotes an overestimation of unconscious performance measures.

The challenging task of finding subliminal semantic priming effects has led to a variety of different experimental designs. Because there is no commonly accepted best choice of how to investigate prime visibility and priming effects, the scientific practice in the field is diverse, making it difficult to generalize findings across experiments (Rothkirch & Hesselmann, 2017). This methodological diversity amongst priming studies is a core issue of this thesis and will be covered in detail in Chapters 1.3.4 and 1.4.

In the previous paragraphs, mechanisms have been introduced that suggest how representations of prime and target words interact to produce semantic priming effects. The starting point of the portrayed mechanisms was that prime representations are activated in the semantic network. Although the research is still in its infancy, this last paragraph aims to convey an impression of which steps may be necessary to activate the representation of a written word in the semantic network, and how semantic representations could be organized in the brain.

According to multistage activation models, before the meaning of a word can be accessed at the semantic level, a lexical analysis of the word is required (McNamara, 2005). In reading, the lexical analysis of words can be understood as a special case of visual object recognition that involves a hierarchical analysis with increasingly complex neural detectors (Dehaene, Cohen, Sigman, & Vinckier, 2005). In this framework, the neural detectors are growing in complexity and receptive field size with each stage, spanning local contrasts, letter shapes and *bigrams* (constellations of two letters that can even be separated by a few intermediate letters) and finally ordered letter strings. The constructed word forms can then be used to retrieve conceptual knowledge linked to the word. With the use of priming experiments, the processing of words can be accessed at various stages. Masked priming experiments have shown that processing of orthographic, lexical and potentially phonological features occurs even when stimuli are not consciously perceived (Kouider & Dehaene, 2007, for a review).

After a lexical processing of the word the way is paved to access its meaning in long term memory. The existence of a lexical processing stage that is separate from a semantic processing stage is still debated (Kiefer & Pulvermüller, 2012; Martin & Chao, 2001) but this debate will not be covered here. In line with distributed memory accounts, access to meaning has been proposed to reflect the co-activation of concept features across the brain, including modality specific information in auditory, visual or motor cortices (Martin & Chao, 2001). In an attempt to map the distributed areas that are selective for semantic concepts during natural speech processing, Huth, de Heer, Griffiths, Theunissen, and Gallant (2016) presented a semantic atlas that spans large areas across both hemispheres in the brain, providing what might be viewed as a visualization of distributed semantic information in the brain.

The activation of such distributed regions may be mediated by areas of the semantic network, primarily the anterior temporal lobe, which may serve as a ‘semantic hub’ linking to modality-specific features of a concept that are stored across the brain (see Kiefer & Pulvermüller, 2012; and Lambon-Ralph, Jefferies, Patterson, & Rogers, 2017, for reviews). The brain areas of this semantic network are assumed to be supramodal, which means they are activated both by reading or hearing words, viewing objects or hearing sounds. This universality may enable the semantic network to act as a gateway for distributed semantic access also to modality-specific areas.

Activations of the semantic network have been observed even when words are not consciously perceived. In a masked priming task, Ulrich et al. (2013) analyzed the characteristic inactivations in human fMRI that are assumed to reflect relative processing benefits in semantically congruent compared to incongruent trials. Ulrich et al. (2013) refer to the relatively larger activations in unrelated versus related trials as “neural priming” and argue that these larger activations reflect a larger processing effort in unrelated trials. Although they found such neural priming in some brain areas only when primes were consciously perceived, conceivably as a result of strategic prime processing, they did not find activations that were exclusively associated with masked priming. Hence, the authors concluded that there is no separate processing route for unconscious semantic processing. Instead, masked words seem to activate parts of the same semantic network that is also active when words are consciously perceived. Such part-activation of the semantic network under masking has also been observed when the activity of masked words is compared with that of masked pseudowords (Diaz & McCarthy, 2007).

The goal of this paragraph was to introduce the LDT as a tool to investigate semantic processing even when stimuli cannot be consciously reported, and convey a brief impression about the mechanisms underlying priming effects in the LDT and semantic assess in the brain more generally. Although the LDT was used to demonstrate semantic processing in the absence of conscious perception, it is still not quite clear what role consciousness plays for semantic processing. While it is plausible that strategic mechanisms exist that function optimally when primes can be consciously perceived, theories of automatic prime processing do not state assumptions about differences of processing conscious versus unconscious primes (see McNamara, 2005, p. 115, for his conclusion about the role of consciousness in models of semantic priming). Whereas influential theories of semantic priming are neutral with regard to the role of consciousness for semantic processing, the final section of this chapter will focus on current theories of consciousness and characterize potential limits of stimulus processing that these studies assume for unconscious stimuli.

1.2.4. Stimulus processing according to theories of consciousness

Three priming tasks have been introduced that are commonly used to explore stimulus processing at different levels of awareness. One goal of priming studies is to define the processing limits of unconscious stimuli in order to highlight the role of consciousness for specific tasks. Whereas processing of perceptual stimulus properties such as shape and color is well-established even under total masking (Chapters 1.2.1. and 1.2.2.), processing of unconscious stimuli at semantic levels is more controversial (Chapter 1.2.3.). Nevertheless, some studies that demonstrate semantic processing of unconscious stimuli have already been integrated into current theories of consciousness. Three influential theories of consciousness will be portrayed in this chapter: The Global Neuronal Workspace Theory (GNW, Dehaene et al., 2006; Naccache & Dehaene, 2001), the feedforward-feedback division discussed by Lamme and co-workers (Lamme, 2010; Lamme & Roelfsema, 2000), and the Integrated Information Theory (IIT) by Tononi and colleagues (Oizumi, Albantakis, & Tononi, 2014; Tononi & Edelman, 1998; Tononi & Koch, 2014). Each of these theories of consciousness builds on the assumption that unconscious, high-level processing is possible to some degree. The goal of this section is to exemplify in what way high-level processing of unconscious stimuli is realized in these models and delimit the degree to which the processing of unconscious stimuli should thus be possible.

In the GNW theory, the "human brain is viewed as a collection of specialized processors that mostly operate non-consciously, but whose content can be consciously accessed whenever they are linked to a global, metastable assembly involving distant prefrontal and parietal neurons with long-range axons" (Kouider & Dehaene, 2007, p. 858). With this distinction, the authors note that it is difficult to draw a firm line between the processing of unconscious and conscious information because both involve the same processors. Like its predecessor, the *Global Workspace Model* by Baars (1993, 2005), the GNW theory rests on the assumption that these specialized processors can analyze stimulus information even up to semantic levels. This assumption is also included in the later version of the model: According to the GNW theory, unconscious processors can analyze stimuli perceptually and semantically, and even trigger motor responses as long as the processors have been consciously prepared to perform these tasks (Dehaene et al., 2006; Naccache & Dehaene, 2001). In this way, Kouider and Dehaene (2007) interpreted the results of Dehaene et al. (1998) in a subliminal number priming task as evidence for strategic rather than automatic prime processing. In this task, subjects had to categorize arabic numbers as larger or smaller than five. Dehaene et al. (1998) found that these numbers could be primed by number words of the same or different category even when visibility was prevented by masks and concluded that subjects were able to apply the task instructions also to unseen numerals. This interpretation implies that prime stimuli are processed strategically rather than automatically. However, the strategic use of the prime is still limited according to the GNW model. Dehaene and Changeux (2011) later proposed that certain strategic mechanisms that are susceptible to variations in the relatedness proportion of prime and target might require the development and testing of novel strategies and therefore be restricted to conscious processing. According to them, there are but three potential limits to the processing of subliminal stimuli: First, priming decreases with processing depth, second, priming decreases with elapsed time (until it ceases after about 500 ms), and third, subliminal stimuli should not be able to exert lasting and flexible modulations in executive control (Dehaene & Changeux, 2011). Consequently, unconscious semantic activation that is due to automatic prime processing may be small, but is overall conceivable within the framework of the GNW.

The GNW theory distinguishes between bottom-up activated, unconscious processing units and a reverberating, conscious workspace that links multiple of these processing units through recurrent connectivity. The distinction also incorporates the differentiation between feedforward and feedback processing that has previously been linked to unconscious and conscious processing, respectively (Dehaene & Changeux, 2011). In this framework (Lamme & Roelfsema, 2000), unconscious processing is characterized by brief waves of feedforward activation, whereas conscious access is established through horizontal and feedback connections from higher to lower areas in the visual hierarchy. Other than the GNW theory, Lamme and Roelfsema do not assume that conscious processing is specifically linked to activations in fronto-parietal brain areas. Instead, local and long-range feedback connections across the visual hierarchy equally contribute to conscious perceptions. It is, however, not clear whether local feedback alone is sufficient to allow conscious percepts (Lamme, 2010).

More recently, Lamme stressed that the spatial extension of feedback connections is an important factor for the development of conscious representations, and proposed that cognitive functions depend on consciousness to the degree they involve brain activation that spans large distances in space and time (Lamme, 2015). Interestingly, he states that semantic access or even inference processes may not involve such complex functions. Rather, complex functions comprise figure-ground segregation, the grouping of image elements according to Gestalt laws (Lamme, 2015) and the integration of information from multiple sources, maintaining information across time, and learning (van Gaal & Lamme, 2012). The fact that consciousness may be related to rather basic functions like figure-ground segregation is somewhat surprising. As a possible reason, Lamme (2015) points to a work of Self, van Korkoerle, Supèr, and Roelfsema (2013), who found that processes like figure-ground segregation require a particularly high degree of horizontal and feedback interactions. Semantic access of words, on the other hand, may be achieved through the feedforward sweep alone, which, as stressed by the authors, can initiate processes in areas even up to the prefrontal cortex (van Gaal & Lamme, 2012). This view is in accordance with the general notion that visual word recognition can be viewed as a special case of object recognition (see Chapter 1.2.3), and rapid object recognition has been proposed to be predominantly driven by a fast feedforward processes (DiCarlo et al., 2012; VanRullen, 2007). It should be noted that when speaking of feedforward processing, DiCarlo et al. (2012) note that small-scale local feedback may still contribute to fast categorizations during the feedforward sweep. A strict separation of feedforward and feedback as grounds for a nonconscious and a conscious mode of processing may not be tenable and is probably not intended by Lamme and colleagues. In his 2015 paper, Lamme considers a more simplified perspective that extends the mere distinction between feedforward and feedback processes:

> What emerges is the nagging feeling that consciousness has nothing to do with the seeming complexity or "high-levelness" of a visual function. Whether a visual function depends on consciousness may simply be related to the amount of space that has to be travelled in the brain, how many processing steps have to be taken in between, and hence how much time it takes to complete. (Lamme, 2015, p. 22).

Although the access of words, including their perceptual identification and extraction of semantic features requires more processing steps than judging the orientation of simple arrows, semantic priming in the LDT should thus be conceivable in the absence of awareness as long as semantic areas can be reached via the fast feedforward sweep and the integration of target and prime information in these areas does not require long-term maintenance via recurrent loops.

In both the GNW theory and the considerations of Lamme and co-workers, recurrent neuronal processes allow for a sustained processing and combination of information from different sources in the brain, thereby enabling conscious perception. The combination of information is also central to the integrated information theory of consciousness. Proponents of the IIT (Oizumi et al., 2014; Tononi & Edelman, 1998; Tononi & Koch, 2014) are less concerned about the psychophysiological correlates of consciousness in the human brain and rather seek to specify more generally how individual elements of a system interact to create a phenomenal experience. According to IIT, consciousness is a graded measure that can be quantified by a measure Φ, whereas large values of Φ indicate that the system stores more information and gives rise to a larger number of possible succeeding states than any subset of its elements. In line with the distinction of feedforward and recurrent processes that is included in the theories described above, a recurrent architecture is essential for integration and the authors state that consciousness is zero for pure feedforward systems. Multiple recurrent systems can co-exist at the same time, but the contents of consciousness will be determined by the largest of these systems alone. This *exclusion principle* is an important assumption in IIT because it enables unconscious information integration to any degree as long as elements of the system are part of a major complex that integrates even more information. Such minor complexes may lead to “paraconscious states” (Oizumi et al., 2014, p. 16) that, along with unconscious feedforward activation, qualify to explain high-level semantic judgements in the absence of full awareness (Oizumi et al., 2014). It is, however, not clear how and whether such paraconscious states would be experienced by the subject, especially because “there is no superposition of multiple experiences, with less or more content”, according to Tononi and Koch (2014, p. 4). This makes it difficult to conceptualize how such multiple conscious states coexist and if and how they are perceived.

To conclude, the portrayed theories of consciousness take previous findings of subliminal semantic priming effects seriously and assume that sophisticated processing is possible in the absence of awareness, including high-level processes that underlie semantic priming effects. Across these theories of consciousness, high level processing in the absence of conscious perception is possible through extensive feedforward activation or localized networks that fail to meet a certain level of complexity that would be achieved through feedback from other areas. While masking methods are widely assumed to prohibit such complex processing underlying stimulus awareness (see next Chapter 1.3), little is known as to whether visual masks also affect processing in the absence of awareness. However, whether and how the processing of unconscious stimuli is altered by visual masks is crucial for the theoretical foundation of current theories of consciousness that seek to identify possible functions of consciousness. The next chapter will therefore cover the effects of visual masks on stimulus processing in more detail.

1.3. Using masks to reduce conscious stimulus processing

In priming studies, masking is solely used as a tool to decrease the visibility of stimuli. However, it is still unclear how masks interfere with stimulus processing. The masking studies that will be presented in this section cast light on the differential effects of masking, exposing that different visual masking methods may interfere with stimulus processing at different stages of stimulus processing.

In visual masking studies, the effectiveness of a mask is determined by asking subjects to report perceptual characteristics of the masked stimulus, such as its luminance or form. As these masking studies do not include a prime and subjects have to report characteristics of the masked stimulus, the masked stimulus is thereby referred to as the target. A wide variety of different masking techniques exists in the literature. These masking techniques vary in a number of features (Breitmeyer & Öğmen, 2006; Enns & Di Lollo, 2000; Francis & Cho, 2008; Kim & Blake, 2005): First, visual masks vary with regard to the spatial layout of the masking stimulus. Whereas *metacontrast masks* have no spatial overlap with the masked stimulus, like two flanking bars masking a central bar (e.g., Alpern, 1953; Macknik & Livingstone, 1998) or a ring surrounding a disc (e.g., Breitmeyer et al., 2006), *pattern masks* can take various appearances including random fields of noise or line structures that are presented at the same location as the masked stimulus (e.g., Schiller, 1966). The temporal order of the mask and masked stimulus is also flexible, and visual masks can be presented prior to the masked stimulus (*forward masking*), subsequent to the masked stimulus (*backward masking*) or a combination of both (*sandwich masking*). In some cases, visual masks are also presented at the same time with the masked stimulus, for example when a stimulus is crowded by surrounding flanker stimuli (*visual crowding*) or when masks are flashed simultaneously to one eye whereas the target is presented on a different eye (e.g., in *continuous flash suppression*, CFS)[1]. Furthermore, these masks can be varied according to a number of other parameters: For example, the eccentricity of the stimuli, or whether the target and mask are presented separately to either eye (dichoptic masking), or to both eyes the same (monoptic masking), which also includes monocular masking whereby all stimuli are presented to only one eye. Given this large variability, it is not surprising that visual masks also differ functionally. A growing body of literature indicates that masks have different effects on the processing of stimuli, varying with regard to their effects on stimulus visibility (Breitmeyer & Öğmen, 2006) and also, indirect measures of stimulus processing such as priming effects (Breitmeyer, 2015). The next paragraphs will introduce the masking techniques that will be contrasted in this thesis, and describe how these masking techniques affect stimulus visibility: The techniques of interest are metacontrast masking, paracontrast masking (Chapter 1.3.1) and pattern forward and backward masking (Chapter 1.3.2). In the final paragraphs of this section (Chapters 1.3.3 and 1.3.4), the effects of visual masks will be considered from a more broad perspective by examining possible masking mechanisms that may underlie the interaction of masks and masked stimuli. To that end, it will be inquired how these individual masking techniques affect not only processes underlying stimulus visibility (which is sometimes referred to as "conscious processing", e.g., Dehaene & Changeux, 2011) but also its effects on nonconscious processing stages that are captured by indirect measures such as subliminal priming effects.

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[1] For the sake of consistency, techniques like visual crowding or CFS will be referred to as masking techniques in this thesis, since they are all used with the aim of reducing the visibility of stimuli. Elsewhere, the term masking is reserved for forward and backward masking and a special case of masking called common-onset masking (Enns & Di Lollo, 2000), and more general terms like "blinding methods" (Breitmeyer, 2015) or "psychophysical techniques for manipulating visual awareness" (Kim and Blake, 2005) are preferred as umbrella terms that also include other techniques like crowding and CFS.

1.3.1. Metacontrast and Paracontrast masking

The contours of a metacontrast mask surround the contours of the masked stimulus with no spatial overlap (e.g., a ring surrounding a disk; see Breitmeyer & Ganz, 1976, and Breitmeyer & Öğmen, 2006, for overviews). By definition, metacontrast masks are backward masks which are usually presented shortly after the masked stimulus, but they may also be used as forward mask (in which case they are called *paracontrast*). Collectively, paracontrast and metacontrast masks are sometimes referred to as *surround masks*, with reference to their spatial layout. When the SOA between target and mask is increased, target visibility can either increase (type-A function) or take a u-shaped form (type-B function), depending on various properties of the experimental setup (Breitmeyer & Öğmen, 2006; Kolers, 1962). As an important indicator, when the stimulus energy of the mask is larger than that of the target, type-A functions of metacontrast masking are more probable (Kolers, 1962). The stimulus energy is, amongst others, determined by the luminance and duration of the stimuli (Breitmeyer & Öğmen, 2006, p. 48; Duangudom, Francis, & Herzog, 2007). The effects of paracontrast masking are often smaller than that of metacontrasts, but can last for a long time span between forward mask and the masked stimulus (Breitmeyer et al., 2006; Öğmen, Breitmeyer, & Melvin, 2003), even when presented dichoptically (Breitmeyer, Ziegler, & Hauske, 2007). The data of Breitmeyer et al. (2006) demonstrate that the obtained masking functions depend on the visibility task: While paracontrast masking exhibited a type-A-like function with maximal masking at an *inter-stimulus-interval* (ISI) of zero milliseconds in a contour discrimination task, the perceived brightness of the target varied according to a complex function and was even increased at ISIs around 50 ms.

In addition to the temporal delay of mask and target, a second important determinant for the strength of paracontrasts and metacontrasts is the spatial proximity of the contours of target and mask. Here, masking is strongest when the contours of the mask tightly fit the contours of the target, and no masking is to be expected when the contours of the mask have much space to that of the target (Alpern, 1953; Kolers, 1962; Mattler & Palmer, 2012; Wernicke, 2014). This property of metacontrast masks creates a limitation regarding the type of stimuli that can be efficiently masked using metacontrast masks. Even though metacontrast have been applied to complex stimuli such as letters (Schiller & Smith, 1965; Weisstein, 1966; Wernicke, 2014), metacontrasts are primarily used to mask simple shapes such as lines (Macknik & Livingstone, 1998), colored discs (Breitmeyer, Ro, et al., 2004; Schmidt, 2002), square versus diamond stimuli (Albrecht, Klapötke, & Mattler, 2010; Mattler & Palmer, 2012), or left versus right arrows (Vorberg et al., 2003). Such simple shapes allow for a good alignment of target and mask contours. Paracontrast and metacontrast masking are not limited to monoptic stimulus presentations but can also be obtained in a dichoptic paradigm where target and masks are presented to different eyes (Breitmeyer & Ganz, 1976; Breitmeyer et al., 2007; Schiller & Smith, 1968), including with colored stimuli (Yellott & Wandell, 1976).

1.3.2. Pattern masking

Other than paracontrast and metacontrast masking, pattern masks overlap with elements of the masked stimulus (e.g., Enns & Di Lollo, 2000). Accordingly, pattern masks can vary greatly with respect to their spatial layout: They can take the forms of random fields of visual noise (e.g., Delord, 1998; Turvey, 1973), superimposed lines (e.g., Turvey, 1973; Breitmeyer & Ganz, 1976) or other geometrical forms (e.g., Dehaene et al., 2001), scrambled pictures (Lähteenmäki et al., 2015; Mudrik & Koch, 2013), and meaningful stimuli like random letter strings to mask words (e.g., Kiefer, 2002; Michaels & Turvey, 1979), or the picture of a house to mask the picture of a face (Loffler, Gordon, Wilkinson, Goren, & Wilson, 2005). Breitmeyer and Ganz (1976) differentiate between two general classes of pattern masks: Noise masks that are designed to bear little resemblance with the masked stimuli (usually fields of visual noise consisting of black and white pixels) and structure masks that share figural features with the masked target, for example the angularity, curvature or orientation of the target contours. According to Breitmeyer and Öğmen (2006), metacontrast and paracontrast masks are therefore special cases of structure masking. For the sake of clarity, a stricter definition of pattern masking will be adopted in this thesis, and metacontrast and paracontrast masks that have no spatial overlap with the target will be treated as a separate class of masks next to pattern masks that are defined by stimulus overlap.

Pattern masks can also be applied as forward and as backward masks. In fact, forward and backward pattern masks are often applied in combination (sandwich masking). When presented in isolation, forward and backward pattern masks typically produce type-A masking (Breitmeyer & Öğmen, 2006, Turvey, 1973). However, backward masking using structure masks may also produce type-B masking when the mask is weaker than the target (Turvey, 1973) or when masks are presented dichoptically (Michaels & Turvey, 1979). Like metacontrast masking, forward and backward pattern masking is also possible in dichoptic masking conditions, even though weaker for noise than for structure masking (Breitmeyer & Öğmen, 2006, p. 73; Michaels & Turvey, 1979, Experiment C1; Turvey 1973, Experiment 3 & 5). The fact that the masking function depends on the energy ratio under monoptic viewing, but type-B masking can be found independent of the energy ratio under dichoptic presentation conditions, has inspired the conclusion that pattern masking at short SOAs under monoptic viewing is due to energy-dependent integration of target and mask at *peripheral* levels (Breitmeyer & Öğmen, 2006; Michaels & Turvey, 1979) which have been vaguely defined as including retina, lateral geniculate nucleus (LGN), and V1 (Turvey, 1973). The strength of pattern masking is generally governed by the amount of spatial overlap between target and mask and is stronger when the composite of target and mask would be difficult to tell apart (Coltheart & Arthur, 1972; Francis & Cho, 2008; Schiller, 1966). When colors are masked, backward and notably forward masking effects are stronger when target and mask colors are processed via the same chromatic channels (Smithson & Mollon, 2001). Generally, when the masks share task relevant features with the masked stimuli, e.g., when letter strings are used to mask words, or alienated faces are used to mask faces, additional masking emerges (Delord, 1998; Enns, 2004; Loffler et al., 2005; Van Opstal, Reynvoet, & Verguts, 2005b).

1.3.3. Possible mechanisms

Pattern and metacontrast masks share many properties, and are often used interchangeably with the common goal to reduce conscious awareness of stimuli. However, the underlying masking mechanisms are still unclear and at closer sight, functional differences between the masking techniques become apparent: Even though metacontrast, paracontrast, pattern forward- and backward masks can produce similar masking effects in some situations, their masking functions diverge in other conditions, indicating that different masking mechanisms are responsible for the individual masking techniques. In the following paragraphs, influential masking theories will be described that illuminate functional differences between forward and backward masking. Afterwards, spatial aspects in current masking theories will be highlighted that may explain functional differences between overlapping (pattern) and surrounding (paracontrast and metacontrast) masks.

1.3.3.1. Disrupting recurrent processing with backward masking

An important contribution regarding the neurophysiological mechanisms of backward masking has been made by studies showing that backward masks interfere with late, presumably feedback activity rather than early feedforward activation of a stimulus. Lamme, Zipser, and Spekreijse (2002) observed that oriented patches exert a biphasic response in V1 of macaque monkeys that are engaged in a figure detection task. The first part of the neuronal response signals the orientation of the line patch, and the later part signals figure-ground differences. Lamme et al. (2002) found that backward masking reduced only this later component of the response. Based on previous findings, they argued that figure-ground segmentation depends on feedback from higher areas, indicating that backward masking specifically reduces feedback processing of the stimulus. Later, Fahrenfort et al. (2007) extended these findings to humans by showing that backward masks specifically reduce a late component in EEG, which they interpreted as reentrant processing toward early visual areas. At the same time, an early component is unaffected by backward masking, suggesting that feedforward processing is preserved even under masking. Similarly, Haynes, Driver and Rees (2005) discovered that metacontrast masking in humans reduces the connectivity between area V1 and higher visual areas rather than the net signal strength per se, which is also compatible with the view that backward masking reduces neuronal feedback, but not early stimulus-dependent signals.

These findings have also been included in current masking models and the notion that backward masking specifically interferes with a late, recurrent stage of stimulus processing is an important feature of many recent masking theories (Breitmeyer, 2007, 2014; Breitmeyer & Öğmen, 2000; Di Lollo, Enns, & Rensink, 2000; Enns & Di Lollo, 2000). To illustrate, consider a newer version of a dual channel model (Breitmeyer, 2014). According to this model, stimuli are processed along two routes: In the first route, a coarse representation of the perceived stimulus is transported via a fast magnocellular-driven route along the dorsal stream. This representation contains low frequency spatial information necessary to construct contours and serves to generate a perceptual hypothesis of the stimulus at prefrontal areas. Next, this perceptual hypothesis is projected top-down to the IT cortex and via reentrant activation to primary visual areas in the ventral stream. At the same time, detailed visual information of the stimulus is processed along the slower ventral stream. This ventral information is necessary for a successful surface processing of the stimulus and lays the foundation for a conscious percept of the stimulus. In area IT, the slow ventral activation is compared with the perceptual hypothesis generated via the dorsal pathway, and the updated perceptual hypothesis becomes conscious. The incoming information in the ventral pathway is thereby continuously modulated by recurrent activity based on the latest perceptual hypothesis. Masking occurs as a result of conflicting stimulus information in and between these two pathways. Its predecessor, the retino-cortical dynamics (RECOD) model, elaborates what processes may play a role in the interaction between the two paths (Breitmeyer et al., 2006; Breitmeyer & Öğmen, 2006). The RECOD model also explains masking by interactions between a transient and a sustained channel that receive inputs from the M and P pathways, respectively, corresponding to the dorsal and ventral pathway above. Optimal type-B metacontrast masking at intermediate SOAs is modeled by a catch-up of the fast M-dominated mask activity with the slower P-dominated activity of the target. In the RECOD model, such interactions between parvo- and magno-cellular pathways are referred to as *inter-channel inhibition*, as opposed to *intra-channel inhibition* that occurs within each channel (Breitmeyer & Öğmen, 2006; Öğmen et al., 2003). According to the newer framework by Breitmeyer & Öğmen (2006) and Breitmeyer (2014), any inhibitory interactions between or within transient and sustained channels will ultimately prevent recurrent processing that is required for conscious perception.

The conclusion that backward masks selectively interfere with recurrent processing that is necessary for conscious percepts (Breitmeyer & Öğmen, 2006; Fahrenfort et al. 2007; Lamme et al., 2002) is compatible with other findings that backward masks do not disturb early stimulus activity (Bacon-Macé, Macé, Fabre-Thorpe, & Thorpe, 2005; Bridgeman, 1980; Haynes et al., 2005; Macknik & Livingstone, 1998; Macknik & Martinez-Conde, 2007;

Rolls, Tovée, & Panzeri, 1999). This early stimulus activity has been characterized as reflecting a fast feedforward-sweep of information processing (Bacon-Macé et al., 2005; Lamme & Roelfsema, 2000; Schmidt et al., 2006). According to research on the fast feedforward-sweep, a large share of information processing takes place already in the first 100 ms after stimulus-presentation. It has been hypothesized that the feedforward sweep is based on the first spikes at each successive neuronal layer up to the frontal cortex, enabling a rapid recognition and categorization of the stimulus (DiCarlo et al., 2012; Lamme & Roelfsema, 2000; Oram & Perrett, 1992; Rolls & Tovee, 1994; Tovee, Rolls, Treves, & Bellis, 1993; van Gaal & Lamme, 2012; VanRullen, 2007). Together, these results may imply that backward masks allow for a high-level analysis of stimulus features even when consciousness of the stimulus is prevented by backward masking.

1.3.3.2. Disrupting feedforward processing with forward masking

While backward masks that are presented with a target-mask SOA of more than 40 ms apparently come too late to impact on early stimulus activation (Bacon-Macé et al., 2005; Kovacs, Vogels, & Orban, 1995; Rolls et al., 1999), matters are more complicated when forward masks are used to mask the target. Here, it has been shown that forward masks reduce early target activity (Judge, Wurtz, & Richmond, 1980; Kondo & Komatsu, 2000; Macknik & Livingstone, 1998) or merge with the response of the target, making target and mask activity undistinguishable (Alwis, Richards, & Price, 2016).

These results have also shaped theories of forward masking. Recall that the main determinant of backward masking in the RECOD model (Breitmeyer & Öğmen, 2006) was a inhibition of ventral target activity by fast M-driven activity of the mask. In forward masking this interaction between transient and sustained channels can take both directions because the sustained activity of the mask is reduced due to reciprocal inhibition with the transient activity of the target, resulting in weaker forward than backward masking. Thus, forward masks may directly interfere with the transient activity of the target via an inter-channel sustained-on-transient inhibition and therefore prolong reaction times to the target (Öğmen et al., 2003). However, the main agent of forward masking in the RECOD model are intra-channel interactions between the sustained activity of target and mask. Combining both, masking by paracontrast is modeled as fast intra-channel suppression due to the center-surround-antagonism of classical receptive fields and a second, longer-lasting intra-channel inhibition between the sustained activity of target and mask (Breitmeyer et al., 2006). The authors also observed a facilitative effect of paracontrast masks that may, according to Breitmeyer et al. (2006), reflect an unspecific activation process similar to that described in Bachmann's *perceptual retouch* theory (1997). The fact that forward masking in this model can also affect the transient activity of the target points to a major difference between the masking mechanisms of forward and backward masking and suggests that forward and backward masks interfere with information processing at different functional levels.

Even though the exact mechanisms of forward and backward masks are still unclear and the contribution of feedforward and feedback mechanisms in backward masking is still debated (Bacon-Macé et al., 2005; Hermens, Luksys, Gerstner, Herzog, & Ernst, 2008; Macknik & Martinez-Conde, 2007; Silverstein, 2015; Tapia & Beck, 2014), current findings and theories of masking suggest that forward masks, by interfering with transient activity of the masked stimulus, impair information processing at an earlier processing stage than backward masks.

1.3.3.3. Integration at early processing levels with overlapping but not surround-masks

Whereas the temporal dynamics of masking have been a core issue for many masking theories, the role of the spatial layout of target and mask has received much less attention. Historically, the role of the spatial overlap of masks has been discussed in the framework of integration-interruption accounts of masking. More specific, it has been suggested that pattern masking involves an integration process that is not present for surround masks.

In an early attempt to differentiate possible mechanisms of visual masking, researchers discussed the influence of two processes (Scheerer, 1973): *Masking by interruption* proposes that target processing is disrupted by signals of the mask. Perceptually, masking by interruption should lead to shorter perceived durations of the target, whereas masking by integration should lead to a degraded, but not shorter target percept (Scheerer, 1973). In line with this, Sperling (1963) demonstrated that the number of identified target elements corresponds to the SOA between mask and target, supporting an interruption account of masking. More recently, interruption theories gained support from neurophysiological studies that measured cell activations in the temporal visual cortex of macaques (Kovacs et al., 1995; Tovee et al., 1993). Their results show that backward masks shorten the duration that cells fire in response to the target, which is in good accord with an interruption account of masking. By definition, masking by interruption can only be applied to cases where the mask comes after the target and cannot explain forward masking (Scheerer, 1973).

Masking by integration, on the other hand, reflects the inability of the visual system to encode rapidly presented stimuli as separate events due to its limited temporal resolution. For example, Eriksen (1966) demonstrated that luminance summation of the target and mask reduces the perceived contrast of the target in a flash-masking paradigm. An integration account of masking is in line with the finding that the degree of visual overlap is a central determinant of visual pattern masking (Coltheart & Arthur, 1972; Francis & Cho, 2008; Schiller, 1966) and masking by integration can be applied to explain both forward and backward masking at short SOAs (Breitmeyer & Ganz, 1976).

It has been suggested the predominance of type-A functions in pattern masking, especially forward masking, is due to integration processes at short SOAs (Breitmeyer & Öğmen, 2006; Michaels & Turvey, 1979; Scheerer, 1973; Spencer & Shuntich, 1970). For example, the masking functions in monoptic viewing conditions depend on the luminance (Michaels & Turvey, 1979; Spencer & Shuntich, 1970; Turvey, 1973) and overlap (Coltheart & Arthur, 1972; Francis & Cho, 2008; Schiller, 1966) of the mask, which would be expected from an integration mechanism. Because type-A masking with pattern forward and backward masking decreases under dichoptic presentation conditions, and type-A backward pattern masking depends on the luminance of the mask, it has been proposed that type-A masking of these masks reflects early, precortical integration mechanisms (Breitmeyer & Öğmen, 2006; Michaels & Turvey, 1979; Turvey, 1973). Comparing different pattern masks, Turvey (1973) found that dichoptic masking of letters was only possible with structure, but not random noise pattern masks, leading him to the conclusion that the locus of noise masks is primarily at precortical levels in the visual system, whereas additional central mechanisms are active for structure masks that bear similarities with the masked stimulus. This view is shared by later reviews that connect integration processes with interactions at early stages of visual processing (Breitmeyer, 2015; Breitmeyer & Öğmen, 2006; Tapia & Beck, 2014). Even though dichoptic masking has later also been reported for noise masks (Breitmeyer & Öğmen, 2006), these findings provide evidence for functional masking differences even across different types of pattern masks, indicating that the spatial layout of the mask regulates masking at peripheral levels of processing.

Lastly, it is important to note that integration processes do not always have to be detrimental, but can also lead to increased visibility. Francis and Cho (2008) compared masking functions with different target and mask stimuli, and concluded that stimulus visibility at short SOAs is determined by the discriminability of target and mask if both stimuli were combined in a merged percept. The authors remark that most contemporary models of masking include only one spatial dimension and thus are not able to account for the differential effect of integrating two-dimensional stimuli. Even though more recent models try to fill in the gap, the authors struggle to model the effects of overlapping masks (Hermens et al., 2008).

One model that accounts for spatial differences between masks was provided by a later modification of the integration-interruption account, the *object substitution theory* of visual masking (Di Lollo et al., 2000; Enns, 2004; Enns & Di Lollo, 2000). According to this theory, backward masking in short SOAs (< 100 ms) is also caused by spatio-temporal integration. This mechanism is also the driving force for forward masking (Enns & Di Lollo, 2000). The authors assert that the temporal integration process is relatively independent of attentional influences and depends on the spatial layout of target and mask. It is characterized by local contour interactions when metacontrasts are being used, and “camouflage” in the case of pattern masks. At later SOAs, masking by object substitution gains weight: The sensory input of the target is constantly compared with incoming information via recurrent loops. When the information of the mask arrives, a mismatch is created and the system drops its current representation of the target in favor of the incoming information of the mask. Whereas the object substitution process at late SOAs is independent of the spatial layout of the stimuli, masking at short SOAs depends on the figural similarities between target and mask, because task-specific expectations determine which contours are bound together (Di Lollo et al, 2000). Therefore their theory takes into account that the appearance of pattern masks varies greatly throughout the literature and the effects of pattern masks vary accordingly. This differentiation between different types of pattern masks is not covered by the RECOD model as of 2006 (Breitmeyer & Öğmen, 2006) or the masking hierarchy developed by Breitmeyer more recently (2015).

However, the RECOD model also holds that additional masking processes are active when stimuli overlap. In the RECOD model put forward by Breitmeyer and Öğmen (2006), the effects of transient-on-sustained inhibition in type-B backward masking and sustained-on-sustained inhibition in forward masking are complemented by an additional integration process between target and mask activity when the stimuli are spatially overlapping and thus share common processing pathways. This integration process was linked to both forward and backward pattern masking and starts as early as the photoreceptor level (Breitmeyer & Öğmen, 2006, p. 165 ff.), thus interfering with information processing at a lower stage than surround masking which is located at a cortical level. Consequently, pattern backward masks have been ranked at a lower level than metacontrast masks in a masking hierarchy that Breitmeyer (2015) presented more recently.

To recap, although the mechanisms for specific masking techniques are difficult to pin down and far from being resolved, different mechanisms have been proposed for certain masking techniques. In particular, forward masking has been linked to integration and contour interactions that interfere with stimulus processing at early levels in the visual hierarchy, whereas backward masking curtails the ongoing processing of the masked stimulus, potentially by interfering selectively with recurrent processes. Regarding the spatial layout of the masks, integration of target and mask may have different consequences for overlapping and surround masks, and overlapping masks may involve integration of stimuli at earlier levels in the visual hierarchy than surround masks do.

1.3.4. The masking hierarchy

In the previous section 1.3.3, central characteristics of different masking techniques were outlined together with implications for possible masking mechanisms. According to these masking mechanisms, masks interfere with stimulus processing at different stages of visual processing, depending on their temporal order and spatial layout. In a nutshell, forward masks may reduce an early part of the neuronal response and thus interfere with information processing at an earlier level than backward masks that do not reduce this early onset activity. Second, overlapping masks may rest more on early integration processes, possibly even starting at the retina, and thus interfere with information processing at a more peripheral level than surround masks.

The main purpose of this thesis is to investigate how masks disturb not only the visibility but also the priming effects elicited by stimuli. While the previous paragraphs described approaches that sought to define the locus of specific masking techniques, there is also research that directly compared the effects of different masks on stimulus processing. An emerging hierarchy of masking techniques can help to define which masks conflict with stimulus processing at a very early stage, thereby disrupting priming effects as well.

So far, two experimental strategies have been used that permit a direct functional comparison of different masking techniques. First, the masking effects of different masks can be directly compared or even played off against each other by examining if one mask can inhibit the effects of a second masking technique. Second, indirect measures such as priming effects can be compared across different masks, indicating how much processing is possible despite masking.

Chakravarthi and Cavanagh (2009) provided an influential example of the first strategy. They compared the effects of different masks by presenting different backward masking techniques in combination. In their experiment, subject had to report the orientation of a small gap in a square stimulus that was presented in the visual periphery. When this stimulus was surrounded by similar stimuli, so-called flankers, its visibility was drastically reduced due to visual crowding. In a next step, the authors investigated whether the suppressive effects of the flankers could be abolished by masking the flankers with additional masks. According to the reasoning of Chakravarthi and Cavanagh, if one masking technique interferes with information processing on a more basic level than another mask, this ‘low-level’ masking technique should be able to abolish the masking impact of another ‘high-level’ mask, thereby rendering a previously masked stimulus visible again. In this manner, backward pattern masks were more efficient than metacontrasts in reducing the effects of flankers in a crowding paradigm, indicating – as suggested by Breitmeyer (2015) – that pattern masks affect information processing at an earlier stage than metacontrasts do. This is in good agreement with the conclusion that overlap masks may disturb information processing on a more basic level than surround masks.

In a similar vein, Breitmeyer, Koc, Öğmen, and Ziegler (2008) previously demonstrated that metacontrast masks are not effective when presented to the non-attended eye during binocular rivalry. Such an effect of binocular rivalry should not be possible if binocular rivalry interferes with processing stages after metacontrasts do, and the authors concluded that visibility suppression by binocular rivalry must occur at the same or previous level than masking by metacontrasts.

Another way to compare the processing level at which suppression by visual masks occurs is by comparing priming effects under masking. As pointed out previously, priming is a tool that can index stimulus processing independent of conscious awareness. Therefore, evaluating the effects of masks on priming may be a more sensitive way to index the effects of masks on stimulus processing because even in the case that masks interfere with stimulus processing before a conscious stage is reached, this interference should be evident from reduced priming effects for these masks. Put another way, although different masking methods may have a similar impact on stimulus visibility, they may allow for a different degree of priming. As outlined in Chapter 1.2, it is frequently assumed that high level priming like semantic priming in the LDT requires more complex processing stages than low level priming of shape or color (for a similar line of argumentation, see Breitmeyer, 2015, Kouider & Dehaene, 2007). Whereas low level masking techniques may interfere with information processing even at these early levels, reducing color and semantic priming alike, another high level masking technique that operates at later processing stages may only interfere with high level, semantic processes and leave color priming in early visual areas unaffected. This results in the idea of a functional hierarchy of visual masks.

Based on the logic presented above, several authors compared effects of visual masking techniques on indirect measures of stimulus processing, including priming effects. For example, Fogelson et al. (2014) compared fMRI activation when stimuli were masked by presenting color-opposite images to both eyes (continuous flicker fusion, CFF) with stimuli masked by CFS. They observed that category information about the CFS-masked stimulus could be decoded only in occipital areas, but additionally from temporal and frontal areas when CFF was used. This suggests that processing in the absence of awareness differs for the two masking methods and provides direct physiological evidence that category information under masking can reach different areas in the brain depending on the specific masking technique.

Faivre, Berthet & Kouider (2012) found behavioral evidence for differential effects of masking by comparing the effects of masks on perceptual and affective priming effects. They observed affective priming only when primes were masked using visual crowding, but not with sandwich pattern masks or CFS. Low level perceptual priming by stimulus repetition on the other hand was evident for these masking methods. The results agree with the frequent classification of CFS as low level masking method that interferes with early stimulus processing prior to other masking methods (Breitmeyer, 2015; Fogelson et al., 2014; Peremen & Lamy, 2014). Regarding sandwich pattern masks, the authors come to a similar conclusion, and raise the possibility that the processing of emotional stimuli is not possible beyond perceptual levels if stimuli are masked by pattern masks. However, findings of larger priming effects in monoptic masking than CFS have been presented for arrow priming using metacontrasts (Peremen & Lamy, 2014) and affective priming of emotional faces using backward pattern masks (Almeida, Pajtas, Mahon, Nakayama, & Caramazza, 2013). Together, these findings suggest that monoptic masking techniques permit larger priming effects than masking techniques involving binocular rivalry. In addition, the results presented by Faivre et al. (2012) provide first evidence that crowding allows for more priming than sandwich masking.

Other results also suggest that different monoptic masks differ with regard to their effects on stimulus processing. In her dissertation, Wernicke (2014) compared priming under sandwich pattern and backward metacontrast masks. She observed that priming in a color and a categorical priming task were only affected by the strength of sandwich masks, but not of metacontrast masks. As a consequence, she concluded that sandwich pattern masks disrupt information processing at a more basic level than metacontrast masks. However, she was not able to tell apart whether this additional suppression resulted from contour overlap or forward masks, both of which are defining characteristics of sandwich pattern masks.

Breitmeyer (2015) provided a comprehensive masking hierarchy that is able to integrate most of these findings. In the masking hierarchy put forward by Breitmeyer, dichoptic masking methods like CFS have been classified as low-level masking techniques that reduce information processing at early processing stages. Monoptic masking techniques such as metacontrast and pattern masking, on the other hand, have been located at higher ranks of the visual masking hierarchy. In line with behavioral (Breitmeyer, Öğmen, & Chen, 2004; Deplancke, Madelain, & Coello, 2016; Wernicke, 2014) and neurophysiological findings (Macknik & Livingstone, 1998; Schiller, 1966), that are reviewed in greater detail elsewhere (Chapter 1.3.3.2 and Chapter 4), Breitmeyer places sandwich masking that includes forward masks on a lower level than backward masking. At the same time, he states that processing under masking can reach semantic levels with both sandwich and backward masking. Regarding backward masking techniques, Breitmeyer assumes that backward pattern masks produce earlier interferences with stimulus processing than metacontrasts do, referring to the unmasking study by Chakravarthi and Cavanagh (2009, see above) and the proposition that pattern masks involve integration processes that are absent for metacontrasts (see previous section 1.3.3). However, direct comparisons of priming effects under backward pattern versus metacontrast masking that validate this ranking are still pending.

A frequent problem with studies that compare the effects of different masks is that stimulus parameters vary greatly between the different masking conditions, even within the same study. For example, in the study of Faivre et al. (2012) the prime duration was 1200 ms in the crowding condition, whereas the prime was only presented for 33 ms in the sandwich masking condition. Naturally, this makes comparisons between priming effects across conditions difficult, to say the least, and could also explain why affective priming was only present in the crowding condition, as Faivre and colleagues acknowledge. When presentation parameters like the prime energy are equalized between masking conditions, the differences between priming effects may disappear. Indeed, a comparison of CFS and monocular sandwich masking revealed comparable priming effects of facial features across masking conditions when the prime duration was equalized (Izatt, Dubois, Faivre, & Koch, 2014). Instead, priming effects with both masking techniques varied as a function of the mask contrasts, reminding of Wernicke’s (2014) results obtained for sandwich pattern masks. To understand the effects of visual masks on stimulus processing, it is necessary to identify the key features of individual masking techniques, and compare priming for masks that vary only with regard to this key feature, with all other variables held constant. This is the approach that will be adopted throughout this thesis.

In closing, when it comes to interpreting priming effects in the literature, it is important to bear in mind the widespread differences between different priming studies, including the use of different masking methods and presentation parameters, which regulate the extent of stimulus processing that is possible for masked stimuli. The masking studies and priming studies presented in this chapter strongly suggest that different masking techniques interfere with different stages of stimulus processing.

1.4. Engaging confounded masks and priming tasks

In Chapter 1.2, different priming paradigms were described that are used to explore processing of subliminal stimuli at various levels of complexity. Whereas robust priming is found in perceptual tasks, such as priming of stimulus color or shape, findings are less clear for semantic priming of masked stimuli. In all of these paradigms, visual masking is used to prevent conscious accessibility of the stimuli. However, visual masks interfere with information processing in different ways, which also affects the degree of priming that is possible under masking (Chapter 1.3).

Consequently, the choice of the masking technique is a determining factor for studies that try to identify the limits of processing subliminal stimuli. However, the effects of most masks on stimulus processing in the absence of awareness are not well specified. Therefore, researchers usually base their choice of masks on other criteria, such as the effectiveness of visual masks to reduce stimulus visibility. The strength of a mask depends in large parts on the nature of the masked stimuli (Chapter 1.3). As a consequence, different masking customs emerged between the different fields of research on unconscious perception. While semantic priming studies are dominated, with few exceptions (e.g. Marcel, 1983) by the use of sandwich pattern masks in lexical paradigms (e.g., Abrams & Grinspan, 2007b; Draine & Greenwald, 1998; Kiefer, 2002; Naccache & Dehaene, 2001; Van den Bussche, Hughes, Humbeeck, & Reynvoet, 2010), or CFS if pictures are used to prime semantic categories (Mudrik et al., 2011), priming of perceptual features like color (Breitmeyer, Öğmen, et al., 2004; Ro et al., 2009; Schmidt, 2000; Schmidt et al., 2006) and shapes (Francken et al., 2011; Klotz & Neumann, 1999; Koivisto et al., 2012; Mattler & Palmer, 2012; Vorberg et al., 2003) is usually combined with backward masking techniques like metacontrast masks.

The use of sandwich pattern masks in semantic studies is based on practical grounds: On the one hand, masks without spatial overlap are less effective than overlapping masks in masking letters (Enns, 2004), unless special care is taken in constructing the fonts and masks used in the experiment (Chapter 2; Wernicke, 2014). The same can be said about forward masks that also boost the effectiveness of masks which explains why forward and backward masks usually come hand in hand in semantic priming paradigms (Kouider & Dupoux, 2004; Schiller & Smith, 1968; Wernicke, 2014).

The resulting confounding between masking techniques and priming tasks causes interpretational problems, because the robust priming effects in perceptual priming tasks on the one hand, and the small and less consistent semantic priming effects on the other can be either attributed to differences in task complexity or low level interferences with information processing that are present with some masks but not others (Wernicke, 2014). To overcome this potential confounding, a complete account of semantic priming effects also needs to consider the role of the mask.

The primary goal of this thesis is to investigate semantic priming under optimal masking conditions and identify possible features of visual masking techniques that influence semantic priming effects. To do so, semantic priming in the LDT will be first combined with a masking technique that is known to produce robust priming effects in the literature: Backward metacontrast masks. With backward metacontrast masks, priming effects were independent of visibility in previous perceptual priming studies (Chapter 1.2) and backward masks have been ranked high in a hierarchy of visual masks, indicating that they interfere with stimulus processing at a late processing stage (Chapter 1.3). Other than the sandwich pattern masks that are most frequently used in semantic priming studies, metacontrasts neither involve forward masks nor overlap of contours between prime and mask, avoiding possible sources of low level mask interference. To measure the impact of the visual mask on priming effects, the strength of the mask will be varied in three steps. This way, it is possible to show whether priming effects are independent of masking strength, or decrease when masking is stronger, as was previously the case in semantic priming studies (Chapter 1.2). As a control condition, this experiment will also involve a color discrimination task as a perceptual counterpart to the LDT. In such a task, perceptual priming effects should be independent of masking strength when using metacontrasts (Chapter 1.2). The subsequent experiments will build on the results of this study, and expand on the role of the mask for priming effects by adapting the spatial layout of the backward masks (Chapter 3) and analyzing the role of forward masks (Chapter 4).

2. Semantic Priming Effects Using Metacontrast Masking

2.1. Abstract

Masked priming experiments have repeatedly demonstrated that perceptual stimulus features (e.g. stimulus shape or color) can be processed independent of stimulus awareness. However, analogous research on processing of semantic features is less conclusive and semantic priming effects are reduced when the stimulus visibility is reduced by masking. This has been interpreted as evidence that semantic processing is limited when stimuli cannot be consciously perceived. However, an alternative explanation is also possible: Studies on semantic processing typically use sandwich pattern masks to reduce the visibility of their stimuli, whereas metacontrast masks are a popular choice in studies on perceptual processing (Wernicke, 2014). It is possible that visual masks not only interfere with processes underlying conscious visibility, but also interfere with processes underlying priming effects. Specifically, it has been argued that sandwich pattern masks disrupt stimulus processing in a more fundamental way than metacontrast masks. Thus, priming tasks and masking techniques are confounded which could explain why semantic processing is limited with sandwich pattern masks. The goal of this study is to find out whether semantic priming effects can be dissociated from visibility if metacontrast masks are being used instead of sandwich pattern masks. Metacontrasts have not yet been tested in semantic priming paradigms. We present novel metacontrast masks for word stimuli and put these masks to the test with two different tasks, a color choice task (Experiment 2.1) and a lexical decision task (Experiment 2.2), to sample prime processing at different processing depths. We found that semantic and color priming effects were not affected by metacontrast masking, even though these masks reduced the visibility of stimuli. Our results point to a dissociation of processes underlying priming effects and visibility even at a semantic level.

2.2. Introduction

Contemporary theories of consciousness identify cognitive functions unique to conscious information processing (Baars, 2005; Crick & Koch, 2003; Dehaene & Naccache, 2001; Lamme, 2010; Oizumi et al., 2014). One approach to identify these functions is to search for processing limits of unconscious stimuli. The masked priming paradigm is a useful paradigm that enables to examine the effects of stimuli even if they cannot be consciously perceived. Masked priming effects indicate to what extent reactions to target stimuli are facilitated by related prime stimuli when the visibility of the primes is reduced by additional masks. Previous experiments of masked priming show that perceptual stimulus features like shape (Francken et al., 2011; Klotz & Neumann, 1999; Mattler & Palmer, 2012; Vorberg et al., 2003) or color (Schmidt, 2000, 2002; Wernicke, 2014) can be processed even when stimulus awareness is prevented by masking. Even more, priming of perceptual features in these studies was completely independent of masking, indicating that a nonconscious extraction of perceptual stimulus information can operate independently of processes underlying stimulus awareness.

Whereas the results are convincing for perceptual priming studies, the evidence is less clear when the processing of stimuli is probed on a more complex, semantic level. Semantic processing refers to the access of semantic concepts that are stored in long-term-memory (e.g., Holender, 1986; Mudrik et al., 2014). Although numerous studies exist that report semantic priming in the absence of stimulus awareness (for reviews see Kouider & Dehaene, 2009; Van den Bussche, Van den Noortgate, & Reynvoet, 2009), these effects are usually small and replication attempts regularly fail (de Wit & Kinoshita, 2015; Holender, 1986; Klinger et al., 2000; Lähteenmäki et al., 2015). Critics have argued that semantic priming effects may be absent when prime visibility is carefully controlled for and confounding non-semantic sources of priming are excluded (Abrams & Grinspan, 2007b; de Wit & Kinoshita, 2015; Kouider & Dehaene, 2007; Kouider & Dupoux, 2004). Influences of partial awareness on priming effects may go unnoticed due to inadequate visibility tasks (Kouider & Dehaene, 2007; Schmidt & Vorberg, 2006) or insensitive data analyses (Dienes, 2015; Shanks, 2017).

At the same time, the size of semantic (de Wit & Kinoshita, 2015; Kiefer, 2002; Kiefer & Spitzer, 2000; Ulrich et al., 2013) and categorical priming effects (Kouider & Dehaene, 2009; Kouider & Dupoux, 2004) and neurophysiological correlates of semantic processing (Dehaene et al., 1998; Kiefer, 2002; Kiefer & Spitzer, 2000; Ulrich et al., 2013) are generally smaller when the visibility is reduced by masks. This is commonly interpreted as evidence that semantic processing is limited in the absence of stimulus awareness, for example because a strategic use of the prime is prevented that is active when primes are consciously processed (e.g., de Wit & Kinoshita, 2015; Marcel, 1983; Ulrich et al., 2013).

Together, the role of consciousness in semantic priming studies is not clear, and the finding that semantic processing is reduced under masking seems to indicate that semantic processing is limited when stimuli cannot be processed consciously. However, an alternative interpretation is also possible: Whereas visual masks in priming studies are employed solely to decrease conscious accessibility of the primes, recent evidence suggests that visual masks not only decrease prime visibility but also directly influence priming effects (Almeida et al., 2013; Breitmeyer, 2015; Faivre et al., 2012; Izatt et al., 2014; Marcel, 1983; Wernicke, 2014). Provided that visual masks not only reduce processes necessary for conscious awareness, but also processes underlying priming effects, a comparison of masked versus unmasked trials may yield the premature conclusion that semantic priming effects rely on visibility. More than that, interferences from masks could lead to a broad underestimation of masked stimulus processing. This possibility calls for a systematic exploration of the effects of visual masks on processes underlying priming effects.

The most frequently used masking technique in lexical semantic priming studies is sandwich pattern masking in which forward and backward masks are combined (e.g., Draine & Greenwald, 1998; Kiefer, 2002; Kouider & Dehaene, 2009; Kouider & Dupoux, 2004; Naccache & Dehaene, 2001; Ortells et al., 2016; Ulrich et al., 2013), with the target sometimes functioning as backward mask (e.g., Bodner & Masson, 2003; de Wit & Kinoshita, 2015). Pattern masks in lexical studies usually consist of random character strings, but may also involve different patterns such as random shapes (Abrams & Grinspan, 2007b; Dehaene et al., 2001).

Besides pattern masking, a number of other masking techniques exists that have been used to mask different types of stimuli in the literature (Breitmeyer, 2015; Enns & Di Lollo, 2000; Kim & Blake, 2005). One masking technique that is often used in priming of perceptual features such as shapes (Klotz & Neumann, 1999; Vorberg et al., 2003) or color (Breitmeyer, Öğmen, et al., 2004; Breitmeyer, Ro, et al., 2004; Schmidt, 2000, 2002; Wernicke, 2014) is metacontrast masking. Unlike sandwich pattern masks, metacontrast masks are backward masks that include no forward masks and are designed in such a way that they have no spatial overlap with the masked stimulus (Breitmeyer & Ganz, 1976; Kolers, 1962). Interestingly, when the strength of metacontrast masks is manipulated experimentally, priming effects of perceptual features (Francken et al., 2011; Mattler & Palmer, 2012; Vorberg et al., 2003; Wernicke, 2014) and more lately, even categorical priming effects (Wernicke, 2014) are independent of the masking strength. This finding indicates that metacontrast masks interfere with stimulus awareness, but not with priming of these stimuli. These results are in contrast to the reduced semantic priming effects under sandwich pattern masks reported above. In fact, a direct comparison of sandwich pattern masks and metacontrasts revealed that color and categorical priming effects that are intact under metacontrast masking are reduced when sandwich pattern masks are applied

(Wernicke, 2014). This raises the possibility that sandwich pattern masks reduce semantic priming effects, and these priming effects may be intact when metacontrast masks are being used.

Typical sandwich pattern masks in lexical priming studies differ from metacontrast masks in terms of three important characteristics: First, the contours of pattern masks overlap with contours of the prime, whereas metacontrasts are designed to surround all possible contours of the prime with no spatial overlap. Second, pattern masks in lexical priming studies often consist of character strings that by themselves carry target-relevant features. Third, sandwich masks include forward and backward masks whereas metacontrast masks do not include forward masks. In the next few sections, we will look at each of these differences, and discuss in what way they may contribute to a reduction of priming-relevant information.

First, the contours of typical pattern masks overlap with the contours of prime words, whereas metacontrasts masks do not. It has been argued that overlapping masks interfere with stimulus processing due to common activation of processing pathways at early, possibly precortical levels in the visual processing hierarchy (Breitmeyer & Öğmen, 2006; Enns, 2004; Turvey, 1973). This conclusion is nourished by the finding that strong overlapping masks produce less masking when they are presented dichoptically and precortical sources of masking are excluded (Michaels & Turvey, 1979; Turvey, 1973). Metacontrast masks on the other hand produce comparable masking in monoptic and dichoptic presentation conditions (Schiller & Smith, 1968, reviewed in Breitmeyer & Öğmen, 2006). With overlapping masks, neural responses to targets are shortened (Kovacs et al., 1995; Rolls & Tovee, 1994) or merge with responses to the mask (Alwis et al., 2016; Judge et al., 1980; Kovacs et al., 1995; Lamme et al., 2002). This merging of neuronal responses may be partially avoided when metacontrast masks are used (e.g., Alwis et al., 2016). These findings suggest that overlapping backwards masks, which includes letter strings that are commonly used in lexical tasks to mask words, may interfere with stimulus processing at an early processing stage, thereby possibly affecting priming effects (Breitmeyer, 2015). In a seminal work, Marcel (1983) found that backward noise masks presented on the same eye with the prime diminish semantic priming effects that are intact when dichoptic backward structure masks are employed. Marcel concluded that noise masks reduce stimulus information even prior to figure synthesis and therefore also prevent lexical processing. Although Marcel’s work does not yet allow to discern the role of spatial overlap of masks from that of dichoptic presentation, his finding provides one of the first demonstrations that monoptic backward pattern masks could lead to reduced semantic priming effects.

Second, the effects of pattern masks on priming effects may also depend on the content of the pattern masks. Evidence for this possibility was brought forward by Van Opstal, Reynvoet, and Verguts (2005a; 2005b), who have shown that categorical priming effects are reduced when masks contain features that are relevant for the task. In their studies, masks containing letters or numbers reduced priming effects in a numerical priming paradigm that were left intact when using hashtag masks. Van Opstal et al. (2005a, 2005b) proposed that prime and mask activation conflict on a high level that does not depend on physical overlap of the mask and prime but rather, whether the masking stimuli are meaningful for the task and activate a common response pathway. Interference of relevant masks with priming effects may apply to many lexical studies that include letters or letter-like symbols to mask their words (e.g., Draine & Greenwald, 1998; Kiefer, 2002; Marcel, 1983; Naccache & Dehaene, 2001). Together, both low-level interference of contours and conflicts due to higher-level similarities between target and mask have been discussed as possible sources for interferences of priming effects by backward masks. Because many semantic paradigms use letter strings as masks that both overlap with the prime and contain task-relevant features, both of these sources could lead to reduced semantic priming effects due to backward masks.

As a third difference to metacontrast masks, sandwich pattern masks contain forward masks whereas metacontrast masks do not. It has been shown that the inclusion of forward masks may reduce priming of color (Breitmeyer, Öğmen, et al., 2004) or location (Deplancke et al., 2016). Even though this effect of forward masks seems to depend on the task, and did not affect priming of shapes in the same paradigm (Breitmeyer, Öğmen, et al., 2004), these findings show that forward masks can interfere with processes relevant for priming effects. Conceivably, such effects of forward masks extend also to semantic priming paradigms. As most studies on unconscious processing of words apply some sort of sandwich masking with masks presented immediately before and after the masked stimulus, measures of unconscious processing may have been limited by the included forward masks. Therefore, the implementation of forward masks in typical semantic priming studies is another possible source of mask interferences with prime processing.

Another difference regarding the temporal dynamics of metacontrast masks and typical sandwich pattern masks is that metacontrasts are often presented with a certain delay after the prime, optimizing the time of undisturbed processing. In metacontrast priming paradigms, the mask is often presented simultaneously with the target. It is known that priming effects of simple shapes increase with a longer stimulus-onset-asynchrony (SOA) between prime and target/mask (Mattler, 2003; Vorberg et al., 2003). This effect cannot be reduced to effects of prime visibility, and it has been suggested that priming effects that rise with SOA reflect a dynamic accumulation of prime evidence (Vorberg et al., 2003). The role of the prime-mask-SOA in semantic priming studies is less clear, because the backward mask is usually presented immediately after the prime. Greenwald, Draine, and Abrams (1996) varied the prime-target SOA by adapting the duration of the prime, and found masked categorical priming only in the shortest SOA that was tested in their study (SOA = 67 ms). They proposed that activation of masked primes decays rapidly, explaining why semantic priming effects decrease when the prime-mask SOA exceeds 100 ms. This conclusion was in part supported by a later EEG-study analyzing priming in the LDT (Kiefer & Spitzer, 2000). In this study, the prime duration was held constant and the prime-target SOA was varied by increasing the ISI between mask and target. Although behavioral priming effects were obtained at both tested prime-target SOAs of 67 and 200 ms, priming in the N400 component that the authors linked to automatic semantic priming vanished in the long SOA. These results indicate that automatic semantic priming effects may cease at SOAs longer than about 100 ms. When the prime-mask-SOA is increased in a briefer interval by adapting the duration of prime, priming effects in different semantic tasks instead increase (Abrams & Grinspan, 2007b; Draine & Greenwald, 1998; Kouider & Dupoux, 2004). When no backward masks are applied, priming effects also increase with SOA (de Groot, 1984; Greenwald et al., 1996), even in relatively short SOAs below 200 ms that are considered too short for a strategic use of the prime (Neely et al., 1989; Perea & Gotor, 1997; Perea & Rosa, 2002). Although speculative, this may imply that semantic priming effects to some extent profit from a brief interval of undisturbed processing. In analogy to findings on response priming (Vorberg et al., 2003), larger priming effects at longer prime-mask SOAs need not reflect an increase of conscious prime processing. Instead, longer prime-mask SOAs may favor the emergence of semantic priming effects because they permit for a longer duration of undisturbed prime processing. The fact that pattern masks are usually presented immediately after the prime may thus be another difference to metacontrasts masks that are often shown after a brief delay.

Together, metacontrast masks combine important properties that make them less prone to interferences with processes underlying priming effects. In line with these arguments, it has been proposed that metacontrast masks interfere with information processing at a later stage than typical masking techniques commonly used to mask lexical stimuli (Breitmeyer, 2015). This makes metacontrast masks a promising candidate to inquire the role of consciousness for semantic priming effects. Because the efficacy of metacontrast masks depends on the proximity of the stimulus contours with the inner contours of the mask (Alpern, 1953; Kolers, 1962), previous attempts to mask regular letters with circular stimuli were limited with regard to the strength of masking (Enns, 2004; Schiller & Smith, 1965; Weisstein, 1966; but see Wernicke, 2014). Accordingly, we know of no previous attempts to mask whole words with metacontrasts. We developed novel metacontrast masks for word stimuli and tested the effects of these masks in two levels of task complexity: A color priming task and semantic priming in lexical decision task.

In the *lexical decision task* (LDT, Marcel, 1983; Meyer & Schvaneveldt, 1971), participants are required to indicate the lexicality of target words by distinguishing real words (e.g., *witch*) from word-like pseudowords (e.g., *lork*). Only word trials are included in the analysis. When these target words are preceded by semantically related words (*broom*), reactions are faster than when preceded by unrelated words (*car*). Unlike categorical semantic priming tasks, which probe whether categorizations of target words are facilitated by prime words of the same semantic category (e.g., Draine & Greenwald, 1998), semantic priming in the LDT has the advantage that it can only be explained by pre-existing semantic associations between prime and target words. Priming in categorical priming tasks on the other hand could also be explained by direct responses to the primes that may be driven by non-semantic features of the prime stimuli if the experiment allows for the acquisition of specific stimulus-response rules (Abrams & Grinspan, 2007b; Ansorge et al., 2014; Kouider & Dupoux, 2007).

In accordance with the previous literature, we expect that metacontrasts should not interfere with processing of perceptual stimulus features like color (Breitmeyer, Öğmen, et al., 2004; Schmidt, 2002). Because metacontrast masks combine many features that make them less likely to interfere with priming effects than traditional sandwich masks, it is possible that metacontrast will also not affect the priming of semantic information. To demonstrate that priming effects are independent of masking, we varied the strength of the metacontrasts in three steps. We propose that both semantic and color priming will not be moderated by masks when metacontrasts are employed instead of the commonly used sandwich pattern masks.

2.3. General Methods

2.3.1. Method

Participants. Participants were 32 students (16 per experiment) from Goettingen University between 19 and 33 years old (M = 24.1 years) who participated for four 1-h sessions on separate days. All participants were German native speakers, had normal or corrected-to-normal vision and received monetary compensation (7€ per hour). They had no known neurological problems and were not diagnosed with dyslexia. Participants were only accepted if they had never participated in a previous experiment with the current stimuli, and had not participated in any masking study of our laboratory for at least one semester.

Apparatus. Stimuli were displayed on a Viewsonic 1900 Perfect Flat monitor with a vertical refresh rate of 100 Hz. Experiments were run on a Windows PC with the software ‘‘Presentation’’ (Version 19.0, www.neurobs.com). Participants were seated in a dark room and placed their head on a chin rest ensuring a viewing distance of 1 m.

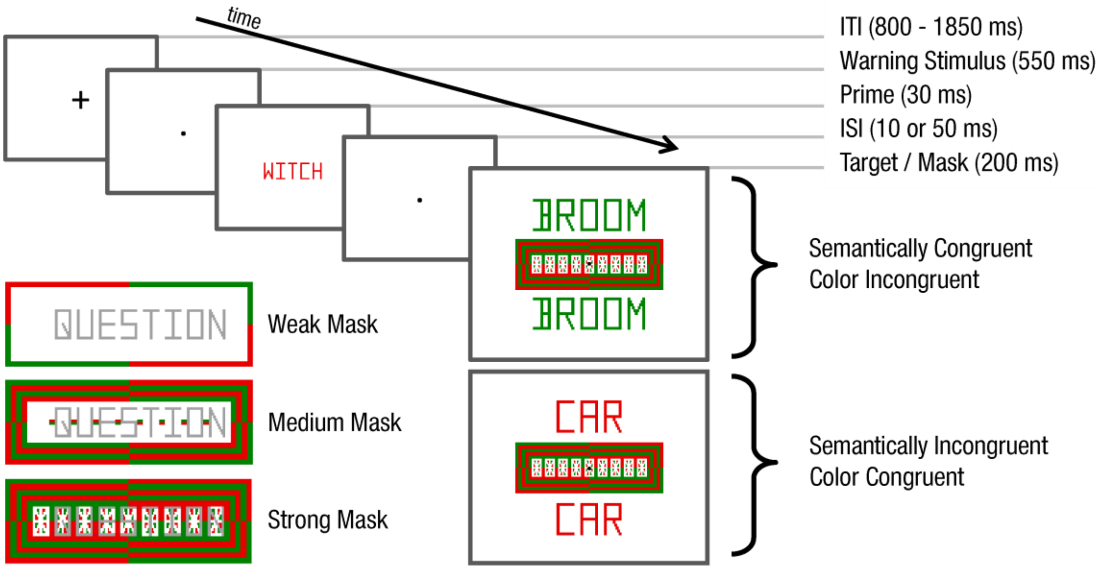

Figure 2.1. Schematic trial sequence for Experiments 2.1 and 2.2. *ITI* = Intertrial-Interval, *ISI* = Interstimulus-Interval. Two example target words are given. The target words can be semantically and color congruent or incongruent with the prime. Color and semantic congruency was balanced in the experiments. For each masking strength (weak, medium and strong) six possible metacontrast masks were used in the experiments. To illustrate the alignment of the word characters with the inner contours of the mask, the word “QUESTION” was inserted at the appropriate position of three example masks. In the experiments, prime words and masks never appeared at the same time.

Stimuli. See Figure 2.1. We presented participants with prime and target words that varied from 3 to 9 letters in length. The maximum angular size of prime words was 2.71° x 0.42° of visual angle. Target words were larger (4.07° x 0.64° of visual angle). Prime and target words were created using an angled font with no curvy shapes to increase shared contours with the masks (see Wernicke, 2014, for a similar approach). As masks we presented metacontrast masks (3.48° x 1.2°) whose inner contours were designed to fit all possible letters of the word stimuli. To construct words, isoluminant red and green colors (24.6 cd/m²) were used. To enable color masking of the prime stimuli, the masks were similarly colored. The masks were divided into green and red subsegments, creating a sample of 6 different strong masks. Masks varied on three levels of strength (weak, medium and strong). The medium and weak metacontrast masks were created by erasing elements of the strong masks to increase the gap between the mask and prime contours. Target words were presented 1.36° above and below fixation.

Congruent prime and target word pairs for the semantic priming task were constructed from word association norms by Hager and Hasselhorn (1994), and word pairs published by Weisbrod et al. (1999). Additionally, we created own words pairs in an online word association pretest using first associations to 70 target words (N = 78 and N = 90 each rated 35 words, respectively). To create incongruent word pairs, prime and target words were randomly reassigned for each participant individually. Pronounceable pseudowords were created using *Wuggy* (Keuleers & Brysbaert, 2010), which operates by replacing word syllables with substitute syllables of equal letter length and comparable transition frequencies of subsyllabic elements. When it was not possible to generate pseudowords with Wuggy, pronouncable pseudowords were created by replacing a single letter. Practice words were constructed according to the same rules except that word pairs had no pre-defined semantic associations.

Tasks. We employed two tasks in this study. Each task comprised three priming-sessions with a speeded choice-task and one subsequent prime recognition session. In the priming sessions of Experiment 2.1, subjects were instructed to indicate as fast and correct as possible whether a target word was displayed in red or green color (color choice task). In Experiment 2.2, subjects were instead instructed to indicate whether a target word was a valid German word or not (LDT). In the prime recognition session, participants were informed about the occurrence of the prime and requested to indicate the color of the prime in the color task (Experiment 2.1), or the lexicality of the prime words in the LDT (Experiment 2.2). Subjects in both experiments performed the experiment with the same randomization and stimuli. Response buttons for both experiments were the left and right Ctrl-button (response mappings were balanced across subjects). After the experiment, participants were interviewed about their experiences and debriefed as to the purpose of the experiment. On the first day, participants were required to read out a 410-word excerpt of a literary text (“Der Grüne Heinreich” by Gottfried Keller) to accommodate them with the font used in the experiment.

Procedure. The trial sequence was the same for both tasks (see Figure 2.1). Each trial started with a fixation cross in the center of the screen which lasted between 800 ms and 1850 ms following a quasi-exponential distribution (inter-trial interval). The fixation cross was replaced by a 550 ms fixation dot (warning stimulus), to prepare subjects for the beginning of the next trial. The prime word appeared in the same location for 30 ms. After a varying inter-stimulus interval (10 and 50 ms, corresponding to prime-target SOAs of 40 and 80 ms) a metacontrast mask was presented at the location of the prime, lasting for 200 ms. Simultaneously, the target word was presented above and below the mask. In the priming task, participants had to respond within 2 s after target onset. Auditory error feedback (440 Hz, 150 ms) was provided in both tasks. In the prime discrimination task, no time pressure was applied. Instead, participants received auditory and visual feedback (“too fast!”) when they responded faster than 500 ms to avoid reactions driven by priming effects.

Design. Each priming session comprised 11 blocks of 64 trials each, plus one demo block of 7 trials. The demo- and first block of each session were considered warm-up and discarded from further analysis. The 64 trials of each experimental block resulted from the factorial combination of 2 prime word lexicalities, 2 target word lexicalities, 2 semantic congruencies (semantically congruent vs. incongruent trials), 2 prime colors (red vs. green), 2 target colors (red vs. green), and 2 SOAs (40 vs. 80 ms). Each combination occurred once in each block. Throughout the three priming sessions factorial combinations of all experimental conditions were realized 10 times, including masking strength (weak vs. medium vs. strong masks), which was randomized across blocks and sessions. Because trials were aggregated across the task-irrelevant factors (in the LDT, color of prime and target; in the color choice task, word lexicality of prime and target and semantic congruency), 160 values per cell were available for data analysis in the color task (= 1920 trials per participant / 12 relevant conditions), and 40 values per cell in the LDT task (48 relevant conditions).

Word pairs were pseudo-randomly assigned to the experimental conditions. The 160 congruent word pairs served as a basis to construct incongruent and pseudoword pairs, leading to a total of 1280 word pairs. In each session, each target lexeme was presented four times, once for both congruencies and target lexicalities. Using a balanced latin square, target lexemes were also balanced for prime and target color, SOA and prime lexicality. Across all participants, every target word was presented four times in every condition except masking strength, which was randomized. The demo- and practice blocks solely contained words of a separate pool of practice words.

The same word pairs used in the priming-sessions were applied in the prime discrimination session. The prime detection session comprised 768 experimental trials (excluding demo and practice block as above). Because trials could be averaged across word colors and lexicality, 128 trials per cell and participant were available for the primary analysis in the visibility task. Every participant encountered each prime word 2-3 times per lexicality. For each participant, all conditions except for the task-irrelevant feature (color in the semantic task, target lexicality in the color task) were balanced.

Data analysis. Trimmed mean reaction times (RTs) per subject and condition were based on correct trials, excluding post-error trials. Outliers were excluded in two steps: First, reactions below 100 ms and greater 2000 ms (response deadline) were omitted. Second, the fastest and two slowest trials of each condition were discarded for each subject. In the prime discrimination task, fast trials below 500 ms were excluded. RTs, arc-sine transformed error rates and *d'* values resulting from signal detection analyses (Macmillan & Creelman, 1991) in the discrimination task were analyzed using repeated-measures-ANOVAs. When the assumption of sphericity was violated, *p*-values are based on Greenhouse-Geisser corrected degrees of freedom, whereas, for the sake of readability, the stated degrees of freedom are uncorrected. Only effects that include the factor Congruency are reported in the results section and complete ANOVA tables are included in Appendix A. Partial η_p^2 will be reported for effect sizes (general η_G^2 will be supplied in Appendix A). Because null effects are meaningful for our hypotheses, we report complementary Bayesian within-subject ANOVAs (Morey & Rouder, 2015; Rouder, Morey, Verhagen, Swagman, & Wagenmakers, 2017) in Appendix A.

2.3.2. Results – Experiment 2.1 (Color Priming)

The mean reaction times, errors, priming effects and prime visibility are depicted in Figure 2.2. The complete results of the ANOVAs are given in the Tables 2.1 to 2.4 in Appendix A.

RTs. Including errors, post-errors and outliers, 15.8% of all RT trials were discarded. Reaction times were shorter in congruent (378 ms) than in incongruent trials (428 ms), as confirmed by a significant main effect for the factor Congruency ($F(1,15) = 135.42$, $p < .001$, $\eta_p^2 = .90$). The priming effects increased with SOA (Congruency x SOA, $F(1,15) = 14.08$, $p = .002$, $\eta_p^2 = .88$), mirroring increased priming effects in the long (*PE* = 73 ms) versus short SOA (*PE* = 27 ms). Our primary goal was to assess whether priming effects were affected by the masks. The priming effects were not affected by the strength of the masks (Congruency x Masking Strength, $F(2,30) = 0.55$, $p = .583$). The three-way-interaction of Congruency x Masking Strength x SOA was also not significant ($F(2, 30) = 1.00$, $p = .382$), supporting the conclusion that priming effects were not affected by the strength of the metacontrast masks.

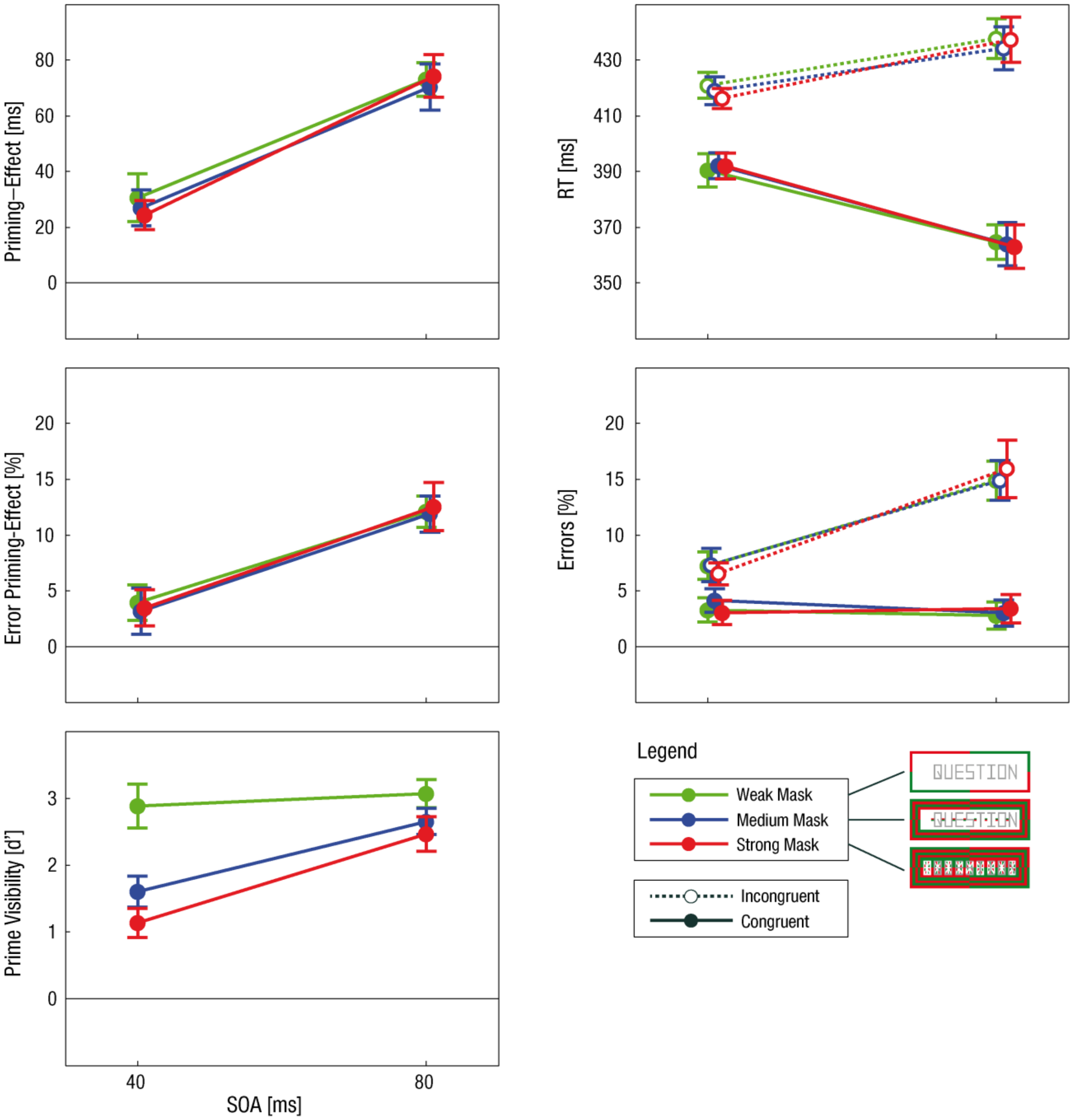

Figure 2.2. Color priming effects and prime discrimination performance in Experiment 2.1. The strength of the metacontrast masks is coded by the line color. The corresponding absolute RTs and errors are depicted in the right column. Here, dashed lines represent incongruent means, whereas congruent means are represented with solid lines. Error bars represent within-subject confidence intervals (Morey, 2008).

Errors. Priming effects for errors paralleled the priming effects for the reaction times. Errors were fewer in congruent (3%) than in incongruent trials (11%) as confirmed by a significant main effect for the factor Congruency ($F(1,15) = 112.43$, $p < .001$, $\eta_p^2 = .88$). Similar to the priming effects in RTs, priming effects rose with SOA (Congruency x SOA, $F(1,15) = 50.77$, $p < .001$, $\eta_p^2 = .77$). The priming effects were not affected by the strength of the masks (Congruency x Masking Strength, $F(2,30) = 0.53$, $p = .596$). The three-way-interaction of Congruency x Masking Strength x SOA was also not significant ($F(2, 30) = 0.75$, $p = .480$), supporting the conclusion that priming effects were not affected by the strength of the metacontrast masks.

Visibility. Due to fast reactions, 2.6% of the trials were excluded. The results confirm that the masks successfully reduced the visibility of the prime ($F(2,30) = 42.11$, $p < .001$, $\eta_p^2 = .74$; *d’* for the weak, medium and strong masks was 3.0, 2.1 and 1.8, respectively). Prime visibility was higher in the long SOA ($F(1,15) = 44.82$, $p < .001$, $\eta_p^2 = .75$; mean *d’* of 2.7 versus 1.9). The interaction of masking strength and SOA was significant ($F(2,30) = 19.1$, $p < .001$, $\eta_p^2 = .56$), indicating that the slope of the visibility functions differed across masks. A follow-up-ANOVA was performed to examine whether masks also affected prime visibility at the late SOA. When only the long SOA was included in the analysis, a main effect of Masking Strength was still significant ($F(2,30) = 9.55$, $p < .001$, $\eta_p^2 = .39$).

2.3.3. Results – Experiment 2.2 (Semantic Priming)

The mean reaction times, errors, priming effects and prime visibility are depicted in Figure 2.3. The complete results of the ANOVAs are given in the Tables 2.5 to 2.8 in Appendix A.

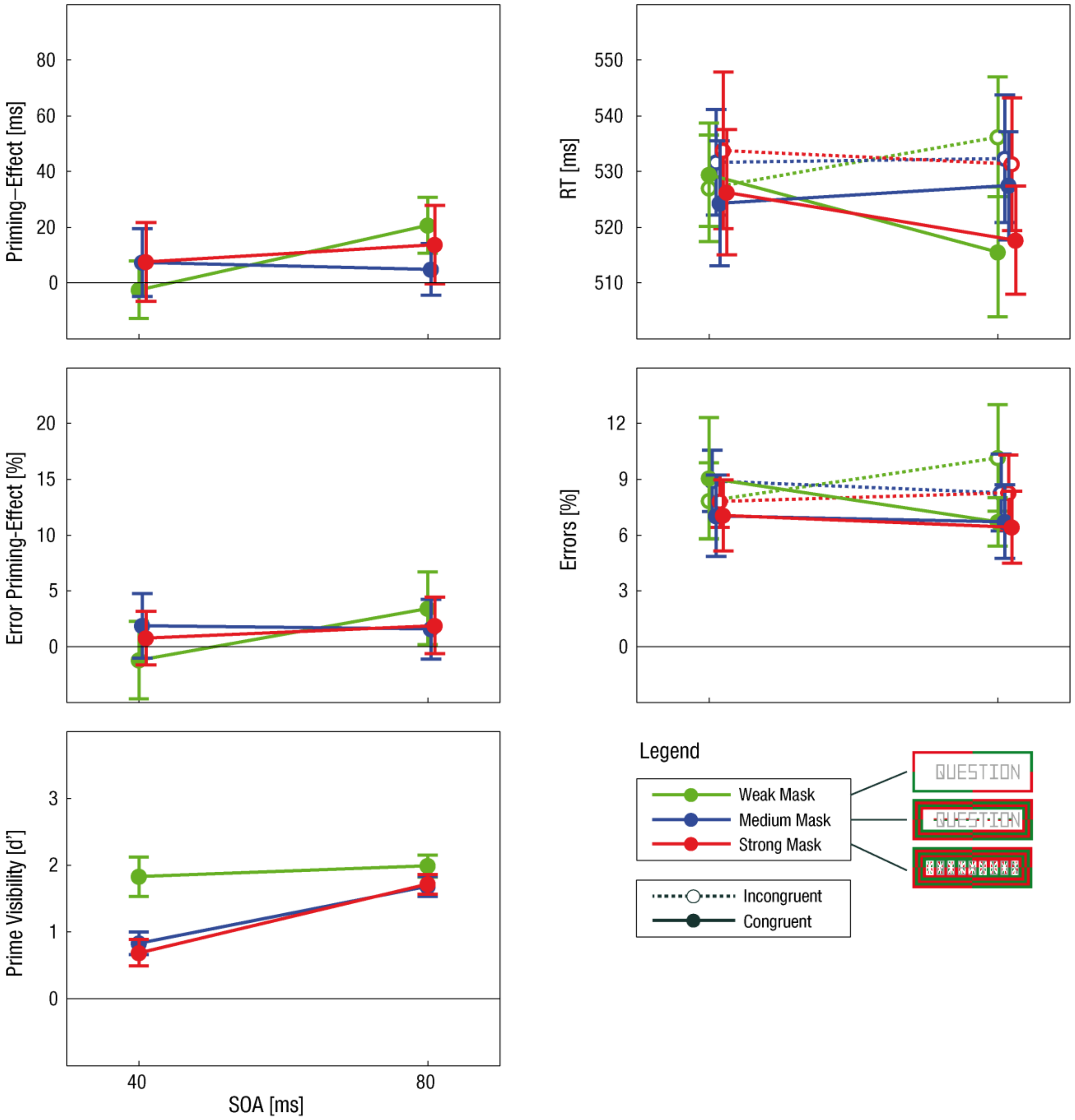

Figure 2.3. Semantic priming effects and prime discrimination performance in Experiment 2.2. The strength of the metacontrast masks is coded by the line color. The corresponding absolute RTs and errors are depicted in the right column. Here, dashed lines represent incongruent means, whereas congruent means are represented with solid lines. Error bars represent within-subject confidence intervals (Morey, 2008).

RTs. Including errors, post-errors and outliers, 25.2% of all RT trials were discarded. Reaction times were shorter in congruent (523 ms) than in incongruent trials (532 ms), as confirmed by a significant main effect for the factor Congruency ($F(1,15) = 12.79$, $p = .003$, $\eta_p^2 = .46$). The priming effects did not increase with SOA (Congruency x SOA, $F(1,15) = 3.42$, $p = .084$). A complementary Bayes analysis (see Appendix A) suggests that the current data are ambiguous with regard to the role of the SOA for priming effects and the hypothesis that semantic priming are moderated by SOA should not yet be rejected. Importantly, the priming effects were not affected by the strength of the masks (Congruency x Masking Strength, $F(2,30) = 0.38$, $p = .688$). The three-way-interaction of Congruency x Masking Strength x SOA was also not significant ($F(2,30) = 2.06$, $p = .164$), supporting the conclusion that priming effects were not affected by the strength of the metacontrast masks.

Errors. Although errors were fewer in congruent (7%) than in incongruent trials (9%) the main effect for the factor Congruency was not significant ($F(1,15) = 3.20$, $p = .094$). All other effects including the factor Congruency were also not significant (all *p*’s > .333). Note that the Bayes analysis included in the appendix identified substantial evidence for error priming effects that were neither moderated by SOA nor by the strength of the masks.

Visibility. Due to fast reactions, 2.8% of the trials were excluded. The results confirm that the masks successfully reduced the visibility of the prime ($F(2,30) = 24.55$, $p < .001$, $\eta_p^2 = .62$; *d’* for the weak, medium and strong masks was 1.9, 1.3 and 1.2, respectively). Prime visibility was higher in the long SOA ($F(1,15) = 102.18$, $p < .001$, $\eta_p^2 = .87$; mean *d’* of 1.8 versus 1.1). The interaction of masking strength and SOA was significant ($F(2,30) = 12.66$, $p < .001$, $\eta_p^2 = .46$), indicating that the slope of the visibility functions differed across masks. A follow-up-ANOVA was performed to examine whether masks also affected prime visibility at the late SOA. When only the long SOA was included in the analysis, the main effect of Masking Strength was still significant ($F(2,30) = 4.68$, $p = .017$, $\eta_p^2 = .24$).

2.4. Discussion

The objective of the present study was to determine whether semantic processing can be dissociated from stimulus visibility if alternative metacontrast masks are used to decrease stimulus visibility instead of the sandwich pattern masks which are commonly used in such tasks. We performed two priming experiments using novel metacontrast masks for word stimuli. Priming effects indicate that words were processed both in terms of color (Experiment 2.1: Color discrimination task) and on a semantic level (Experiment 2.2: Lexical decision task) even when masked by a metacontrast mask. The strength of the metacontrast mask was varied in three steps to uncover how the strength of the masks influences processes underlying conscious awareness and priming effects. The strength of the mask affected prime visibility in both experiments, indicating that metacontrasts interfered with processes underlying prime awareness in a color and a semantic task. Yet, neither color (Experiment 2.1) nor semantic priming effects (Experiment 2.2) varied according to masking strength. These results point to a dissociation of priming effects and visibility independent of the processing domain.

The fact that color priming is not affected by the strength of metacontrast masks is in good agreement with previous research on priming effects using metacontrasts (Breitmeyer, Ro, et al., 2004; Vorberg et al., 2003), and validates that the novel masks constructed for this study exhibit typical properties of metacontrast masks. Importantly, semantic priming effects were also not affected by the strength of metacontrast masks. The finding that semantic priming effects were unaffected by masks contrasts with the results obtained in typical studies using sandwich pattern masking (see Introduction).

Why are semantic priming effects with metacontrast masks not affected by visual masking as they were in other studies investigating semantic (Holcomb, Reder, Misra, & Grainger, 2005; Kiefer, 2002; Kouider & Dupoux, 2004; Ulrich et al., 2013) and also orthographic and phonological priming of lexical stimuli (Kouider et al., 2007)? As stated in greater detail above, metacontrast masks combine properties that increase the likelihood of undisturbed stimulus processing: Unlike pattern masks, metacontrast masks do not overlap with the masked stimuli, carry no meaning, and involve no forward masks. Each of these features is a potential source of mask interference (elaborated in the Introduction). On the basis of the current findings, it is not possible to discern which of these factors accounts for the reduced priming effects in sandwich pattern masking. Since priming effects did not benefit from high prime visibility in the present studies, it seems unlikely that prime awareness is the determining factor for priming effects in similar paradigms.

Backward masks in general have been proposed to leave early feedforward activation intact, and only interfere with late sustained or recurrent processing that is associated with conscious awareness of stimuli (Breitmeyer, 2014; Fahrenfort et al., 2007; Lamme & Roelfsema, 2000; Lamme et al., 2002). The early feedforward sweep is regarded a key part in information processing and conveys information that is sufficient for high-level categorizations (Bacon-Macé et al., 2005; Tovee et al., 1993; van Gaal & Lamme, 2012; VanRullen, 2007), possibly including semantic access of words. It is not quite clear whether backward masks may be able to catch up with early feedforward information if the prime-mask SOA is sufficiently short (Bacon-Macé et al., 2005; Schmidt et al., 2011). It has been suggested that disrupting effects of masks depend on the spatio-temporal overlap between mask and masked stimulus (Bacon-Macé et al., 2005), suggesting that interferences of the mask may have been absent in the current study because metacontrast masks did not overlap with the prime. Generally, if backward masks must immediately follow the prime in order to be able to disrupt early prime processing, they may not have interfered with relevant prime information in this study because the prime lasted already sufficiently long. A similar mechanism has already been proposed for priming of perceptual features. Here, it has been suggested that color priming is due to early stimulus activity that is independent of trailing mask activity (Breitmeyer, Öğmen, et al., 2004; Schmidt, 2002; Schmidt et al., 2006). Possibly, early prime activity is also sufficient to transport information relevant for activations of semantic concepts. Once semantic concepts are activated, semantic priming effects could either be explained by automatic processes like spreading activation between semantic concepts (Anderson, 1983; Collins & Loftus, 1975) or arise as consequence of part activation of correlated target concepts in distributed memory frameworks (e.g., Lerner et al., 2012; Masson, 1995; Plaut, 1995). If early prime activation is sufficient to convey information for an activation of semantic concepts, and backwards interfere only with a late part of prime processing, it is plausible that backward masks do not reduce priming effects.

The majority of semantic priming studies, however, does not confine to backward masks but employs additional masks that are presented prior to or simultaneously with the prime. Such masks have been suspected to interfere with priming effects: Reduced or absent priming effects have been obtained with sandwich masks (Breitmeyer, Öğmen, et al., 2004; Wernicke, 2014) and continuous flash suppression (Hesselmann et al., 2016; Izatt et al., 2014; Peremen & Lamy, 2014), which are popular choices when investigating high level processing of unconscious stimuli. In line with the current data, these findings suggest that the temporal sequence in masked priming paradigms may play a crucial role in mediating whether priming effects are affected by the masks.

Another interpretation of the current findings is that backward metacontrast masks did not interfere with semantic priming effects because they were presented simultaneously with the target. If semantic priming effects can be fully attributed to early activity elicited by the primes, backward masks that are presented simultaneously with the target may simply come too late to moderate priming effects. For example, it is possible that the prime and target are processed strictly serially and the processing of the target always replaces the ongoing processing of the prime. In this case, masks that are presented simultaneously with the target are not able to interfere with priming effects. Such a serial account of priming has been previously proposed for priming of shapes and even object categories like animals versus objects (Schmidt et al., 2006, 2011; Vorberg et al., 2003). In this model, priming effects arise because prime information accumulates undisturbed until the target takes over and disrupts the prime processing. The resulting priming effects directly depend on the SOA between prime and target. This model may serve to explain the color priming effects observed in Experiment 2.1 that were also closely tied to SOA. Although this model is plausible for priming effects of simple features like shapes or color, the situation is different for the LDT: Here, it has been argued that processes that shape the semantic priming effect are not completed with the onset of the target, but endure while the target is processed (Neely, 1991; Norris & Kinoshita, 2008; Yap, Balota, & Tan, 2013). Possible variants of post-lexical interactions between prime and target that take place *after* lexical access to the target include semantic matching of prime and target (Chwilla, Hagoort, & Brown, 1998; de Groot, 1984; Neely et al., 1989), retrospective activation of primes based on target information that is currently evaluated (Yap et al., 2013), the formation of a prime-target compound that is retrieved from memory rather than the target alone (Ratcliff & McKoon, 1994), or a confusion of prime and target evidence in the Bayesian reader account (de Wit & Kinoshita, 2015). If the prime is processed parallel to and in interaction with the target, it is feasible that backward masks presented simultaneously with the target could interfere with semantic priming effects. However, as observed in Experiment 2.2, this is not the case when metacontrast masks are applied.

Metacontrasts did, however, interfere with prime visibility, suggesting that priming effects and prime visibility measure independent processes – a conclusion that has been reached before for priming of perceptual features (e.g., Schmidt, 2002; Vorberg et al., 2003).

Note that only small SOAs in which effects of masking on visibility can be expected were covered by this experiment. When the SOA between prime and mask is sufficiently long strategic mechanisms can additionally emerge that further complicate a direct comparison of supraliminal and subliminal semantic priming effects (Kouider & Dehaene, 2007; Neely, 1991; Ortells, Daza, & Fox, 2003). For both of these reasons, we chose to analyze semantic priming at short SOAs, maximizing the chances of undisturbed priming under masking, and different results may be obtained for longer SOAs between prime and mask.

The finding that metacontrasts reduces visibility in a lexical decision task, but not semantic priming effects, seems to be at odds with previous reports of reduced semantic priming effects when visibility is reduced. For example, a meta-analysis revealed that categorical priming effects increase as a function of stimulus visibility (Van den Bussche et al., 2009). Experimental variables like the choice of the mask could account for this pattern of results and moderate the relation of priming effects and visibility. In general, prime visibility may often be controlled by variables that inadvertently also affect priming effects, like the duration of prime, or the SOA between prime and target. If these variables are not controlled for, conclusions regarding the relation of priming effects and visibility may be misguided as result of an omitted-variable bias (see Van den Bussche et al., 2013 for a similar point). To illustrate, consider the role of SOA in the color priming task. In Experiment 2.1, SOA had a strong impact on both visibility and priming effects. As a consequence, a direct regression of priming effects on visibility would yield a positive correlation. If SOA is treated only as a means to reduce prime visibility and its direct effect on priming effects is ignored, the correlation between visibility and priming effects across SOAs may be interpreted as indication for a causal relation where there is in fact none. The correlation between visibility and priming effects disappears when the data are split according to SOA. Although the current data were not clear as to whether semantic priming effects also increase with SOA, other variables may introduce similar biases in the literature of semantic priming effects: For example, prime visibility is manipulated by varying the duration of the prime (Holcomb et al., 2005; Kouider & Dupoux, 2004; Lähteenmäki et al., 2015; Marcel, 1983), the presence of masks, including forward masks (Kiefer & Spitzer, 2000; Kouider et al., 2007; Kouider & Dupoux, 2004; Ortells et al., 2016; Ulrich et al., 2013; van Gaal et al., 2014; van Gaal, Lamme, Fahrenfort, & Ridderinkhof, 2011), the temporal delay between primes and masks (Dehaene et al., 2001), or attentional fluctuation across trials that potentially underlies comparisons like seen versus unseen trials or inter-individual differences in visibility (Lähteenmäki et al., 2015; Shanks, 2017; Van den Bussche et al., 2013, 2010). Any of these variables may not only affect prime visibility, but prime signal strength as a whole, and therefore directly modulate semantic priming effects (see Holender, 1986, for a similar point). This dilemma can hardly be circumvented, and led authors to cautiously point out that visibility manipulations like masking may influence measures of stimulus processing independent of stimulus awareness (e.g., Dehaene et al., 2001; Kiefer, 2002). Backward metacontrast masks may present an exciting new option, because they provide a possibility to control stimulus visibility independent of processes underlying semantic priming effects. Thus, metacontrasts may provide a possible tool to compare neurophysiological and behavioral effects of masked stimuli without having to fear that these measures are directly affected by masks.

The finding that semantic processing can be dissociated from consciousness has theoretical and practical implications for the study of masked stimulus processing. First, it supports theories of consciousness proposing that semantic features can be analyzed independent of conscious awareness (Lamme, 2015; Naccache & Dehaene, 2001; Oizumi et al., 2014). Furthermore, our findings have implications for accounts of semantic priming that include assumptions about the role of masking for semantic priming. For example, proponents of the Bayesian reader account (Norris & Kinoshita, 2008) have argued that masked priming is smaller because perceptual information of the prime is reduced by masks. Based on the current results, it seems unlikely that the amount of perceptual information that is disturbed by masks has implications for semantic priming effects.

The present study demonstrates that metacontrast masks do not interfere with semantic priming effects in the LDT. It should be noted that our results are limited to semantic priming effects between highly associated word pairs and do not cover pure semantic relations with no associations (Lucas, 2000). By highlighting the role of the mask for the processing of masked stimuli, our data contribute to resolve discrepant findings regarding the role of conscious processing for semantic processing. We propose that certain masks, including the commonly used sandwich pattern masks, lead to a systematic underestimation of priming effects that can be avoided when using backward metacontrast masks.

3. Intact Semantic Priming Using Backward Pattern Masking

3.1. Abstract

Researchers use priming effects to investigate whether stimuli can be processed in the absence of stimulus awareness. However, recent studies show that priming effects are influenced by the type of mask that is used to prevent stimulus awareness. Whereas priming effects are often reduced when sandwich pattern masking is used, metacontrast masking does not affect priming effects. This is especially important for semantic priming studies, which routinely use sandwich pattern masks to mask their stimuli. The current study examines possible characteristics of sandwich pattern masks that could explain why sandwich pattern masks reduce priming effects which are left intact using metacontrast masks. Sandwich pattern masks generally differ from metacontrast masks in terms of three important features: (1) they include a forward mask, (2) the mask itself has features carrying semantic content, (3) the mask spatially overlaps with the prime. Either one of these features or any combination may be responsible for reduced priming effects in the literature. The two experiments presented in this study are designed to isolate the latter of these three options by investigating priming effects with overlapping pattern masks that include no forward masks and carry no semantic content. To explore the impact of the masks on priming effects, we varied the strength of the masks in three steps by increasing the amount of overlap between mask and prime. We found priming effects both in a perceptual color-priming and a semantic priming experiment. Even though the strength of the masks affected the visibility of the prime, the observed priming effects were independent of masking strength. These results indicate that spatial overlap of backward masks has no effect on perceptual and semantic priming-effects. We propose that backward masks in this paradigm generally do not interfere

with priming effects, and discuss alternative mechanisms for the influence of sandwich pattern masks on priming effects.

3.2. Introduction

How efficient can stimuli be processed if they cannot be consciously perceived? One preferred approach to this question is the use of the masked priming paradigm. Priming is a tool that allows measuring how behavioral or neurophysiological responses to one stimulus, the target, are affected by a preceding stimulus, the prime, even when this stimulus cannot be consciously reported. To reduce the visibility of the primes, researchers generally apply visual masks – additional stimuli such as, for example, letter strings that are presented immediately before and after a masked prime word. While these masks are solely applied with the purpose of reducing the visibility of the prime, little is known as to whether visual masks also reduce processes underlying priming effects. In this study, we will look at backward pattern masks, and examine whether these masks interfere with priming of perceptual and semantic features of identical stimuli.

The effects of masks in on priming of semantic features is particularly important, because semantic priming effects (Kiefer, 2002; Kiefer & Spitzer, 2000; Kouider & Dupoux, 2004; Lucas, 2000; Marcel, 1983; Ulrich et al., 2013; Van den Bussche et al., 2009) and neurophysiological correlates of semantic processing (Dehaene et al., 1998; Kiefer, 2002; Kiefer & Spitzer, 2000; Ulrich et al., 2013) usually decrease with masking. Two competing explanations are possible to explain these results. First, semantic processing may be limited in the absence of stimulus awareness, for example because a strategic use of the prime is prevented that facilitates semantic processing when primes are consciously processed (e.g., de Wit & Kinoshita, 2015; Marcel, 1983; Ulrich et al., 2013).

Alternatively, it is possible that masks not only affect processes underlying stimulus awareness, but also nonconscious processes that are relevant for priming effects (Holender, 1986; Wernicke, 2014). Most studies on semantic processing use sandwich pattern masks to prevent the visibility of their stimuli (see Kouider & Dehaene, 2007; and Wernicke, 2014; for reviews). In other areas of literature, however, different masks have been used to mask the stimuli (Breitmeyer, 2015; Enns & Di Lollo, 2000; Kim & Blake, 2005). There is growing evidence that these masking techniques have different effects on stimulus processing, and some masks interfere with processes underlying priming effects that may be intact when other masks are being used (Breitmeyer, Öğmen, et al., 2004; Faivre et al., 2012; Izatt et al., 2014; for reviews, see Breitmeyer, 2015 and Wernicke, 2014). This assertion has recently received additional support from studies that show that priming of semantic categories (Wernicke, 2014) and word meaning (Chapter 2) is not reduced if an alternative type of mask – metacontrast masks – is used instead of the usual sandwich pattern masks.

What are possible differences between sandwich pattern masks and metacontrasts that can account for the interference of sandwich pattern masks with priming effects? Sandwich pattern masks and metacontrasts differ in terms of at least three features: First, *sandwich masking* refers to a paradigm in which masks are presented before and after the masked word in close temporal sequence, thus combining forward- and backward masking. Metacontrast masks, on the other hand, are by definition backward masks that are only presented after the masked stimulus (Breitmeyer & Ganz, 1976). Second, pattern masks often contain meaningful characters or symbols, whereas metacontrasts usually consist of simple frame-like stimuli that do not carry any semantic content. Third, pattern and metacontrast masks also differ in terms of their spatial layout. When words are being masked, pattern masks often consist of random letter or character strings (de Wit & Kinoshita, 2015; Draine & Greenwald, 1998; Kiefer, 2002; Klinger et al., 2000; Kouider & Dupoux, 2004; Marcel, 1983; Naccache & Dehaene, 2001) or superimposed patterns like geometrical forms that overlap with the position of the prime (Abrams & Grinspan, 2007b; Dehaene et al., 2001). Because the target word is generally presented at the same location as the prime, it thereby serves as an additional backward pattern mask (e.g., Bodner & Masson, 2003; de Wit & Kinoshita, 2015;

Draine & Greenwald, 1998). According to the definition adopted in Wernicke (2014) and also this paper, the defining feature of pattern masks is that their contours overlap with the contours of the masked stimulus. Metacontrast masks on the other hand have no overlap with the masked stimulus.

According to these three differences between both masking techniques, three compatible interpretations are conceivable: As opposed to metacontrast masks, sandwich pattern masks may interfere with priming effects due to their included forward masks, due to the content of the masking elements, or because of stimulus overlap. Each of these features, or any combination, may be responsible for reduced priming effects under sandwich pattern masking. The objective of the current study is to investigate the latter of these features, and examine to what extent the overlap of masks leads to reduced priming effects.

Functional differences between overlapping pattern masks and non-overlapping masks like metacontrasts have been identified early on using psychophysical masking experiments. Early masking theories have proposed that masks interfere with information processing in two ways (Scheerer, 1973): In *masking by interruption*, the ongoing processing of a stimulus is disrupted by the incoming information of the mask, thus reducing the processing time of the masked stimulus. On the other hand, *masking by integration* results from the limited temporal resolution of the visual system, causing the summation of stimulus signals when two stimuli are presented in close temporal succession. The fusion of the mask and the masked stimulus leads to a degradation of the stimulus information that depends on the amount of overlap between the contours of both stimuli. The notion of masking by integration is compatible with the finding that pattern masking is stronger with increasing spatial overlap between stimuli (Coltheart & Arthur, 1972; Schiller, 1966). Also, masking by integration is by definition strongest for short stimulus-onset-asynchronies (SOA) between mask and masked stimulus, producing visibility functions that rise with SOA (type-A function; Scheerer, 1973; Spencer & Shuntich, 1970). Indeed, the masking function with pattern masking is mostly type A (Breitmeyer & Öğmen, 2006; Enns, 2004; Francis & Cho, 2008; Turvey, 1973), except for less typical cases in which the energy of the mask is smaller than that of the target (Turvey, 1973) or masks and target are presented to different eyes (Michaels & Turvey, 1979). Due to its dependence on the stimulus energy and its reduction under binocular presentation conditions, it has been proposed that the type-A function in pattern masking is due to an integration process that is located at early, possibly precortical, stages in the visual hierarchy (Breitmeyer & Öğmen, 2006; Enns, 2004; Scheerer, 1973; Tapia & Beck, 2014; Turvey, 1973). The assumption that masking by integration is a main determinant of masking by pattern masks was incorporated into subsequent theories of masking. For example, Enns (2004) assumes that overlapping pattern masks merge with the masked stimulus in a temporally early process which is largely independent of attention. In the RECOD model (Breitmeyer et al., 2006; Breitmeyer & Öğmen, 2006) the effects of spatial overlap are modeled by integration due to shared processing pathways. According to the authors, this integration of signals may begin very early, including photoreceptor levels, and is not active for metacontrast masks. The association of pattern masks with integration masking is important because it may imply that pattern masks interfere with information processing at earlier stages in the visual hierarchy than metacontrast masks. For this reason, backward pattern masks have been ranked at a lower level than metacontrasts in a masking hierarchy formulated by Breitmeyer (2015), implying that backward pattern masks allow for less nonconscious processing than metacontrasts.

However, direct comparisons of priming effects between backward pattern masks and metacontrasts with all other experimental variables held constant are scarce. The current study aims to fill this gap by examining priming effects in relation to mask overlap. To do so, we systematically vary the spatial overlap of masks. At the same time, we exclude other factors of sandwich pattern masks that may interfere with priming effects. First, we do not include forward masks. Furthermore, we created pattern masks that do not carry any meaning, specifically avoiding stimuli such as letters or symbols which may create additional competition with the prime words at a semantic level (Enns, 2004; Loffler et al., 2005; Van Opstal et al., 2005a, 2005b).

To understand whether the effects of spatial overlap on priming effects depend on the processing level we perform two experiments, one focusing on low level features (color of words) whereas the other focuses on high level semantic features (word meaning). The experimental design of this study was adopted from our previous study (Chapter 2) which showed that backward metacontrast masks selectively reduce stimulus visibility, but not semantic or color priming effects. To maximize comparability between the studies, the experimental design and material are largely identical (two exceptions are denoted in the methods section). As a semantic task, we use the *lexical decision task* (LDT, Marcel, 1983; Meyer & Schvaneveldt, 1971). In this task, subjects have to quickly categorize strings as either words (such as *tiger*) or pseudo-words (*lomel*). If the words are preceded by semantically associated words (such as *lion*), reaction times to the words are sped up. If such priming is observed, it is concluded that the meaning of the prime word has been processed by the subject, even in cases when the prime word cannot be consciously reported (Marcel, 1983). Semantic priming in the LDT clearly indicates that the meaning of words has been processed, and thus may be superior to priming in categorical tasks, which may also be explained by non-semantic processes (Abrams & Grinspan, 2007b; Ansorge et al., 2014; Kouider & Dupoux, 2007).

A previous study (Wernicke, 2014, experiments 4.1 and 4.3) has already compared backward pattern and metacontrast masks and found no difference in color and categorical priming effects. However, masking was not successful in her study. Therefore, the missing interference of masks with the priming effect may be due to the weak masks that were being used. By using effective backward pattern masks, and investigating semantic priming in the LDT instead of a categorical priming task, we hope to clarify the role of mask overlap in semantic priming studies. If overlap of pattern masks causes integration of prime and mask contours at early visual processing levels, we expect priming effects to be reduced as a function of masking strength. Alternatively, priming effects may be immune to this reduction if masking by pattern masking occurs at a later processing stage than processes underlying color and semantic priming effects (Breitmeyer, 2015).

3.3. General Methods

3.3.1. Method

Participants. Parallel to Chapter 2, participants were 32 students (16 per experiment) from Goettingen University between 19 and 29 years old (*M* = 23.1 years) who participated for four 1-h sessions on separate days. All participants were German native speakers, had normal or corrected-to-normal vision and received monetary compensation (7€ per hour). They had no known neurological problems and were not diagnosed with dyslexia. Participants were only accepted if they had never participated in a previous experiment with the current stimuli, and had not participated in any masking study of our laboratory for at least one semester.

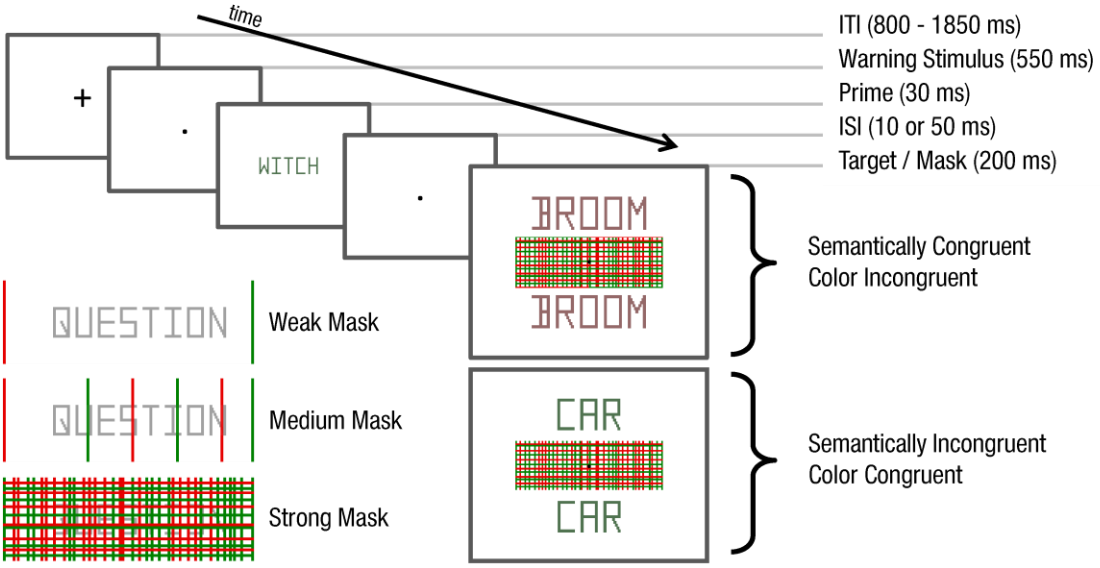

Figure 3.1. Schematic trial sequence for Experiments 3.1 and 3.2. *ITI* = Intertrial-Interval, *ISI* = Interstimulus-Interval. Two example target words are given. The target words can be either semantically or color congruent or incongruent with the prime. Color and semantic congruency were balanced in the experiments. For each masking strength (weak, medium and strong) 100 possible pattern masks were used in the experiments. To illustrate the overlap of the word characters with the contours of the mask, the word "QUESTION" was inserted at the appropriate position of three example masks. In the experiments, prime words and masks never appeared at the same time.

Tasks. The tasks in this study were identical to that of our previous study (Chapter 2): In three priming sessions on separate days, subjects had to indicate the color (Experiment 3.1) or lexicality (Experiment 3.2) of target words and pseudowords as fast as possible. Participants had to respond within 2 s after target onset. In the subsequent prime recognition session, participants were informed about the presence of the prime and instead had to indicate the color (Experiment 3.1) or lexicality (Experiment 3.2) of the prime words. In the prime recognition session, participants were requested to respond slow and deliberate, to prevent reactions driven by the prime. Reactions faster than 500 ms triggered error feedback ("too fast") and were excluded from the analysis.

Stimuli. See Figure 3.1. The current experiments are replications of the experiments reported in Chapter 2, except for the following changes to the stimuli. First, the metacontrast masks used in Chapter 2 were replaced with backward pattern masks. The pattern masks were constructed of horizontal and vertical lines of red and green color, thus any effect of the pattern masks on semantic priming effects should only be attributable to overlap of the prime and mask contours. Whereas the masks were not task relevant in the semantic priming task, this was not possible in the perceptual color priming task because the mask had to be colored to achieve sufficient masking of the prime color. Pattern masks were created in three different strengths that allowed monitoring priming effects as a function of spatial overlap between prime and mask. The strength of the pattern masks was varied by adapting the number of lines in a mask. A set of 100 random masks was created for each masking strength. Weak pattern masks consisted of two vertical lines that did not overlap with the primes. Masks of medium strength contained four additional vertical lines at the position of the prime words. However, it was taken care that these lines did not overlap with the vertical elements of the prime letters. Strong masks consisted of multiple overlapping horizontal and vertical elements, creating a dense pattern. The masks had equal amounts of red and green pixels and had the same dimensions as the metacontrast masks in Chapter 2 (3.48° x 1.2°). Because pattern masks were less effective in reducing the visibility of the prime colors in Wernicke (2014) and own pilot studies, the color of the prime and target stimuli was desaturated to 30% saturation in the current experiment. However, the luminance was kept constant at 24.6 cd/m^2 and was thus equal to the luminance of word stimuli in the metacontrast study.

Apparatus, Procedure and Design. Except for the changed stimuli, the experimental setup and design of Experiments 3.1 and 3.2 were identical to that of Experiments 2.1 and 2.2 in Chapter 2, respectively.

Analysis. The statistical analysis was performed analogously to that of Chapter 2. Trimmed RTs, arc-sine transformed error rates and *d'* values in the discrimination task were analyzed using repeated-measures-ANOVAs. Again, within-subject ANOVAs are reported in the main text, whereas a second version of the results section based on Bayesian ANOVAs can be found in Appendix B. Only effects that include the factor Congruency are reported in the results section. The complete ANOVA tables are given in Appendix B. When the assumption of sphericity was violated, *p*-values are based on Greenhouse-Geisser corrected degrees of freedom.

3.3.2. Results – Experiment 3.1 (Color Priming)

The mean reaction times, errors, priming effects and prime visibility are depicted in Figure 3.2. The complete results of the ANOVAs are given in the Tables 3.1 to 3.4 in Appendix B.

RTs. Including errors, post-errors and trimmed reaction times, 19.6% of all RT trials were discarded. Reaction times were shorter in congruent (397 ms) than in incongruent trials (434 ms), as confirmed by a significant main effect for the factor Congruency ($F(1,15) = 74.85$, $p < .001$, $\eta_p^2 = .83$). The priming effects increased with SOA (Congruency x SOA, $F(1,15) = 80.28$, $p < .001$, $\eta_p^2 = .84$), mirroring increased priming effects in the long (*PE* = 55 ms) versus short SOA (*PE* = 18 ms). Our primary goal was to assess whether priming effects were affected by the masks. The priming effects were not affected by the strength of the masks (Congruency x Masking Strength, $F(2,30) = 2.31$, $p = .116$). The three-way-interaction of Congruency x Masking Strength x SOA was also not significant ($F(2, 30) = 0.15$, $p = .861$), supporting the conclusion that priming effects were not affected by the strength of the pattern masks.

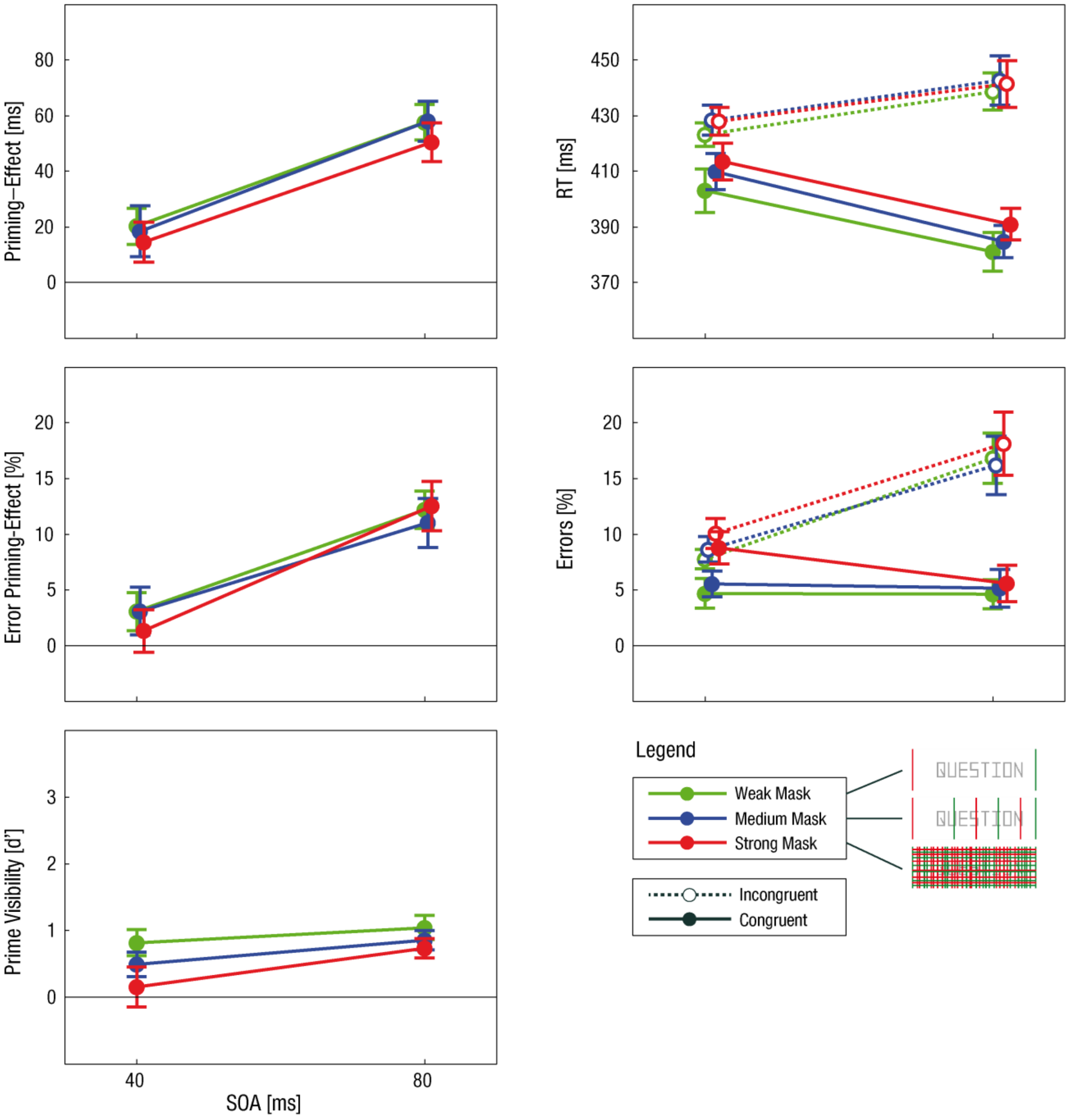

Figure 3.2. Color priming effects and prime discrimination performance in Experiment 3.1. The strength of the pattern masks is coded by the line color. The corresponding absolute RTs and errors are depicted in the right column. Here, dashed lines represent incongruent means, whereas congruent means are represented with solid lines. Error bars represent within-subject confidence intervals (Morey, 2008).

Errors. Priming effects for errors paralleled the priming effects for the reaction times. Errors were fewer in congruent (6 %) than in incongruent trials (13 %) as confirmed by a significant main effect for the factor Congruency ($F(1,15) = 62.85$, $p < .001$, $\eta_p^2 = .81$). The priming effects increased with SOA (Congruency x SOA, $F(1,15) = 67.58$, $p < .001$, $\eta_p^2 = .82$). The priming effects were not affected by the strength of the masks (Congruency x Masking Strength, $F(2,30) = 1.60$, $p = .218$). The three-way-interaction of Congruency x Masking Strength x SOA was also not significant ($F(2, 30) = 2.40$, $p = .108$), supporting the conclusion that priming effects were not affected by the strength of the pattern masks.

Visibility. Due to fast reactions of the participants that were below the minimum response time of 500 ms, 1.5 % of the trials were excluded. The results confirm that the masks successfully reduced the visibility of the prime ($F(2,30) = 7.93$, $p = .009$, $\eta_p^2 = .35$; *d'* for the weak, medium and strong masks was 0.9, 0.7 and 0.4, respectively). Prime visibility was higher in the long SOA ($F(1,15) = 18.82$, $p < .001$, $\eta_p^2 = .56$; mean *d'* of 0.9 versus 0.5). The interaction of masking strength and SOA was not significant ($F(2,30) = 3.28$, $p = .051$). Because a *p*-value of .051 is difficult to interpret, a follow-up-ANOVA was performed to examine whether masks also affected prime visibility at the late SOA. When only the long SOA was included in the analysis, a main effect of Masking Strength was still significant ($F(2,30) = 4.75$, $p = .031$, $\eta_p^2 = .24$).

3.3.3. Results – Experiment 3.2 (Semantic Priming)

The mean reaction times, errors, priming effects and prime visibility are depicted in Figure 3.3. The complete results of the ANOVAs are given in the Tables 3.5 to 3.10 in Appendix B.

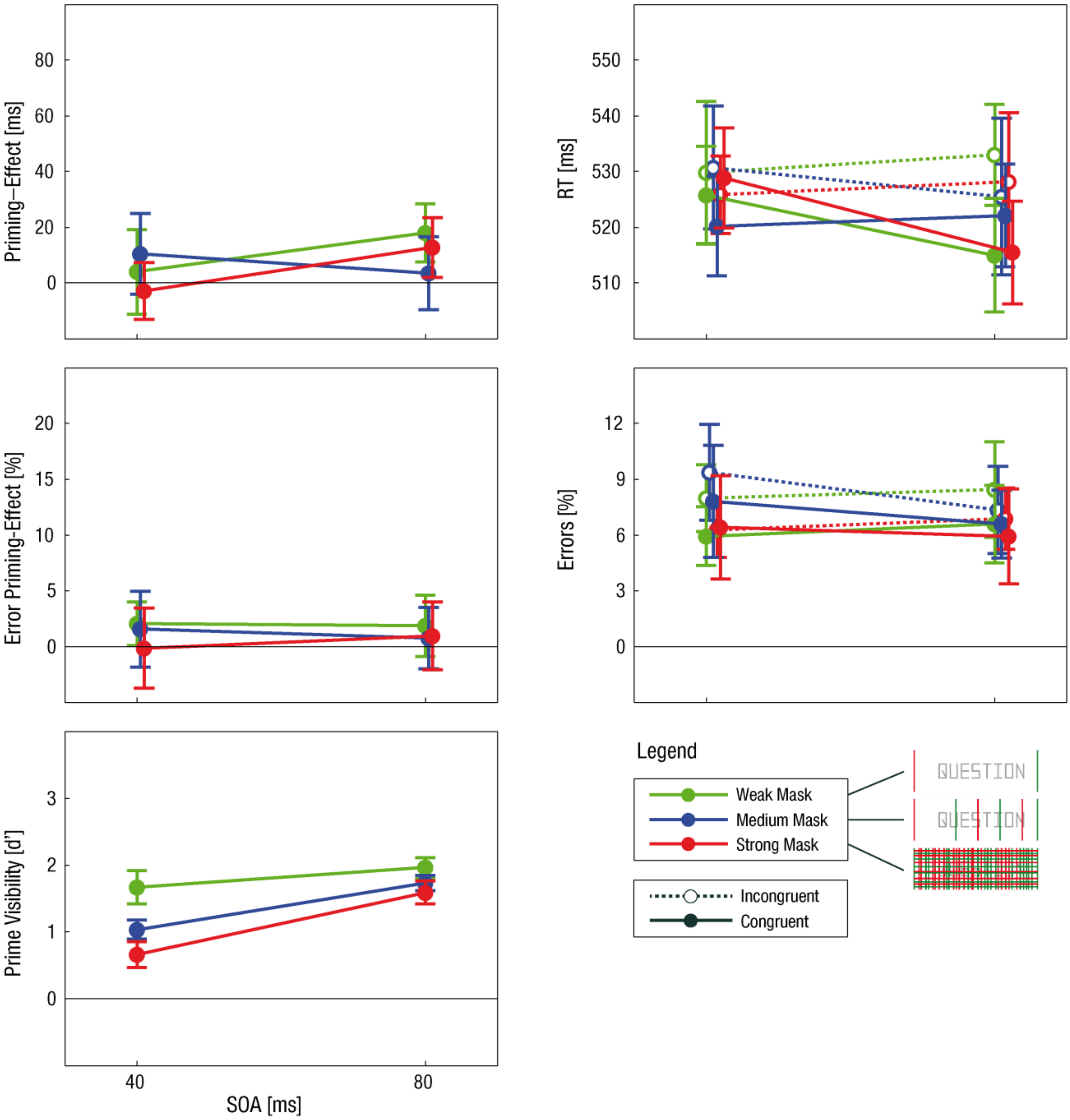

Figure 3.3. Semantic priming effects and prime discrimination performance in Experiment 3.2. The strength of the pattern masks is coded by the line color. The corresponding absolute RTs and errors are depicted in the right column. Here, dashed lines represent incongruent means, whereas congruent means are represented with solid lines. Error bars represent within-subject confidence intervals (Morey, 2008).

RTs. Including errors, post-errors and trimmed reaction times, 24.2% of all RT trials were discarded. Reaction times were shorter in congruent (521 ms) than in incongruent trials (529 ms). Noteworthy, these mean reaction times are nearly identical to the reaction times with metacontrast masks in Chapter 2, even though a different group of participants was tested. Faster reaction times in congruent than in incongruent conditions were confirmed by a significant main effect for the factor Congruency ($F(1,15) = 8.92$, $p = .009$, $\eta_p^2 = .37$). The priming effects were neither moderated by SOA (Congruency x SOA, $F(1,15) = 1.36$, $p = .262$), nor, importantly, by the strength of the masks (Congruency x Masking Strength, $F(2,30) = 0.48$, $p = .649$). However, a significant three-way-interaction of Congruency x Masking Strength x SOA, $F(2, 30) = 3.97$, $p = .030$, $\eta_p^2 = .21$, may indicate that priming effects were affected by the masks only at specific SOAs. To test for this possibility, two follow-up ANOVAs were performed for each of the two SOAs separately. At the short SOA, no significant priming effects were obtained ($F(1,15) = 0.71$, $p = .412$; with 4 ms mean RT difference). At the long SOA, priming effects were significant ($F(1,15) = 9.92$, $p = .007$, $\eta_p^2 = .40$; with 11 ms mean RT difference) but did not interact with the strength of the masks ($F(2,30) = 1.74$, $p = .193$). Although we found no evidence for a moderating effect of masks, it is possible that such a moderating effect of the masks at long SOAs remained undetected because our statistical power was not sufficient. However, the absolute priming effects at the long SOA were not sorted as a function of masking strength. According to the Bayes ANOVA reported in the appendix, there is substantial evidence that semantic priming effects are not affected by the masks, but more evidence would be needed to evaluate the relation of priming effects and masks at the level of single SOAs.

Errors. Although errors were fewer in congruent (7 %) than in incongruent trials (8 %), the error priming effect did not reach significance ($F(1,15) = 1.96$, $p = .182$). All other effects were also not significant (all p's > .630).

Visibility. Due to fast reactions of the participants, 4.5% of the trials were excluded. The ANOVA indicates that visibility was influenced by Masking Strength ($F(2,30) = 18.80$, $p < .001$, $\eta_p^2 = .56$), SOA ($F(1,15) = 95.47$, $p < .001$, $\eta_p^2 = .86$) and an interaction between Masking Strength and SOA ($F(2,30) = 13.50$, $p < .001$, $\eta_p^2 = .47$). These results confirm that the masks successfully reduced the visibility of the prime (*d'* for the weak, medium and strong masks was 1.8, 1.4 and 1.1, respectively). Prime visibility was higher in the long SOA (mean *d'* of 1.8 versus 1.1). The interaction of masking strength and SOA indicated that the slope of the visibility functions differed across masks. To examine whether masks also affected prime visibility at the late SOA, a subsequent ANOVA was performed including only the 80-ms-SOA, revealing a main effect of Masking Strength ($F(2,30) = 6.53$, $p = .004$, $\eta_p^2 = .30$).

3.4. Discussion

The aim of this study was to understand whether spatial overlap of masks with the prime is responsible for the reduced semantic priming effects that were observed in previous studies using sandwich pattern masks. For this purpose, we systematically varied the degree of spatial overlap of the masks. We avoided other features of sandwich pattern masks that may additionally interfere with the prime by only using backward masks that consisted of non-meaningful features. To examine whether spatial overlap disturbs the priming effect differently depending on the processing level, we performed two experiments, one focusing on low level features of word stimuli (word color) whereas the other tested priming of high level features (semantic content) of the same words. It was assumed that if integration processes at early levels in the visual hierarchy contribute to the effectiveness of overlapping masks, overlapping masks may not only interfere with processes underlying prime awareness, but also with priming effects.

However, no such reduction of priming effects was observed in the current experiments. Priming effects were obtained in a perceptual and a semantic task, thus replicating the priming effects reported for metacontrast masks in Chapter 2 with the same experimental design. More important, the priming effects were not moderated by the strength of the pattern masks. While masking was successful and visibility varied according to masking strength there was no interaction between prime-target congruency and the strength of the masks. Although a three-way interaction of congruency, masking strength and SOA was present in the semantic task, there was no effect of masking strength on priming effects at the level of the individual SOAs. Rather, this three-way interaction may indicate that the effects in the weak and strong mask tended to increase with SOA, whereas they decreased with medium masks. Because the priming effects were not sorted meaningfully according to the masking strength, the three-way interaction does provide no evidence that more overlap between prime and mask leads to smaller priming effects. We conclude that pattern masks that are presented simultaneously with the target reduce the visibility of critical stimulus features, but do not systematically interfere with priming effects in either the low-level color priming task, nor in the high level semantic task. The semantic priming effects in this study were in a very similar range than the priming effects obtained with metacontrasts in Chapter 2, which further supports this claim[2]. In pair with the metacontrast data of Chapter 2, the current findings provide additional evidence for a dissociation of semantic priming effects and prime visibility.

In the following sections, we will speculate on why priming effects were reduced in earlier studies using sandwich pattern masking, but not with the backward pattern masks used

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[2] The priming effects in the color priming tasks of Chapter 2 and 3 cannot be compared across experiments, because the saturation and therefore stimulus energy of the primes was reduced in the current study to compensate for weaker masking of color by pattern masks in our pretests.

in this study. The most rigorous interpretation of the current data is that integration processes that have previously been linked to pattern masking (Breitmeyer & Öğmen, 2006; Enns, 2004; Scheerer, 1973; Tapia & Beck, 2014; Turvey, 1973) do not affect perceptual or semantic priming effects. Such an interpretation challenges the notion that overlapping masks interfere with prime processing at a more basic level than metacontrast masks (Breitmeyer, 2015). Even though metacontrast and pattern masks have different effects on stimulus visibility, suggesting that both masking methods interfere with stimulus processing in different ways (Alwis et al., 2016; Breitmeyer & Öğmen, 2006; Enns, 2004; Francis & Cho, 2008; Schiller & Smith, 1965), neither was found to disrupt priming effects when other experimental factors are controlled for (see also Chapter 2). The current findings imply that mask overlap is not the responsible variable for reduced priming effects in sandwich pattern masking of previous studies (see Introduction). Therefore, other features of typical sandwich pattern masks may be responsible for the interference with priming effects.

First, a typical feature of studies on masked lexical processing is that the masking elements carry some sort of meaning. The degree of meaning that is imposed on masks varies from letter fragments (Abrams & Grinspan, 2007b) to special characters like hash marks or ampersands (de Wit & Kinoshita, 2015; Kouider & Dupoux, 2004) to complete letter-strings (Kiefer, 2002; Marcel, 1983; Naccache & Dehaene, 2001). According to Van Opstal and colleagues (2005a, 2005b) meaningful masks may activate similar response pathways with the prime, thus creating noise and concealing potential priming effects. Another possibility is that meaningful stimuli could serve as intervening neutral prime words which are known to reduce semantic priming effects in supraliminal priming (Neely, 1991). Both of these options involve higher-level competition that goes beyond conflicting interactions between prime and mask contours. Whereas efforts were made to preclude such high-level interactions in the current study, they may be responsible for reduced priming effects in typical semantic priming studies that use letter strings to mask their primes.

Second, the pattern masks applied in this paper were presented simultaneously with the target. It is possible that backward masks that are presented at the same time with the target generally do not interfere with priming effects, regardless of their spatial layout. This possibility was also raised in Chapter 2, and is further supported by the current data. According to this notion, the ongoing read-out of prime information is replaced by the processing of the target, no matter whether or which masks are presented at the same time. In this case, the present study cannot rule out that pattern masks may in fact interfere with processing at an early stage of processing but this interference is not relevant for priming effects because processes underlying priming effects are disrupted by the target anyways. As a related alternative, it is possible that backward masks generally do not interfere with processing of primes, regardless of stimulus overlap and the temporal delay between prime and mask. Such an explanation has already been used to explain why priming of color was independent of backward metacontrast masking in previous studies: In this framework, the extraction of color features necessary for color priming effects has been linked to information encoded in a fast feedforward sweep that evades interference by subsequent masks through its time advantage (Breitmeyer, Ro, et al., 2004; Schmidt et al., 2006). Based on the present results, these two interpretations cannot be discerned.

If the target disrupts ongoing prime processing, it is an open question how the same masks behave when presented prior to the target. In this case, the masks may interfere with prime processing before the lexical decision is initiated and thus reduce priming effects. The vast majority of studies on masked semantic processing presents masks before the onset of the target word (see Introduction). Therefore, it is still possible that overlapping masks caused reduced priming effects in previous studies as long as they were presented prior to the target. Preliminary evidence against this possibility was presented in a meta-analysis by Van den Bussche and colleagues (2009) who compared categorical priming effects for studies that use letter strings as interposed backward masks with studies that only use the target as backward mask, but did not find any differences. However, these findings are restricted to categorical priming effects and the authors did not control for the presence of forward masks, or the SOA between prime and target, making it difficult to interpret their results. On the other hand, the experiments of Van Opstal and colleagues (2005a, 2005b) demonstrate effects of interposed masks on categorical priming effects in a systematic comparison of different masks. All in all, the effects of masks presented prior to the target are still not well understood and may, unlike masks presented simultaneously with the target, also differ depending on the contents of the mask.

Finally, an important feature of many semantic priming studies is the use of additional forward masks preceding the prime. Studies performed by Wernicke (2014) in a paradigm similar to that of the present studies indicate reduced categorical and color priming with sandwich pattern masks compared with backward metacontrast masks. As in our study, the backward pattern masks in Wernicke’s studies were presented at the same time as the target and did not include meaningful stimuli. In light of the present results, the reduced priming effects with sandwich pattern masks observed by Wernicke (2014) should therefore be attributed to the presence of forward masks rather than to the spatial layout of the masks. In line with this interpretation, previous studies show reduced processing with forward compared to backward masking using either overlapping (Deplancke et al., 2016) or surround masks (Breitmeyer, Öğmen, et al., 2004). For example, in a pointing task, hand trajectories of subjects were influenced more strongly by distractors that were masked by backward- than by forward masks under identical visibility conditions (Deplancke et al., 2016). These results suggest that forward masks interfere with stimulus information that is left intact when backward pattern masks are being used.

In line with these findings, neurophysiological studies show that forward masks affect early neuronal responses to the prime (Judge et al., 1980; Macknik & Livingstone, 1998) which may be crucial for fast categorization processes underlying priming effects (Lamme & Roelfsema, 2000; Schmidt et al., 2006; VanRullen, 2007). This early stimulus activation may be unaffected when backward masks are being used, including backward pattern masks. Single-cell recordings in macaque monkeys have shown that neuronal responses - albeit shortened by subsequent pattern masks - can travel through the ventral pathway and trigger stimulus-selective responses in inferotemporal cortex (Rolls & Tovee, 1994). Although it has been debated whether these early responses suffice to explain discrimination performance (Bacon-Macé et al., 2005; Kovacs et al., 1995; Rolls et al., 1999), the results suggest that early neuronal responses convey task-relevant stimulus information even in the presence of backward pattern masks. In a psychophysiological counterpart of these experiments, VanRullen and Koch (2003) found that the early time course of motor responses in a masked categorization task did not differ for masked versus unmasked trials, which they interpreted as further evidence that backward (pattern) masks do not interfere with decision-relevant information carried by an early feedforward sweep (VanRullen & Koch, 2003).

Together, the present findings show that overlapping backward masks do not interfere with priming of perceptual features or word meaning. The results parallel findings that perceptual and semantic priming effects are not affected by backward metacontrast masks (Schmidt, 2002; Vorberg et al., 2003; Wernicke, 2014) and extend these findings to backward pattern masks. It appears that backward masks presented simultaneously with the target generally not interfere with priming effects. This interpretation is in agreement with previous behavioral (Schmidt et al., 2006; VanRullen & Koch, 2003) and neurophysiological research

(Fahrenfort et al., 2007; Lamme & Roelfsema, 2000) indicating that backward masks specifically interfere with information necessary for a conscious perception of the primes, but do not affect an early stage of prime processing that may be sufficient for priming effects. However, it is unclear how masks presented prior to the target or prime interact with prime processing. Understanding the temporal dynamics of masks and primes may thus prove to be an important next step to make sense of reduced priming effects in the context of semantic priming studies.

4. Forward Masks reduce Priming Effects

Authorship contribution note: This chapter is based on the manuscript "Becker, N. & Mattler, U. (in preparation). Forward Masks reduce Priming Effects". Experiments 4.1 and 4.5 comprise data of two Bacherlor's theses.

4.1. Abstract

Visual masking has been used to study visual awareness and its role for information processing. Many studies demonstrated that the processing of stimuli can take place even when conscious awareness is abolished by masking. However, the mechanisms and effects of different masking procedures are not yet clear. Whereas some studies use simple backward masking like meta-contrast masking to abolish stimulus visibility, other studies use sandwich masking procedures in which an additional forward mask is presented prior to the stimulus. Here we report the effects of forward and backward masking procedures on the processing of stimulus information in a speeded choice response task. When only backward masking is employed, our results replicate previous findings showing that backward masks reduce prime visibility, but do not affect priming effects. With additional forward masking, however, priming effects were severely reduced. This detrimental effect increased with the duration of the forward mask and was strongest when the forward mask preceded the prime without delay. The current results support theories of stimulus processing suggesting that forward masks limit early feedforward activity that is vital for priming effects whereas backward masks interfere with late, possibly recurrent, processes necessary for conscious perception.

4.2. Introduction

One idea about consciousness is that it allows stimuli to be processed in a sophisticated way that is unavailable when stimuli are not consciously perceived (Mudrik et al., 2014; van Gaal & Lamme, 2012). In order to examine the effects of unconscious stimuli, researchers have employed a number of different masking procedures (Breitmeyer & Öğmen, 2006; Kim & Blake, 2005). While these procedures aim to selectively reduce conscious awareness, little is known whether masking also reduces cognitive functions that are independent of conscious awareness. As a consequence, the choice of the mask may also determine to what extent stimuli can be processed in the absence of awareness (Breitmeyer, 2015; Faivre et al., 2012; Fogelson et al., 2014; Wernicke, 2014).

Here we examine the effects of forward and backward masking on stimulus awareness and priming effects in a metacontrast masking paradigm. In metacontrast masking, a visual stimulus is followed by a masking stimulus which surrounds the contour of the stimulus like a ring surrounds a disk, thereby decreasing its visibility (Breitmeyer & Öğmen, 2006). When participants have to respond to the shape of the mask, the masked stimulus can prime response times (RTs) independent of conscious awareness (priming effects; Fehrer & Raab, 1962; Mattler & Palmer, 2012; Vorberg et al., 2003). These findings suggest that the processing of critical prime features is not affected by the presence and strength of backward metacontrast masks, and thus, independent of prime visibility.

Meanwhile, a different conclusion can be reached when forward masks are used to reduce the visibility of priming stimuli. The effects of forward masks have been addressed by behavioral and neurophysiological studies. First, it has been shown that forward masking reduces the visibility of the masked stimuli (Breitmeyer & Öğmen, 2006; Schiller & Smith, 1965; Turvey, 1973). Second, forward masks not only modulate conscious accessibility, but also priming effects (Breitmeyer, Öğmen, et al., 2004). When participants responded to the color of a ring that was preceded by a colored disk, the priming effect of the disk was reduced by a forward mask consisting of a preceding ring. However, in a similar paradigm using form primes, forward masks did not affect the priming effect. Similarly, Deplancke et al. (2016) presented a low intensity distractor stimulus near threshold which redirected the trajectories of hand movements from a start position to a target location. When the distractor was preceded by a forward mask, its effect was reduced. In sum, these two studies suggest that forward masks reduce not only processes underlying awareness, but also nonconscious processes underlying priming effects.

The detrimental effects of forward masking on priming effects accord well with the view that processes underlying priming effects of simple stimulus features are triggered by an early part of the neuronal response to the stimulus, which has been shown to be reduced by forward masks in neurophysiological studies (Judge et al., 1980; Kondo & Komatsu, 2000; Macknik & Livingstone, 1998). The view that priming effects are related to an early part of the neuronal response is backed by behavioral findings of Vorberg et al. (2003) showing that priming effects rise with unit slope as the stimulus onset asynchrony (SOA) between the stimulus and the mask increases. In a pointing task, Schmidt noticed that participants' hand movements were time locked to prime onsets (Schmidt, 2002). The view that prime onsets are responsible for priming effects is consistent with the neurophysiological distinction between fast feedforward processing that is related to the initial part of the neuronal response and recurrent activation in a later time window (Breitmeyer, 2014; Fahrenfort et al., 2007; Lamme & Roelfsema, 2000; Lamme et al., 2002; Macknik & Livingstone, 1998; Macknik & Martinez-Conde, 2007; Rolls & Tovee, 1994). The distinction between fast feedforward and feedback processing has been used to explain the effects of backward masks: According to this notion, backward masks selectively interfere with feedback processes necessary for a construction of an organized, conscious percept. At the same time, backward masks leave an early feedforward sweep, which encodes simple stimulus features that are relevant for priming effects, intact (Fahrenfort et al., 2007; King, Pescetelli, & Dehaene, 2016; Lamme et al., 2002; Schmidt et al., 2006; van Gaal & Lamme, 2012). Forward masks, on the other hand, may reduce these early onset activations (Judge et al., 1980; Kondo & Komatsu, 2000; Macknik & Livingstone, 1998) and therefore, priming effects.

Here, we demonstrate suppressive effects of forward masking on priming effects in a robust motor priming paradigm (Vorberg et al., 2003; Mattler & Palmer, 2012). In this paradigm, participants respond to left or right arrow stimuli with a speeded choice response. These target arrows also serve as metacontrast masks for smaller arrow primes that precede the targets with different SOAs. To examine the effects of forward masking we presented a forward mask which preceded the prime in some trials (see Figure 4.1). We varied the intensity and temporal characteristics of the forward masks to examine their influence on priming effects and prime visibility.

4.3. Experiment 4.1

In this initial experiment we examined priming effects of simple arrow stimuli when forward masks are either present or absent. We varied the strength of the masks to discriminate the effects of prime awareness and forward masks on priming effects.

Method

Participants. Participants were 14 students from the University of Goettingen aged between 19 and 26 years old (*M* = 21.7 years, *SD* = 2.2 years) who participated for three 1-h sessions on separate days. All participants had normal or corrected-to-normal vision, no known neurological problems and received course credit or monetary compensation (7 € per hour).

Tasks. All participants completed two experimental sessions with the choice RT-task and a separate prime recognition session. (1) In the choice RT-task, participants were instructed to respond as fast and accurately as possible to the target, indicating target directions of the arrows pointing to the left and to the right with the left and right Ctrl-button on a computer keyboard, respectively. (2) In the prime recognition session, participants were informed about the presence of the prime. Participants were asked to indicate the orientation of the prime using the same buttons that were used for target discrimination before. In the prime recognition session, participants were instructed to respond slow and deliberate.

Apparatus. The same apparatus was used in all experiments of this study. Stimuli were displayed on a Viewsonic 1900 Perfect Flat monitor with a vertical refresh rate of 75 Hz. In Experiments 4.2 to 4.4, the refresh rate was increased to 100 Hz. Experiments were run on a Windows PC with the software ‘‘Presentation’’ (Version 19.0, www.neurobs.com). Participants placed their head on a chin rest ensuring a viewing distance of 1 m.

Stimuli. Stimuli and sequence of events are shown in Figure 4.1. Stimuli comprised small black arrows as primes (1.74° x 0.58° of visual angle), and larger target arrows (5.79° x 1.94°) pointing to the left or right. The target arrows also served as weak or strong metacontrast masks: Strong metacontrast masks were black arrows with a central opening in the shape of two superimposed prime arrows. Weak backward masks were slim double arrows with the same outer dimensions as the strong mask. Forward masks (3.90° x 1.94°) consisted of two straight lines (weak forward masks) or a filled rectangle with the same central opening as the target stimuli (strong forward masks). When forward masks were present, forward and backward masks had the same strength in Experiment 4.1.

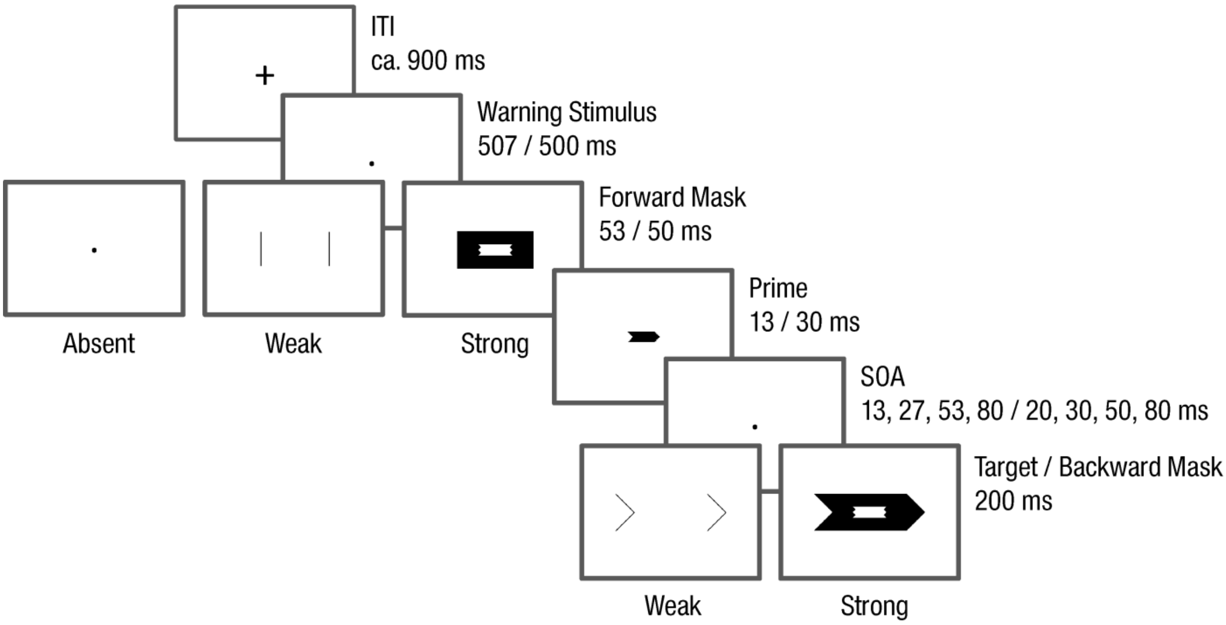

Figure 4.1. Stimulus sequence for Experiment 4.1. *ITI* = Intertrial-Interval, *SOA* = Stimulus-onset asynchrony. In Experiment 4.2, the prime was presented for 30 ms and stimulus times were adapted to 100 Hz (see adapted timings to the right).

Procedure. Each trial started with a fixation cross in the center of the screen, which lasted between 800 and 1853 ms following a quasi-exponential distribution (inter-trial interval, ITI). The fixation cross was replaced by a 507 ms warning dot. In trials that included forward masks, the warning dot was followed by a 53 ms forward mask. In conditions without forward masking, the dot was instead continued for another 53 ms. The prime lasted for 13 ms. After a variable SOA between 13-80 ms the target appeared for 200 ms. In the choice-RT task, participants received auditory (450 Hz Gaussian tone) feedback if their response was wrong, or combined auditory and visual feedback (“too slow”), if their response exceeded 900 ms. In the prime recognition session, participants received error feedback if they were wrong or faster than 500 ms to discourage prime-driven responses.

Design. Each of both sessions included 13 blocks of 64 trials each, plus one demo block of 8 trials. The demo- and first block of each session were considered warm-up and discarded from further analysis. In each block, all possible trials resulting from a factorial combination of 2 prime-target Congruency (congruent vs. incongruent), 2 Masking Strengths (weak vs. strong), 2 Masking Type (without vs. with forward mask) and 4 SOAs (13, 27, 53, and 80 ms) were repeated once for each target orientation, balancing for all conditions. Within each block, all trials were presented in randomized order. Excluding practice trials, participants thus completed 48 trials per experimental condition in both the choice-RT and the prime recognition task.

Data analysis. Trimmed mean RTs per subject and condition were based on correct trials of the participant, excluding post-error trials. Outliers were excluded in two steps: First, reactions < 100 ms and > 900 ms (response deadline) were omitted. Second, the fastest and two slowest trials of each condition were discarded for each subject, thus rejecting 4% of trials when no errors were made. In the prime discrimination task, only fast trials below 500 ms were excluded from the analysis. RTs, arc-sine transformed error rates and *d'* values in the discrimination task were analyzed using within-subject ANOVAs. When the assumption of sphericity was violated, *p*-values are based on Greenhouse-Geisser corrected degrees of freedom, whereas, for the sake of readability, the stated degrees of freedom are uncorrected. Partial η_p^2 will be reported for effect sizes. To keep the results concise, only priming effects (effects containing the factor Congruency) will be reported in the RT and error results section. The complete ANOVA tables can be found in Appendix C. The statistical analysis remained identical across experiments.

Results

RTs. See Figure 4.2 A and B. Including errors, post-errors and outliers as reported above, 18.6% of all RT trials were discarded. Reaction times were shorter on congruent (346 ms) than on incongruent trials (374 ms), as indicated by the significant main effect of Congruency, $F(1,13) = 323.35$, $p < .001$, $\eta_p^2 = .96$. Priming effects were moderated by the

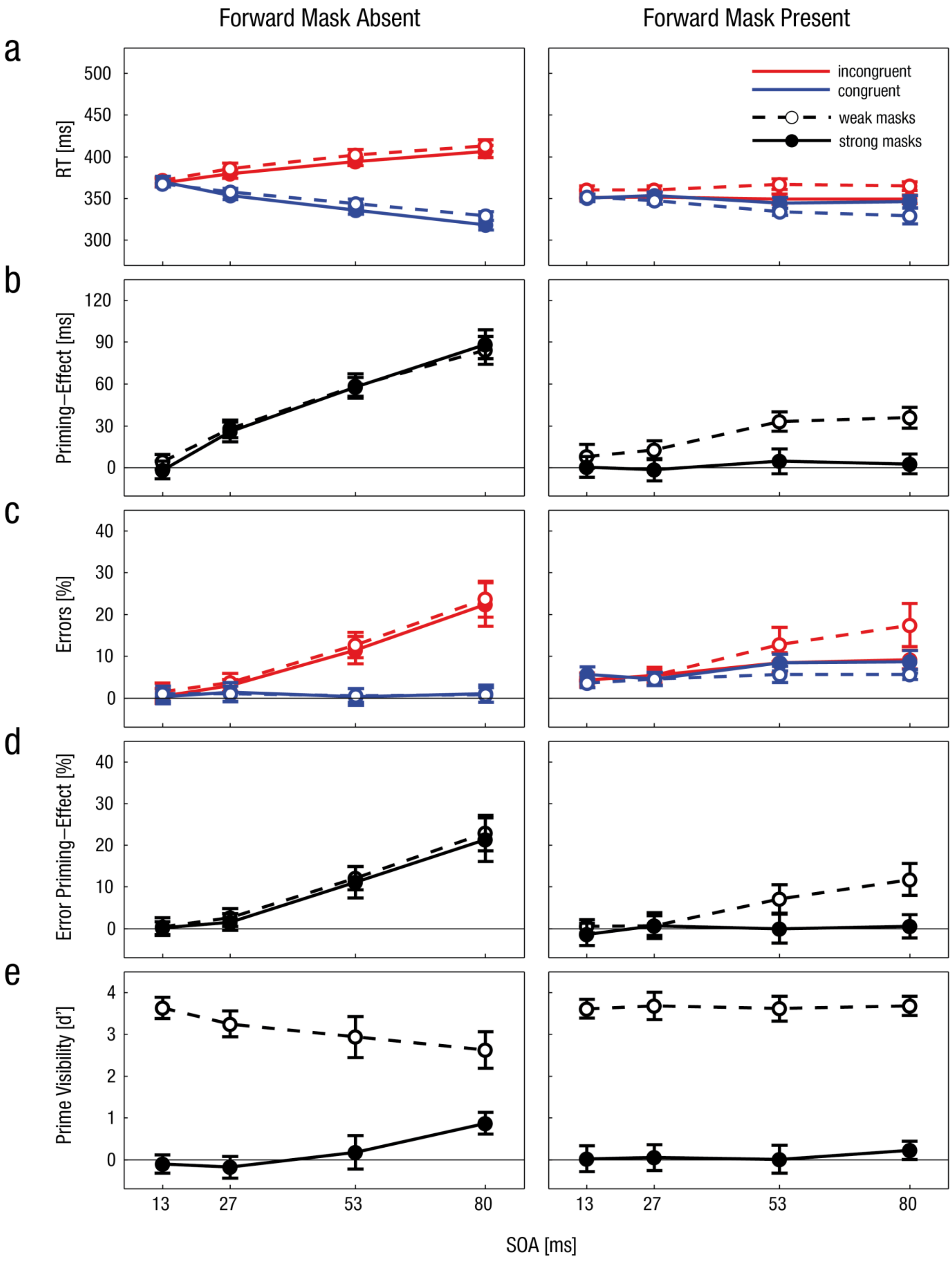

Figure 4.2. The effects of forward masks on prime processing in Experiment 4.1. Results include mean reaction times (a), priming effects for reaction times (b), mean errors (c), priming effects for errors (d) and the corresponding prime discrimination performance (e). Open symbols represent weak backward masks, closed symbols represent strong backward masks. Red and blue lines represent congruent and

incongruent conditions, respectively. Error bars represent within-subject confidence intervals (Morey, 2008).

presence of forward masks (Congruency x Masking Type, *F*(1, 13) = 105.02, $p < .001$, $\eta_p^2 = .89$), the strength of the masks (Congruency x Masking Strength, *F*(1, 13) = 31.68, $p < .001$, $\eta_p^2 = .71$) and SOA (Congruency x SOA, *F*(3, 39) = 88.04, $p < .001$, $\eta_p^2 = .87$). The significant three-way interaction of Congruency x Masking Type x Masking Strength, *F*(1, 13) = 16.15, $p = .001$, $\eta_p^2 = .55$, indicates that priming effects were moderated by masking strength only on trials with forward masking. This interpretation was validated by separate ANOVAs for each masking type which revealed that priming effects were moderated by masking strength with forward masking (Congruency x Masking Strength, *F*(1, 13) = 32.36, $p < .001$, $\eta_p^2 = .71$) but not without (Congruency x Masking Strength, *F*(1, 13) = 0.19, $p = .667$). Post-hoc *t*-tests revealed priming effects with weak forward masking (*PE* = 23 ms, *t*(13) = 9.19, $p < .0005$, Cohen's *d* = .56), but not with strong forward masking (*t*(13) = 0.88, $p = .397$). The four-way interaction of Congruency x Masking Type x Masking Strength x SOA, *F*(3, 39) = 8.53, $p < .001$, $\eta_p^2 = .40$, was also significant. Visual inspection of Figure 4.2 suggests that priming effects overall increased with SOA, but not at the same rate for all masking conditions.

Errors. See Figure 4.2 C and D. Error priming effects closely mirrored the results of the reaction times. Errors were fewer in congruent (3.3 %) than in incongruent trials (9.1 %), as indicated by the significant main effect of Congruency, *F*(1,13) = 122.41, $p < .001$, $\eta_p^2 = .90$. Priming effects were moderated by the presence of forward masks (Congruency x Masking Type, *F*(1,13) = 69.56, $p < .001$, $\eta_p^2 = .84$), the strength of the masks (Congruency x Masking Strength, *F*(1,13) = 11.12, $p = .005$, $\eta_p^2 = .46$) and SOA (Congruency x SOA, *F*(3,39) = 59.32, $p < .001$, $\eta_p^2 = .82$). Unlike with reaction times, the three-way interaction of

Congruency x Masking Type x Masking Strength, *F*(1,13) = 4.42, *p* = .055, was not significant. Also, the four-way interaction of Congruency x Masking Type x Masking Strength x SOA, *F*(3,39) = 2.0, *p* = .239, was not significant. Still, as the error results showed the exact same pattern as the reaction times (see Figure 4.2), and the *p*-value of the three-way interaction pointed to a potential trend, the post-hoc analyses reported for the reaction times will be presented below for the error data, although these results should be treated with reservation. Separate ANOVAs for each masking type were conducted, revealing that with backward masks, priming effects were not moderated by masking strength (Congruency x Masking Strength, *F*(1,13) = 1.55, *p* = .234), whereas masking strength was a significant moderator for priming effects when sandwich masks were being used (Congruency x Masking Strength, *F*(1,13) = 10.46, *p* = .007, η_p^2 = .45). Post-hoc *t*-tests revealed priming effects for weak sandwich masks (*PE* = 5.07%, *t*(13) = 6.87, *p* < .0005, Cohen's *d* = .52), but not for strong sandwich masks (*t*(13) = 0.07, *p* = .944).

Prime Recognition. See Figure 4.2 E. Due to fast reactions, 0.2% of the trials were excluded from analysis. Prime visibility in terms of *d'* (Figure 4.2E) decreased with stronger masks as indicated by the significant main effect of Masking Strength, *F*(1,13) = 241.01, *p* < .001, η_p^2 = .95, with *d'* = 3.38 and *d'* = 0.13 for weak and strong masks, respectively. Neither the main effect of Masking Type (*F*(1,13) = 3.14, *p* = .100) nor that of SOA (*F*(3,39) = 1.60, *p* = .206) reached significance. However, the interactions Masking Strength x Masking Type (*F*(1,13) = 18.38 *p* < .001, η_p^2 = .59), Masking Strength x SOA (*F*(3,39) = 19.00, *p* < .001, η_p^2 = .59) and the interaction Masking Strength x Masking Type x SOA were significant (*F*(3,39) = 19.73, *p* < .001, η_p^2 = .60). Subsequent analyses revealed that the interaction Masking Strength x SOA was only present for backward masks (*F*(3,39) = 25.71, *p* < .001, η_p^2 = .66), but not when forward masks were added (*F*(3,39) = 0.57, *p* = .635).

4.4. Experiment 4.2

Experiment 4.1 showed a strong suppressive effect of forward masking on priming effects and only little effects of forward masking on prime visibility. In Experiment 4.2, we varied the strength of forward and backward masks orthogonally to examine the individual impact of forward and backward masks on both priming effects and visibility.

Method

Participants. 14 students (4 male) from the University of Goettingen aged between 19 and 32 years (*M* = 24 years, *SD* = 4.3 years) participated in three 1-h priming sessions and one subsequent prime recognition session.

Stimuli & Procedure. The same stimuli as in Experiment 4.1 were used and stimulus times were adapted to a refresh-rate of 100 Hz (see Figure 4.1). Thus, the alert and forward mask lasted for 500 and 50 ms, respectively. The prime was presented for 30 ms, and SOAs varied in 4 steps between 20 and 80 ms. To this end we increased the refresh-rate of the computer monitor to 100 Hz.

Design. Excluding warm-up blocks, each RT session included 8 blocks and the prime recognition session 10 blocks of 96 trials each, corresponding to a factorial combination of 2 prime-target Congruency (congruent vs. incongruent), 3 Forward Masking Strength (weak vs. strong vs. none), 2 Backward Masking Strength (weak vs. strong) and 4 SOAs (20, 30, 50, & 80 ms) that were repeated once for each target orientation. Excluding practice trials, participants thus completed 48 trials per experimental condition in the choice-RT task, and 40 trials per condition in the prime recognition task.

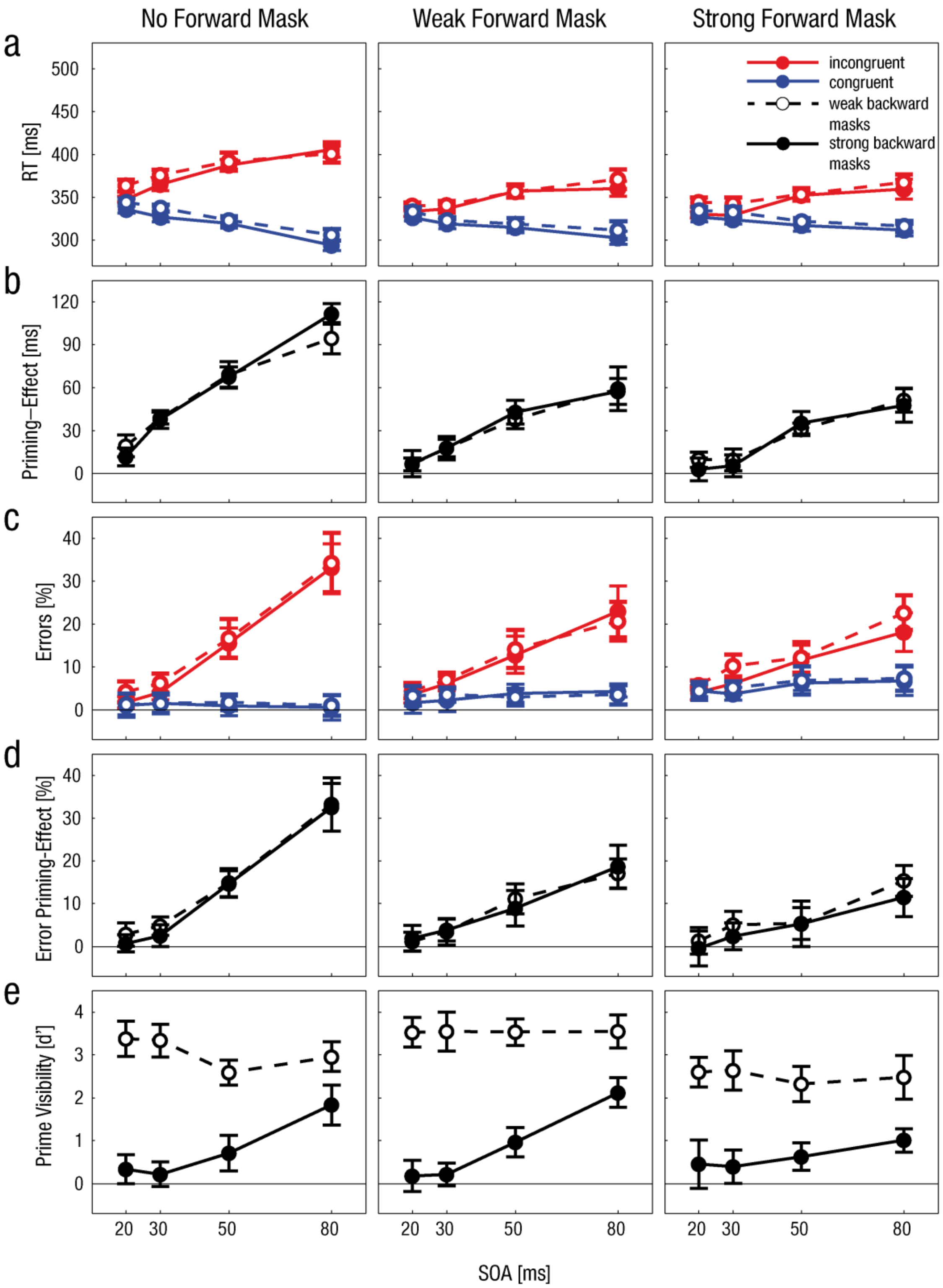

Figure 4.3. The effects of forward masks on prime processing in Experiment 4.2. Results include mean reaction times (a), priming effects for reaction times (b), mean errors (c), priming effects for errors (d) and the corresponding prime discrimination performance (e). Open symbols represent weak backward masks, closed symbols represent strong backward masks. Red and blue lines represent congruent and

incongruent conditions, respectively. Error bars represent within-subject confidence intervals (Morey, 2008).

Results

Data treatment proceeded as in Experiment 4.1, excluding 21.6% of the trials in the RT task. The results of Experiment 4.2 are displayed in Figure 4.3.

RTs. See Figure 4.3 A and B. Reaction times were shorter in congruent (322 ms) than in incongruent trials (359 ms), as indicated by the significant main effect of Congruency, $F(1,13) = 131.05$, $p < .001$, $\eta_p^2 = .91$. Priming effects were moderated by the strength of forward masks (Congruency x Forward Mask, $F(2,26) = 106.31$, $p < .001$, $\eta_p^2 = .89$), but not by the strength of the backward masks (Congruency x Backward Mask, $F(1,13) = 0.00$, $p = .993$). Priming effects increased with SOA (Congruency x SOA, $F(3,39) = 132.12$, $p < .001$, $\eta_p^2 = .91$). The significant three-way interaction of Congruency x Forward Mask x SOA, $F(6,78) = 10.91$, $p < .001$, $\eta_p^2 = .46$, may indicate that the slope of the priming effects depended on the strength of the forward mask. To determine whether priming effects differed for weak vs. strong forward masks in particular, a second ANOVA was performed that did not include the ‘no forward mask’-condition. Again, priming effects were moderated by the strength of the forward mask, although the effect was much smaller (Congruency x Forward Mask, $F(1,13) = 10.09$, $p = .007$, $\eta_p^2 = .44$). The non-significant three-way interaction of Congruency x Forward Mask x SOA, $F(3,39) = 0.88$, $p = .462$, indicates that the slope of the priming effects might be comparable for weak and strong forward masks. All other interactions that included the factor Congruency were not significant.

Errors. See Figure 4.3 C and D. Error priming effects closely mirrored the results of the reaction times. Errors were fewer in congruent (3.3 %) than in incongruent trials (12.4 %), as indicated by the significant main effect of Congruency, $F(1,13) = 92.24$,

$p < .001$, $\eta_p^2 = .88$. Priming effects were moderated by the strength of forward masks (Congruency x Forward Mask, $F(2,26) = 36.43$, $p < .001$, $\eta_p^2 = .74$), but not by the strength of the backward masks (Congruency x Backward Mask, $F(1,13) = 0.84$, $p = .377$). Priming effects increased with SOA (Congruency x SOA, $F(3,39) = 74.93$, $p < .001$, $\eta_p^2 = .85$). The significant three-way interaction of Congruency x Forward Mask x SOA, $F(6,78) = 12.16$, $p < .001$, $\eta_p^2 = .48$, may indicate that the slope of the priming effects depended on the strength of the forward mask. To determine whether priming effects differed for weak vs. strong forward masks in particular, a second ANOVA was performed that did not include the 'no forward mask'-condition. Priming effects were moderated by the strength of the forward mask, although the effect was smaller (Congruency x Forward Mask, $F(1,13) = 16.83$, $p = .001$, $\eta_p^2 = .56$). Other than for reaction priming, the three-way interaction of Congruency x Forward Mask x Backward Mask ($F(1,13) = 4.77$, $p = .048$, $\eta_p^2 = .27$) indicates that forward masks had a different impact on priming effects depending on the backward mask, reflecting somewhat higher error priming effects with weak backward masks than with strong backward masks when strong forward masks were applied.

Prime Recognition. See Figure 4.3 E. Due to fast reactions, 0.5% of the trials were excluded from analysis. Prime visibility as measured in the final prime discrimination task was affected by the strength of the forward masks ($F(2,26) = 7.10$, $p = .015$, $\eta_p^2 = .35$), as well as backward masks ($F(1,13) = 118.97$, $p < .001$, $\eta_p^2 = .90$). The mean *d'* with strong masks was *d'* = 0.76, whereas with weak masks it was again nearly perfect, with *d'* = 3.04. Prime visibility increased with SOA ($F(3,39) = 18.17$, $p < .001$, $\eta_p^2 = .58$). All other effects were also significant, indicating that prime visibility depended on the specific masking condition (Forward Mask x Backward Mask, $F(2,26) = 8.21$, $p = .002$, $\eta_p^2 = .39$), whereby the SOA-function depended on the strength of the forward mask (Forward Mask x SOA, $F(6,78) = 6.03$, $p < .001$, $\eta_p^2 = .32$), the strength of the backward mask (Backward Mask x

SOA, $F(3,39) = 49.24$, $p < .001$, $\eta_p^2 = .79$), and the specific masking condition (Forward Mask x Backward Mask x SOA, $F(6,78) = 4.10$, $p = .001$, $\eta_p^2 = .24$).

4.5. Experiment 4.3

The two previous experiments demonstrated a suppression effect of forward masking on prime processing. In contrast to the previous study of Breitmeyer et al. (2004), we used masks with rather long durations and a zero interstimulus-interval (ISI) between forward mask and prime. In a final study, we seek to inquire the temporal dynamics of the suppression effect in more detail. While it is widely assumed that stimulus onsets mark critical time points for unconscious processing, it is unclear how the suppressive effects of forward masks fit into this picture. To discriminate interferences of onsets versus offsets of forward masks, we varied the duration, SOA and ISI between forward masks and primes.

Method

Participants. Participants were 14 students from Goettingen University between 19 and 30 years old (*M* = 23.9 years, *SD* = 2.8 years) who came for two 1-h RT sessions.

Stimuli & Design. See Figure 4.4. In each block, all possible trials resulting from a factorial combination of 2 prime-target Congruency (congruent vs. incongruent) and 20 possible temporal configurations were repeated once for each target orientation, balancing for all conditions. Each session included a demo block of 8 trials and a 48 trials practice block that were not included in the analysis. The timing of the forward masks was chosen such as to realize a range of different ISIs for each of two fixed SOAs between forward mask and prime, and vice versa different values of SOA while keeping ISI constant. In this way, ISI was varied in 7 (from -10 to 50 ms) and 5 steps (-10 to 30 ms) at fixed SOAs of 60 and 40 ms, respectively. Negative values of ISIs indicate a temporal overlap of forward masks and primes because the offset of the forward masks occurred after the onset of the prime.

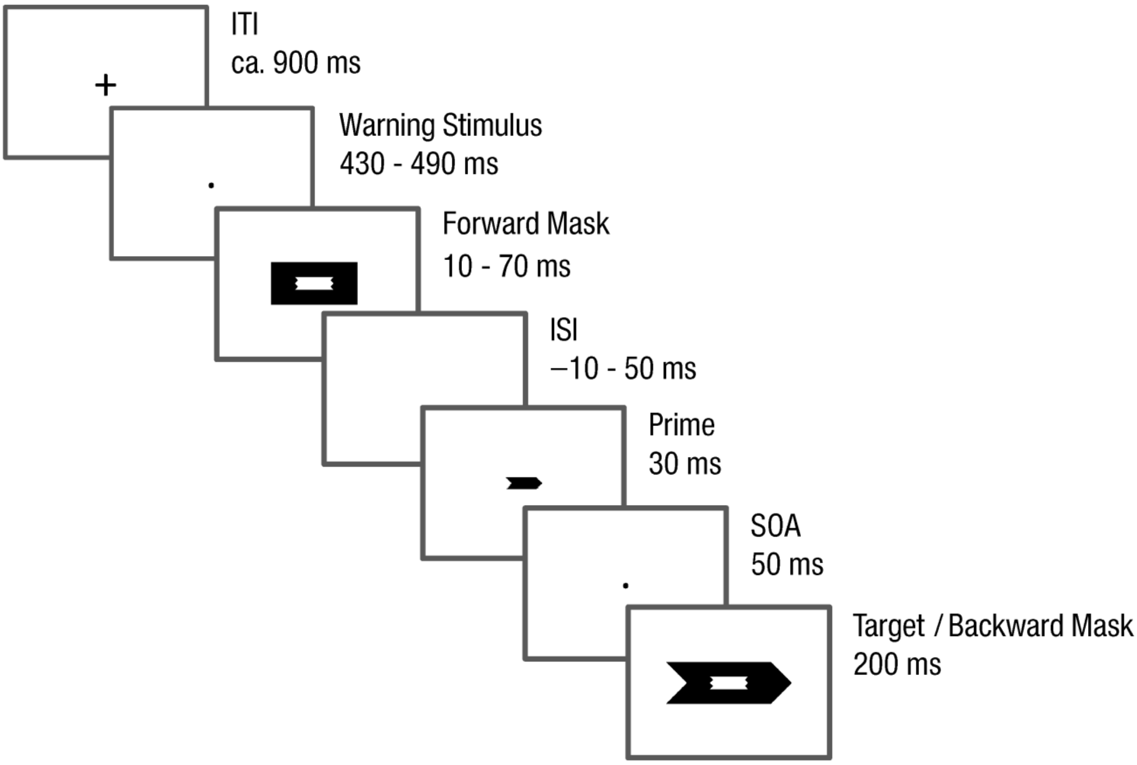

Figure 4.4. Stimulus sequence for Experiment 4.3. *ITI* = Intertrial-Interval, *SOA* = Stimulus-onset asynchrony. A blank screen with no fixation was inserted between forward mask and prime when the ISI between forward mask and prime was positive. When the ISI was negative, forward mask and prime overlapped.

Likewise, SOA was varied in 7 (from 10 to 70 ms) and 5 steps (50 to 10 ms) at fixed ISIs of 0 and 20 ms. As a result, 20 different timing conditions were tested in this experiment, with ISIs varying from -10 to 50 ms, SOAs varying from 10 to 70 ms and durations of the forward masks varying between 10 and 70 ms. The time of the alert varied in a way that the onset of the alert was always 500 ms before the onset of the prime.

Results

Data treatment proceeded as in Experiment 4.1, excluding 19.4% of the trials. The priming effects of Experiment 4.3 are displayed in Figure 4.5. Although forward mask SOA, ISI and duration refer to different events of the forward mask, and call for different predictions depending on whether forward mask onset, offset or duration are essential for the suppression effect, their effects cannot be discerned using inferential statistics. As SOA is equal to the sum of ISI plus duration of the forward mask, every possible model will have two equivalent models depending on which two factors are entered into the analysis. With this is mind, we constructed a range of models with the goal to describe the data in the most informative and straightforward way. Because linear models did not provide a good fit of the data, we constructed a non-linear model that contained an exponential transformation of ISI. Our candidate model was chosen based on the best BIC. It included the factors mask duration and a corrected ISI that would allow for an exponential transformation:

$$PE = \mathrm{A} * \mathrm{MDur} * (\mathrm{ISI} + 11) + B * (1 - e^{(-\mathrm{C}*(\mathrm{ISI}+11))}), \qquad A + B|Subject$$

where A = -0.03 ($t(264) = -6.76$, $p < .001$), B = 82.02 ($t(264) = 13.43$, $p < .001$), and C = 0.05 ($t(264) = 12.98$, $p < .001$), while coefficients A and B could vary for individual subjects. The model predictions are included in Figure 4.5 B. Two components can be derived from this model regarding the temporal dynamics of the suppression effect: First, the suppression effect increases exponentially with shorter ISIs between forward mask and prime. Second, longer forward masks produce stronger suppression of the prime. This effect of mask duration decreases with short ISIs, resulting in equal suppression across forward masks when ISI is sufficiently short (Figure 4.5).

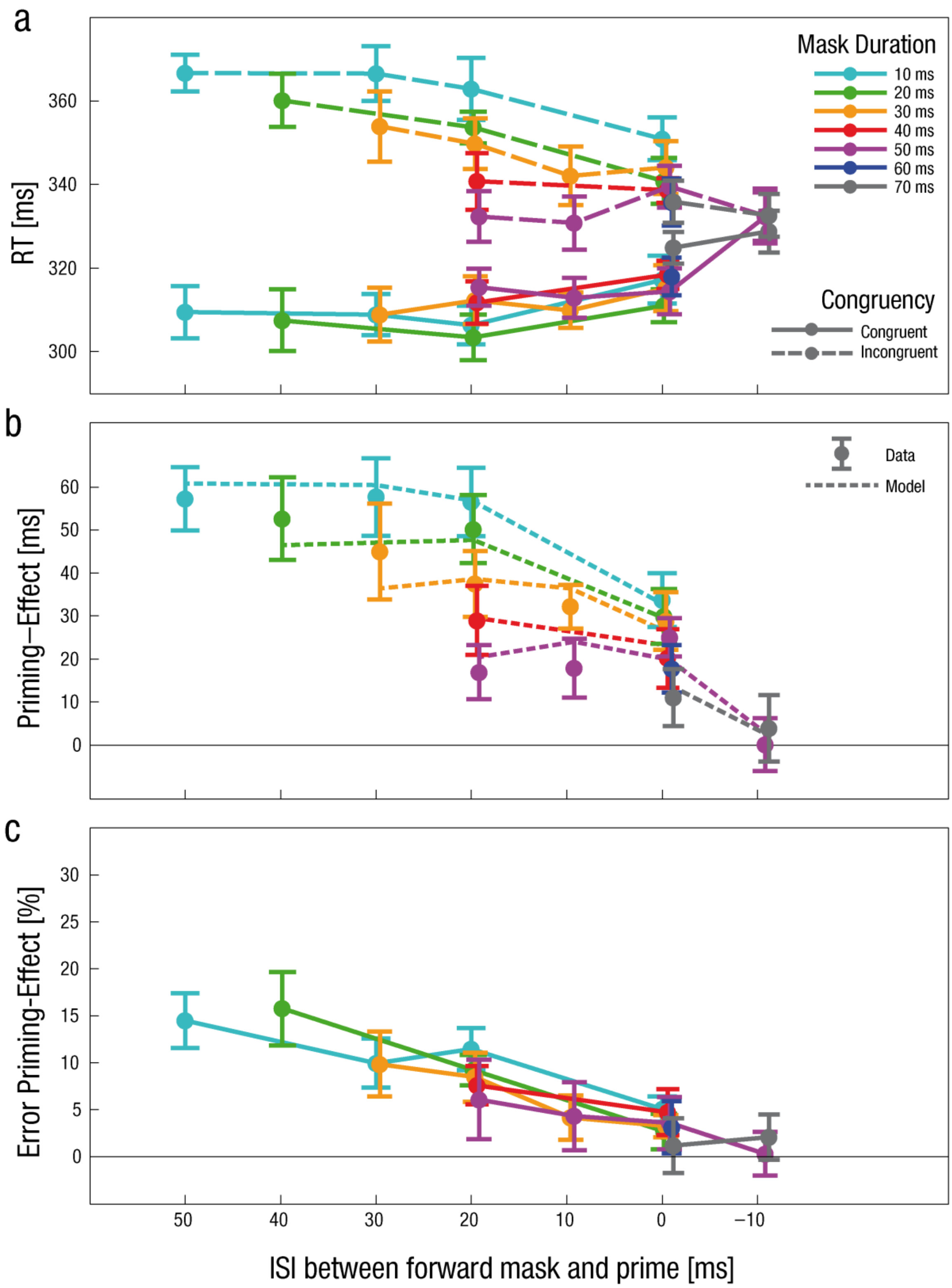

Figure 4.5. Priming effects for reaction times and errors in Experiment 4.3, plotted as a function of ISI between forward mask and prime. The duration of the mask is coded with color. The line type differentiates incongruent and congruent RTs in the top panel (a). In panel b, the lines correspond to the predictions of a model (see Results). A negative ISI indicates that forward masks and primes

overlapped. The target was always presented 50 ms after onset of the prime. Error bars represent within-subject confidence intervals (Morey, 2008).

4.6. Experiment 4.4

To explore the characteristics of the suppressive effect of forward masks in very long ISIs, an additional exploratory study was performed analogously to Experiment 4.3. This study included forward masks with two different durations, 30 and 50 ms. Since the suppression effect seemed to increase with ISI when forward masks last long, this experiment aimed to define the range of this additional suppression at intermediate ISIs.

Method

Participants. Participants were 8 students from Goettingen University, 6 naïve and 2 experienced subjects, including the author NB. They were between 19 and 30 years old (*M* = 25.4 years, *SD* = 2.7 years) and came for two 1-h RT sessions, and one prime discrimination session.

Design. Excluding warm-up blocks, both RT sessions and the prime discrimination session each comprised 12 blocks of 64 trials. In each block, all possible trials resulting from a factorial combination of 2 prime-target Congruency (congruent vs. incongruent), 2 forward mask durations (30 vs. 50 ms) and 7 ISIs between forward mask and prime (-10, 0, 10, 20, 30, 50, 100, and 150 ms) were repeated once for each target orientation, balancing for all conditions. Excluding practice trials, participants thus completed 48 trials per experimental condition in both the choice-RT and the prime recognition task.

Procedure. The procedure was identical to that of Experiment 4.3, except for the different duration of ISI and the duration of the forward masks.

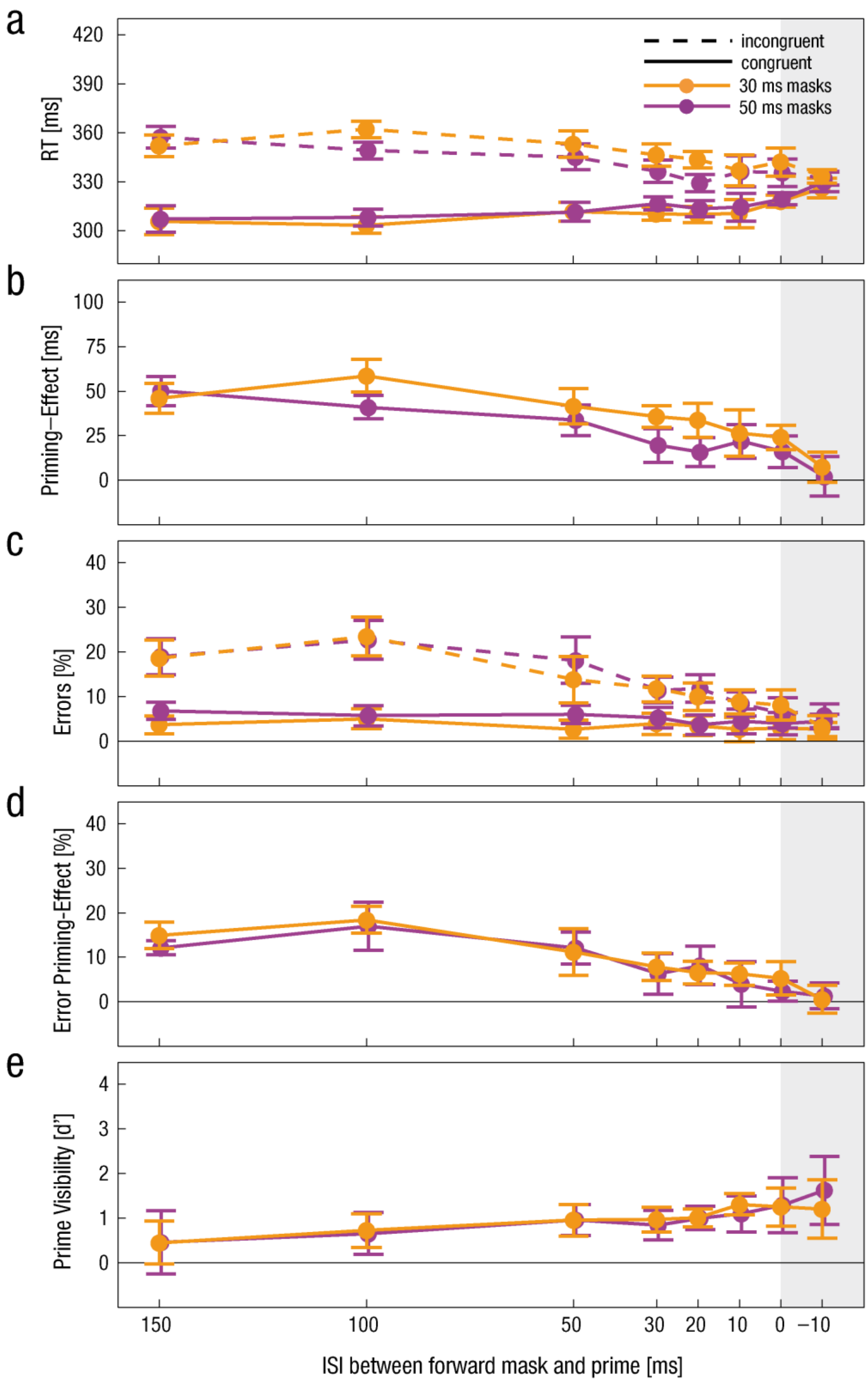

Figure 4.6. Mean priming effects and prime visibility in Experiment 4.4, plotted as a function of ISI between forward mask and prime. The duration of the mask is coded with color. A negative ISI indicates that forward masks and primes overlapped. A shaded area starting at 0 ms ISI illustrates the time in which the forward mask and prime are presented simultaneously. As in Experiment 4.3, the

target was always presented 50 ms after onset of the prime. Error bars represent within-subject confidence intervals (Morey, 2008).

Results

Data treatment proceeded as in Experiment 4.1, excluding 23.0% of the trials in the RT task and 2.3% fast trials in the visibility task. The results are depicted in Figure 4.6 and Figure 4.7.

RTs. See Figure 4.6 A and B. Reaction times were shorter in congruent (313 ms) than in incongruent trials (343 ms), as indicated by the significant main effect of Congruency, $F(1,7) = 154.38$, $p < .001$, $\eta_p^2 = .96$. Generally, priming effects were most strongly reduced at short or negative ISIs and recovered at long ISIs between forward mask and prime, in line with a significant interaction of priming effects and ISI, $F(7,49) = 18.15$, $p < .001$, $\eta_p^2 = .72$. Priming effects were more affected by 50 ms forward masks than by 30 ms forward masks (Congruency x Mask Duration, $F(1,7) = 54.50$, $p < .001$, $\eta_p^2 = .89$). The three-times interaction of Congruency, Mask Duration and ISI was not significant, $F(7,49) = 1.52$, $p = .243$.

Errors. See Figure 4.6 C and D. Errors were less frequent in congruent (4.2 %) than in incongruent trials (12.6 %), as indicated by the significant main effect of Congruency, $F(1,7) = 57.47$, $p < .001$, $\eta_p^2 = .89$. Generally, priming effects were most strongly reduced at short or negative ISIs and recovered at long ISIs between forward mask and prime, in line with a significant interaction of priming effects and ISI, $F(7,49) = 8.37$, $p < .001$, $\eta_p^2 = .54$. Priming effects were not significantly different for the two durations of forward masks (Congruency x Mask Duration, $F(1,7) = 2.56$, $p = .154$). The three-times interaction of Congruency, Mask Duration and ISI was also not significant, $F(7,49) = 0.98$, $p = .458$.

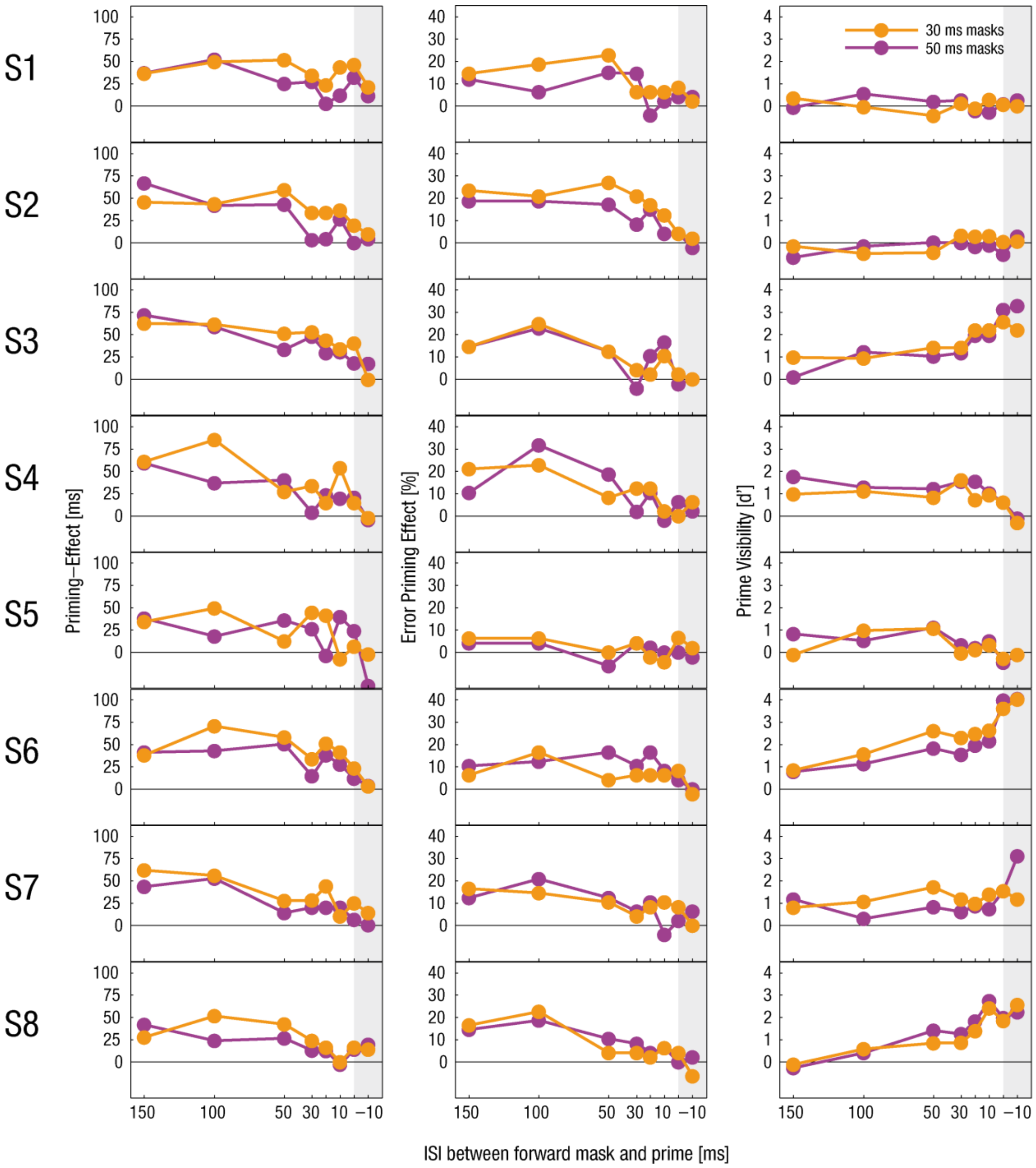

Figure 4.7. Reaction time priming effects, error priming effects and prime visibility of the eight individual subjects (S1-S8) in Experiment 4.4, plotted as a function of ISI between forward mask and prime. The duration of the mask is coded with color. A negative ISI indicates that forward masks and primes overlapped. A shaded area starting at 0 ms ISI illustrates the time in which the forward mask and prime are presented simultaneously.

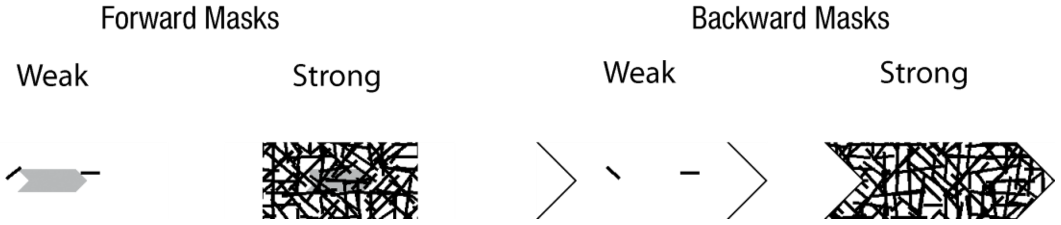

Figure 4.8. Example pattern masks used in Experiment 4.5: From left to right, example stimuli show weak and strong forward pattern masks and weak and strong backward pattern masks, respectively. A grey prime stimulus has been inserted into the forward masks to illustrate the spatial relation of prime and mask stimuli. In the actual experiment, prime and masks never appeared at the same time.

Prime Recognition. See Figure 4.6 E. Prime visibility as measured in the final prime discrimination task was neither affected by the strength of the forward masks, *F*(1,7) = 0.01, *p* = .921, the ISI between forward masks and primes, *F*(7,49) = 1.97, *p* = .191, nor the interaction of Mask Duration and ISI, *F*(7,49) = 1.06, *p* = .401.

4.7. Experiment 4.5

The previous studies demonstrated the suppressive effects of paracontrasts for a wide variety for parameters. Because many studies that employ forward masks in the literature use pattern masks that – other than paracontrast masks – overlap with the masked stimuli, we will provide one last study that uses pattern forward and backward masks. The aim of this experiment is to show that the suppression effect of forward masks is not restricted to paracontrast masks. To this end, pattern forward and backward masks will be applied using the same experimental design as in Experiment 4.2, but with the timings of Experiment 4.1 where the suppression effect was most clear.

Method

Participants. Participants were 10 students from Goettingen University between 19 and 26 years old (*M* = 22.2 years, *SD* = 1.8 years) that came for two 1-h RT sessions, and one prime discrimination session.

Stimuli & Procedure. The previously used forward and backward masks were replaced by pattern masks (see Figure 4.8). For strong masks, 100 randomly generated line patterns were used to construct each 100 forward masks and left and right target arrows. For weak forward masks, an additional 100 patterns were used that only included two random elements of varying length. To create weak backward pattern masks, these masking elements were inserted into the double-arrows that have been used as weak masks in the previous experiments. The masking segments of the weak masks were placed approximately at the location that corresponded to location of the left and right boarders of the prime to create overlap.

Design. Excluding warm-up blocks, each RT session and the prime recognition session included 10 blocks of 96 trials each, corresponding to a factorial combination of 2 prime-target Congruency (congruent vs. incongruent), 3 Forward Masking Strength (weak vs. strong vs. none), 2 Backward Masking Strength (weak vs. strong) and 4 SOAs (13, 27, 53, & 80 ms) that were repeated once for each target orientation. Excluding practice trials, participants thus completed 40 trials per experimental condition in the choice-RT and the prime recognition task.

Results

Data treatment proceeded as in Experiment 4.1, excluding 26.9% of the trials in the RT task and 7.2% fast trials in the visibility task. The results of Experiment 4.5 are displayed in Figure 4.9.

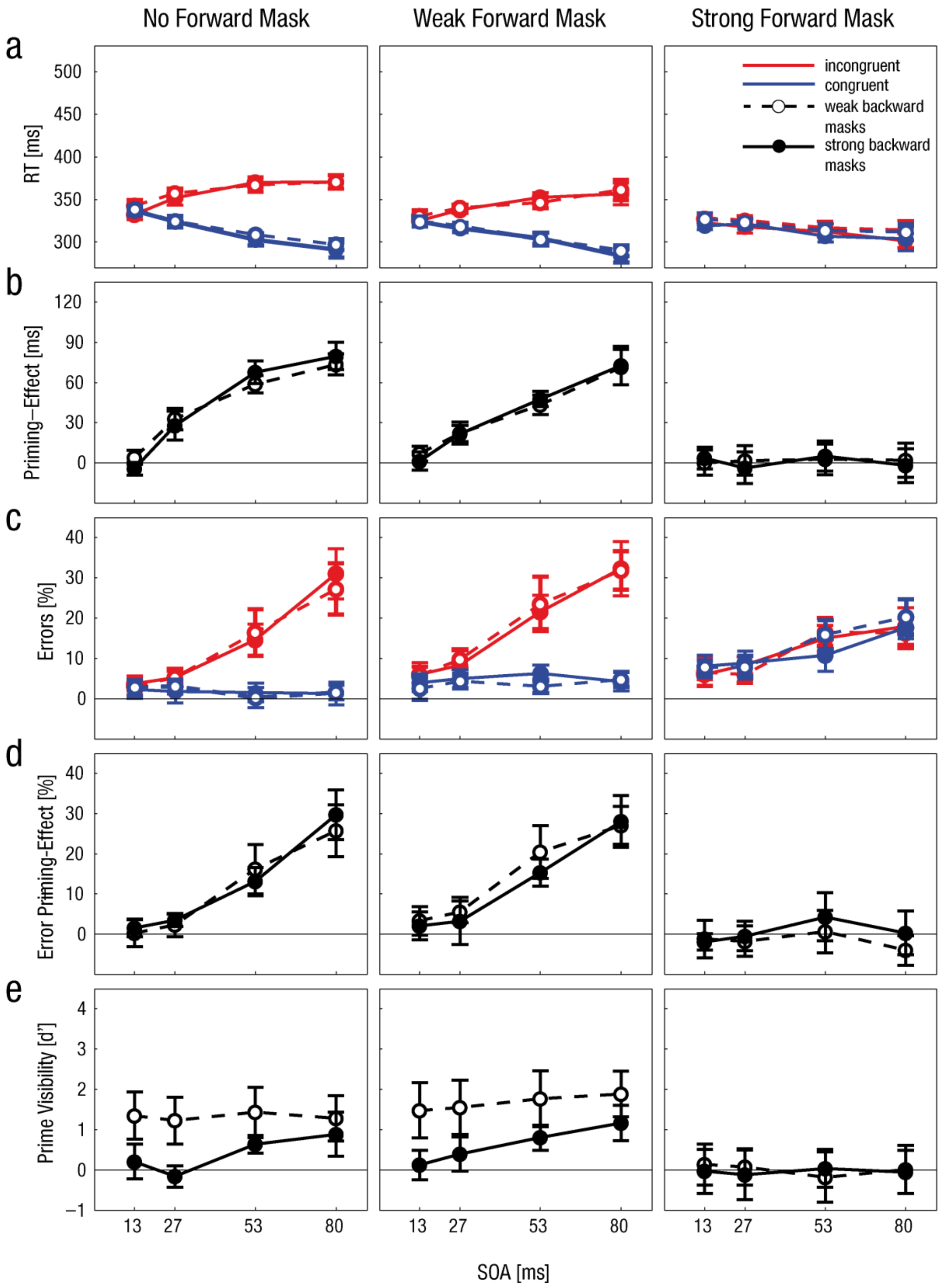

Figure 4.9. The effects of forward masks on prime processing in Experiment 4.5 using pattern masks. Results include mean reaction times (a), priming effects for reaction times (b), mean errors (c), priming effects for errors (d) and the corresponding prime discrimination performance (e). Open symbols

represent weak backward masks, closed symbols represent strong backward masks. Red and blue lines represent congruent and incongruent conditions, respectively. Error bars represent within-subject confidence intervals (Morey, 2008).

RTs. See Figure 4.9 A and B. Reaction times were shorter in congruent (312 ms) than in incongruent trials (339 ms), as indicated by the significant main effect of Congruency, $F(1,9) = 207.33$, $p < .001$, $\eta_p^2 = .96$. Priming effects were moderated by the strength of forward masks (Congruency x Forward Mask, $F(2,18) = 128.79$, $p < .001$, $\eta_p^2 = .93$), but not by the strength of the backward masks (Congruency x Backward Mask, $F(1,9) = 0.00$, $p = .957$). Priming effects increased with SOA (Congruency x SOA, $F(3,27) = 82.70$, $p < .001$, $\eta_p^2 = .90$). The significant three-way interaction of Congruency x Forward Mask x SOA, $F(6,54) = 29.21$, $p < .001$, $\eta_p^2 = .76$, may indicate that the slope of the priming effects depended on the strength of the forward mask. Whereas priming effects were clearly reduced with strong forward masks, the pattern was less clear for weak forward masks in this experiment. To determine whether priming effects were reduced by weak forward masks, a second ANOVA was performed that did not include the ‘strong forward mask’-condition. Again, priming effects were moderated by the strength of the forward mask, although the effect was much smaller (Congruency x Forward Mask, $F(1,9) = 11.00$, $p = .009$, $\eta_p^2 = .55$). The significant three-way interaction of Congruency x Forward Mask x SOA, $F(3,27) = 3.04$, $p = .046$, $\eta_p^2 = .25$, indicates that the slope of the priming effects might be steeper without forward masks. Unexpectedly, the three-way interaction of Congruency x Backward Mask x SOA, $F(3,27) = 5.52$, $p = .004$, $\eta_p^2 = .38$, was also significant, probably due to mild reductions of priming effects with weak versus strong backward masks in the condition without forward masks (on average, 7.6 ms in the longest two SOAs).

Errors. See Figure 4.9 C and D. Error priming effects generally mirrored the results of the reaction times. Errors were fewer in congruent (6.1 %) than in incongruent trials

(14.1 %), as indicated by the significant main effect of Congruency, $F(1,9) = 103.79$, $p < .001$, $\eta_p^2 = .92$. Priming effects were moderated by the strength of forward masks (Congruency x Forward Mask, $F(2,18) = 73.77$, $p < .001$, $\eta_p^2 = .89$), but not by the strength of the backward masks (Congruency x Backward Mask, $F(1,9) = 0.01$, $p = .943$). Priming effects increased with SOA (Congruency x SOA, $F(3,27) = 55.03$, $p < .001$, $\eta_p^2 = .86$). The significant three-way interaction of Congruency x Forward Mask x SOA, $F(6,54) = 14.28$, $p < .001$, $\eta_p^2 = .61$, may indicate that the slope of the priming effects depended on the strength of the forward mask. As for the reaction times, an additional ANOVA was performed to compare the priming effects with weak forward masks and without forward masks. This analysis showed that error priming effects were not moderated by the strength of the forward mask (Congruency x Forward Mask, $F(1,9) = 0.63$, $p = .447$). A significant three-way interaction of Congruency x Forward Mask x Backward Mask, does, however, indicate that error priming effects were weaker with strong than with weak backward masks when weak forward masks were applied, $F(1,9) = 7.37$, $p = .024$, $\eta_p^2 = .45$.

Prime Recognition. See Figure 4.9 E. Prime visibility as measured in the final prime discrimination task was affected by the strength of the forward masks ($F(2,18) = 7.37$, $p = .021$, $\eta_p^2 = .45$), as well as backward masks ($F(1,9) = 10.61$, $p = .010$, $\eta_p^2 = .54$). The mean *d’* was *d’* = 0.32 with strong masks was and *d’* = 1.00 with weak masks which is considerably less than with weak backward masks in the previous studies. Prime visibility increased with SOA ($F(3,27) = 6.01$, $p = .017$, $\eta_p^2 = .40$). An interaction between the strength of forward masks and SOA indicates that forward masks affected the visibility functions ($F(6,54) = 3.61$, $p = .004$, $\eta_p^2 = .29$), and an interaction of forward and backward masks ($F(2,18) = 6.09$, $p = .010$, $\eta_p^2 = .40$) indicates that the effect of backward masks differed when weak or strong forward masks were being used, which is probably due to a bottom effect in visibility with strong forward masks.

4.8. Discussion

We varied the strength and presence of forward and backward masks in a typical metacontrast paradigm, to estimate the masks' impact on prime visibility and priming effects. We found that priming effects were consistently reduced when forward masks were applied, even down to complete elimination (Experiment 4.1), whereas priming effects were unaffected by backward masks (the latter replicating Vorberg et al., 2003). This suppressive effect of forward masks was not systematically related to a reduction in prime visibility. Similar detrimental effects of forward masks have been shown before for color priming (Breitmeyer et al., 2004) and spatial priming effects (Deplancke et al., 2016). This study shows that the suppression effect extends to shape-priming. Furthermore, the suppression effect is moderated by the contour proximity of the forward mask, its duration, temporal delay to the prime, and the duration of the prime. Regarding prime visibility, the pattern was reversed: Prime visibility was strongly affected by the strength of backward masks whereas forward masks had less influence on prime visibility. These results support theories that posit differential effects of forward and backward masks on stimulus processing.

In previous studies, priming effects have been linked to feedforward activation of prime onsets (Lamme & Roelfsema, 2000; Schmidt et al., 2006), in accord with the notion that the first burst of spikes carries more information than sustained firing (Rolls & Tovee, 1994). Visibility on the other hand has been associated with late recurrent activity (Breitmeyer, 2014; Fahrenfort et al., 2007), or activity of stimulus offsets (Macknik & Martinez-Conde, 2007). As a plausible possibility, forward masks may specifically impair early stages of processing that are relevant for priming effects, whereas backward masks predominantly affect late stimulus activity. This explanation fits with single-cell studies showing diminished neuronal responses in early time windows when forward masks are applied (Judge et al., 1980; Kondo & Komatsu, 2000; Macknik & Livingstone, 1998), whereas backward masking is characterized by specific reductions of late activity (Bridgeman, 1980; Kondo & Komatsu, 2000; Lamme et al., 2002; Macknik & Livingstone, 1998; Schiller, 1968).

Masking effects of forward masks have been explained with lateral inhibition triggered by stimulus onsets and offsets (Macknik & Martinez-Conde, 2007) and sustained activity of the mask (Breitmeyer et al., 2006). These theories suggest the contour proximity and temporal delay of the forward mask may be important factors for the suppression effect. Regarding the contour proximity of forward masks, the suppression effect was indeed smaller for weak than strong masks with closely surrounding contours. Interestingly, the contour proximity of the forward masks plays a different role for the suppression of priming effects depending on the duration of the prime: With weak and strong forward masks, the slope of the priming effects across prime-target-SOAs was reduced, indicating that the processing rate of the prime is reduced by forward masks (Vorberg et al., 2003). While the processing rate was affected similarly for weak and strong forward masks when the prime was long (Experiment 4.2), strong masks additionally reduced the priming effects by a constant value across prime-target SOAs. This pattern may result from an additional effect of strong forward masks that works similar to delaying the processing of the prime. Such a delay of prime processing could also explain why priming was completely disrupted by strong forward masks when primes lasted only 13 ms. These results may indicate that contour proximity is one important variable for the suppression effect, but a contour-independent process might also be at work that affects priming effects similarly for weak and strong forward masks.

As another interesting aspect regarding the spatial layout of the masks, the comparison of paracontrast and pattern forward masks (Experiments 4.1 and 4.5, respectively) revealed that weak paracontrasts reduced priming effects more strongly than weak pattern masks. This is unlikely due to an inefficiency of weak pattern masks because the same weak patterns led to a substantial reduction of prime visibility when applied as backward masks. Since weak paracontrast masks resembled weak target arrows more than weak pattern masks did, this finding may indicate that a figural similarity between forward masks and targets contributes to the size of the suppression effect.

We also examined the temporal dynamics of the suppression effect. Provided that the suppression effect of forward masks is time-locked to onset or offset events of the forward masks, suppression should vary as a function of SOA or ISI, respectively. For example, optimal forward masking at SOAs of 10 ms (corresponding to an ISI of 0 ms) have been explained by a delayed surround suppression of classical receptive fields that is time-locked to the onset of forward masks (Breitmeyer et al., 2006). Alternatively, this effect could be explained by interferences associated with stimulus offsets in the framework of Macknik and Martinez-Conde (2007). The results of Experiment 4.3 suggest that two processes contribute to the suppression effect: First, the suppression effect decreased as a function of ISI, underlining the transient nature of the suppression effect. Second, the suppression effect was stronger when forward masks lasted longer. These findings cannot be reduced to the timing of stimulus on- and offsets alone. Instead, the duration of the forward masks directly determines the strength of the suppression effect. Neurophysiological findings show that the duration of a stimulus not only affects the time span that neurons fire, but also their response magnitude, discrimination probability and tuning (Keysers, Xiao, Földiák, & Perrett, 2001). Longer stimulus durations will lead to activations of more and different cell types: Brief stimulation due to saccades (Snodderly, Kagan, & Gur, 2001) or moving stimuli (Cleland, Dubin, & Levick, 1971) may suffice to activate transient, but not sustained cells in macaque V1 and cat’s retina and LGN, respectively. Finally, neuronal off-responses in visual cortex of cats have been shown to increase with longer stimulus durations (Duysens, Schaafsma, & Orban, 1996). All of these findings provide arguments why longer forward masks cause more activation and a stronger suppression of the prime. At the same time, they could also explain why priming effects benefit from longer prime durations (Experiment 4.1 vs. 4.2; but see Vorberg et al., 2003).

Long forward masks showed another interesting peculiarity because, contrary to short masks, they produced an additional prime suppression that increased with ISI. Priming effects were generally reduced when forward masks preceded the primes by short ISIs, but sufficiently long forward masks produced an additional dip in priming functions at around 20 ms ISI (Figure 4.5). In an additional exploratory study (Experiment 4.4), it appeared that this dip lasts only for a brief period, and is also present, though somewhat smaller, with intermediate masking durations. Data of individual subjects which showed a clear shape of this dip (eg., S1, S6 and S8 in Figure 4.7) indicate that the location of this second peak of suppression may be comparable across different durations of forward masks, but its peak varies between subjects in a range of 10 to 30 ms ISI. Such inter-individual variability will obscure the position and amplitude of local maxima when the data is averaged. So far, the origins of this second masking dip are not clear and may point to a delayed activation of forward mask that is only present for long forward masks.

The fact that the suppression effect responds to the duration and spatial layout of the forward masks and is strongest at short ISIs is compatible with the notion that the suppression effect is due to low-level interferences with early prime processing. As an alternative explanation for the suppression effects of forward masks, it might be argued that forward masks may not directly interfere with the initial response to the prime, but generally reduce the excitability of the system. Across Experiments 4.1 and 4.2, the impact of weak forward masks on priming effects is striking, given that weak forward masks were simply a pair of two-pixel vertical lines, with much space to the contours of the prime. The effects of such forward masks may be difficult to explain with low-level mechanisms such as contour-interactions between prime and forward mask, and suggest that forward masks reduce the responsiveness to the prime on a higher level, for example by invoking shifts of attention. But such attentional effects are difficult to align with the temporal dynamics of the suppression effect. Cuing effects demonstrate that preceding stimuli may capture attention even at very short SOAs (Nakayama & Mackeben, 1989; Seya, Tsutsui, Watanabe, & Kimura, 2012). However, cuing-effects increase up to an SOA of 100-150 ms (Nakayama & Mackeben, 1989; Posner, 1980; Seya et al., 2012), contrasting the effects of forward masks that decrease with SOA (Experiment 4.3). A similar objection can be raised against the attentional blink, a phenomenon that describes decreased processing of subsequent stimuli presented in rapid succession (Raymond, Shapiro, & Arnell, 1992). Raymond et al. (1992) observed that the attentional blink does not impair the first element after an attended target, unless an ISI of 90 ms is inserted. By contrast, the effects of forward masks clearly wane when an ISI is inserted after the prime. Mechanisms that cause a general reduction of cortical excitability, including attentional disengagement, should also predict marked reductions in stimulus visibility. However, prime visibility was only little impaired or even increased by some forward masks (Experiment 4.1 and 4.2). This opposes a role of the attentional blink that was shown to leave early visual potentials intact and only affect later activity associated with conscious perception (Sergent, Baillet, & Dehaene, 2005).

Together, our findings show that forward masks specifically interfere with processes underlying priming effects. Based on neurophysiological studies of forward masking, it is plausible that this interference is due to a reduction of early prime signals that are relevant for priming effects. Our data show that this suppression responds to the duration, temporal delay and contour proximity of forward masks. Future research should be aware that certain masking techniques, especially those including forward masks, may limit or abolish potential priming effects. A number of studies use forward masks to reduce the visibility of their stimuli. Our findings show that forward masks reduce processes underlying priming effects, which may lead to an underestimation of priming effects in studies using forward masks (e.g., de Wit & Kinoshita, 2015; Kouider & Dupoux, 2004) and affect comparisons of masked versus unmasked stimulus processing (e.g., Dehaene et al., 2001; Ulrich et al., 2013). On the other hand, the study of forward masks offers interesting possibilities to test current theories of stimulus processing, potentially offering a tool to selectively control early versus late processing stages.

5. General Discussion

5.1. Main results

The study of stimulus processing in the absence of awareness has inspired a variety of experimental designs, many of which involve visual masking techniques to reduce the visibility of the stimuli. Only recently, attention has been drawn to the fact that masks not only reduce conscious visibility of the masked stimuli, but also their effects on behavior and neurophysiology that have been used to index stimulus processing in the absence of awareness (Almeida et al., 2013; Breitmeyer, 2015; Faivre et al., 2012; Izatt et al., 2014; Peremen & Lamy, 2014; Wernicke, 2014). Here, we compared the effects of monoptic forward and backward masking, which are among the most frequently used masking techniques. We find that forward and backward masks have different effects on priming effects and visibility. Our main results are that (A) backward masks do not interfere with priming effects of shape, color or semantic contents of words, regardless of the spatial layout of the masks, and (B) forward masks strongly reduce priming effects. Even though backward masks did not interfere with priming effects, backward masks reduced the visibility of the primes. Forward masks also reduced the visibility of the prime, albeit to a lesser extent than backward masks.

In Chapter 2, we analyzed semantic and color priming effects when newly constructed metacontrast masks were used to reduce the stimulus visibility. The priming effects in both tasks were independent of the strength of the mask. In this way, priming effects with metacontrasts differ from conventional semantic studies using sandwich pattern masks in which priming effects typically depend on masking strength. To uncover possible reasons for this difference between metacontrast and sandwich pattern masks, we replicated our results using backward pattern masks instead of metacontrast masks (Chapter 3). In contrast to the metacontrast masks, pattern masks involve contour overlap of the prime and mask. Contour overlap between prime and target may produce conflicts at early levels in the visual hierarchy and therefore also reduce priming effects. However, semantic and color priming effects were again not moderated by the strength of the masks using backward pattern masks. We concluded that stimulus overlap of masks and primes is not relevant for priming effects using our stimulus timings. Combining both experiments, priming effects appear to be independent of backward masking regardless of the spatial layout of the mask. A second feature of sandwich pattern masks that are commonly used to mask lexical stimuli is that they include forward masks. Therefore, we analyzed the effects of forward masks in a final study (Chapter 4). Unlike backward masks, the effects of forward masks on priming effects are relatively unknown. We therefore decided to test the effects of forward masks first in a priming paradigm with basic perceptual features. To that end, we used a priming paradigm with oriented arrows which is renowned for its robust effects. It was found that forward masks exhibit a strong suppression of priming effects. This suppression of priming effects by forward masks is abbreviated as *suppression effect* in the following text. Although the suppression effect of forward masks was demonstrated only for priming of shapes, semantic and categorical priming effects are frequently reduced in paradigms that involve forward masks, suggesting that forward masks also account for commonly observed reductions of priming effects under masking in these tasks. To define possible processes underlying the suppression effect, we explored the characteristics of the suppression effect by manipulating the appearance, duration and temporal delay of the forward masks (Chapter 3). It was found that forward masks exert a transient suppression on priming effects that depends on the duration and contour proximity of the forward masks, and cannot be explained by reductions of prime visibility.

In the remainder of this chapter, the main findings will be summarized along central implications for the study of masked stimulus processing. After that, the theoretical implications of the suppression effect of forward masks will be discussed in more detail (Chapter 5.2). Possible limitations in our experiments that may limit the generalizability of our data will be addressed in Chapter 5.3. Finally, in Chapter 5.4 possible research directions will be outlined that result from the presented studies.

5.1.1. Semantic priming effects do not depend on visibility

Semantic priming effects in the LDT were studied in two experiments using metacontrast (Chapter 2) and backward pattern masks (Chapter 3). In both experiments, semantic priming effects were obtained. Even though the masks affected the visibility of the primes, they did not influence semantic priming effects. If semantic access to lexical stimuli is limited to consciously perceived words, reduced semantic priming would have been expected with strong masks that reduce stimulus visibility. However, no such reductions in semantic priming were observed in either experiment, indicating that semantic priming in the current experiments reflects semantic access that is independent of conscious processing.

The role of consciousness in semantic tasks has been debated, and while two meta-analyses on semantic priming effects identified a positive correlation of prime visibility and semantic priming effects (Van den Bussche et al., 2009; Wernicke, 2014), neither of these specifically analyzed priming in the LDT. Priming effects in the LDT reflect semantic access to the prime word and may thus differ from other semantic priming tasks. For example, commonly used semantic categorization tasks have been suspected to allow for a circumvention of elaborate semantic processing by applying learned response-rules to the target stimuli that are generalized to subliminal primes (Abrams et al., 2002; Klinger et al., 2000; Kunde et al., 2003). In this way, perceptual features of the prime may suffice to activate a set of pre-defined “action triggers” with no need for a full analysis of the prime’s semantic content (Kiesel et al., 2007; Kunde et al., 2003). While such mechanisms may contribute to explain subliminal priming effects in categorical priming tasks, they cannot explain priming in the LDT. Consequently, the LDT may be better suited than categorical tasks to assess the role of consciousness for the processing of semantic concepts. Experimental studies that vary the visibility of primes in the LDT typically observe a reduction of semantic priming effects when visibility is decreased (de Wit & Kinoshita, 2015; Kiefer, 2002; Ulrich et al., 2013), in accordance with the meta-analyses on categorical semantic priming reported above (Van den Bussche et al., 2009; Wernicke, 2014). However, the results of Chapters 2 and 3 demonstrate a successful dissociation of prime awareness and semantic priming effects in the LDT.

The current results allow conclusions about the role of consciousness for the semantic access to lexical stimuli: The masks reduced the chance of correctly identifying the prime words, but did not influence priming effects. This may imply that strategic mechanisms like expectancy generation and retrospective semantic matching that benefit from conscious awareness of the stimuli (Neely, 1991; Neely et al., 1989) do apparently not contribute to the semantic priming effects observed in our experiments. Rather, the priming effects in the current studies appear to reflect a process that operates independently of stimulus awareness. Together with previous experiments on subliminal semantic priming (reviewed in Chapter 2) these results support the notion that semantic processing does not require awareness of the primes. Although the parametric visibility manipulation that was pursued in the current studies has important advantages over subliminal priming studies with only one level of prime visibility, the current studies did not aim to create conditions of null visibility. Therefore, it cannot be ruled out that the emergence of semantic priming effects requires a minimum level of stimulus awareness. This possibility is further discussed in the “Limitations” section of this chapter (Chapter 5.3).

Because no influence of stimulus awareness on semantic priming effects was observed in the current experiments, the present data favor accounts that do not contain assumptions about the awareness of stimuli. In the past, spreading activation between semantic nodes and partial activation of distributed semantic representations have been proposed to explain subliminal semantic priming effects in the LDT (Kiefer, 2002; Neely, 1991; Ortells et al., 2016; Ulrich et al., 2013). Either of these accounts rests on the assumption that subliminal stimuli can successfully activate semantic concepts or features. One possibility is that high-level access to stimuli can be achieved via a first wave of feedforward processing that is able to reach virtually any area in the brain (van Gaal & Lamme, 2012), but does not by itself cause conscious awareness. This theory is compatible with the findings that the first reactions in a speeded categorization task are independent of masking, indicating that stimulus categorizations can be performed based on early prime activity that is not affected by masking (Schmidt et al., 2011; VanRullen, 2007; VanRullen & Koch, 2003). Similarly, the brain activation associated with stimuli whose visibility is experimentally reduced unfolds essentially unchanged for a time span of some 270 ms when visibility is reduced by visual masking or even longer when stimulus visibility is reduced by the attentional blink – a time span that may be sufficient for the extraction of semantic stimulus properties (reviewed in Dehaene, 2011). Van Gaal and Lamme (2012, p. 296) conclude that the range of the fast feedforward sweep is yet to be defined: “Indeed, it might be the case that the FFS [i.e., fast feedforward sweep] is able to trigger all (sub)cortical brain regions and thereby all possible cognitive functions supported by these regions”.

Assuming that semantic access of words can be conveyed by early prime activity that is independent of conscious awareness, why do the priming effects in many previous studies increase with visibility? Two complementary explanations come to mind: First, priming in visible conditions was increased in these studies because strategical processes that benefit from stimulus awareness added to the priming effects in visible conditions. These strategic mechanisms may have not viable in the current studies. As a second possibility, the experimental visibility manipulations in these studies may have been confounded with variables affecting priming effects.

Regarding the first possibility, strategic effects that benefit from conscious awareness may be absent in the current studies because we used relatively short SOAs and the experimental design did not favor strategical use of the prime. Controlled prime processing is thought to be slow (McNamara, 2005; Neely, 1991) and in line with this assumption priming effects underlying strategic prime processing increase with SOA between prime and target (de Groot, 1984; Ortells et al., 2003). In studies that use longer SOAs between prime and target than the 80 ms applied in the current experiments, additional consciously controlled processes may drive the priming effects. Apart from the timing, the present version of the LDT does also not favor controlled strategies because the prime is never predictive for the target. Based on the follow-up interviews that were held with the subjects after each session, it appears that subjects quickly decided to ignore the primes once they became aware of their presence. A similar point has been made by Bodner and Masson (2003), and whereas these authors speculate that active suppression of the prime may even counteract strategic use of primes and thereby reduce priming effects in visible conditions, no such reduction of priming effects is to be found in the current data. Finally, strategic retrieval of the prime may also be relevant when the target words are difficult to recognize (Yap et al., 2013), which was also not the case in the present studies. Together, these characteristics of the experimental design discourage strategical use of prime information that may have been responsible for elevated priming effects in visible conditions of previous studies.

Second, priming effects may have been reduced due to confounded variables if certain visual masking techniques interfere with both prime visibility and priming effects. Priming effects have also been elevated in visible conditions of experiments that used a similar task and temporal sequence of the stimuli as the current studies, so strategical mechanisms should have played a similar role in these studies and the current experiments. For example, Kiefer (2002) compared semantic priming in a masked version of the LDT with an unmasked control condition. He found that behavioral priming effects and the N400 component, a proposed correlate of spreading activation, are present under masking, but smaller than in an unmasked condition. Although Kiefer himself refrains from such an interpretation, one might erroneously deduce from this data that awareness is beneficial for semantic priming effects. For example, in a previous paper with similar design and results, Kiefer and Spitzer (2000, p. 2406) concluded that “the different time courses of ERP priming effects in the masked and unmasked conditions establish a qualitative change in the effects of conscious and unconscious processing”, thereby missing that these effects may be caused directly by their masks and independent of conscious awareness. Based on the current experiments, it is likely that their masking procedure itself interferes with behavioral priming and neurophysiological processing indices of the masked words. Kiefer (2002) vaguely hinted at this possibility by stating that the “relatively short prime duration may have temporally delayed and weakened the activation within semantic networks, particularly for the masked words” (p. 38). Armed with the knowledge that forward masks interfere with priming effects of perceptual stimulus features (Chapter 4), and backward metacontrast and pattern masks do not interfere with semantic priming in the LDT (Chapters 2 and 3), it seems very likely that the forward masks included in the studies by Kiefer (2002) and Kiefer and Spitzer (2000) also reduced the priming effects and neurophysiological correlates of prime processing. Other possibilities that cannot be excluded on the basis of the current experiments are that the inclusion of a backward mask before the onset of the target reduces the processing time of the prime. Alternatively, priming effects in the masked condition may have been reduced because the letter strings that these authors used as masks additionally interfere with priming effects, possibly because they function as some sort of neutral prime (see discussion of Chapter 3).

Direct effects of experimental manipulations on priming effects can also explain why priming effects often increase across different visibility-conditions, but at the same time not necessarily correlate with visibility when the semantic priming effects are regressed on individual visibility scores at the level of each condition (Draine & Greenwald, 1998; Kiefer, 2002; Kouider & Dehaene, 2009; Van den Bussche et al., 2010). Such regression analyses have been criticized, among other things, because they may not adequately correct for measurement error in the predictor variable (Miller, 2000). In the example of Kiefer (2002), additional caution is advised because prime visibility scores reached considerable negative values, which could either reflect measurement error or systematic misinterpretation of prime information by the subjects, turning true positive *d*' values into negative ones and thereby distorting the results of the regression (Klauer & Greenwald, 2000). Assuming that the regression estimates are essentially correct, these results support the interpretation that certain experimental variables that affect stimulus visibility can also affect priming effects, even though visibility is really unrelated to priming effects. The study of Kiefer (2002) was discussed due to its methodological similarities to the experiments reported in this thesis, but the same logic applies to other studies that compare priming effects across different conditions of prime visibility. Certain masks, including the commonly used sandwich masks, may lead to a systematic underestimation of priming effects and thus also account for failed attempts to show priming under masking (e.g., de Wit & Kinoshita, 2015; Izatt et al., 2014). In this way, the implementation of forward masks may also explain the results of previous studies claiming that priming effects depend on prime visibility. For example, in a study by

Kouider and Dupoux (2004), stroop priming effects of brief color words were obliterated when forward masks were added. Kouider and Dupoux concluded that priming is truly absent if visibility is rigorously controlled, and state that the priming effects observed in conditions without forward masks are really due to partial prime visibility. Perhaps, these authors would have come to a different conclusion if prime visibility was not confounded with the presence of forward masks. In this case, priming may have been independent of prime awareness. As an alternative, prime visibility may be manipulated by backward masks of different strength as was done in the current studies. Of course, complete masking of the primes by backward masks requires less prime energy in the first place, because primes are more difficult to mask without forward masks (some ideas to solve this dilemma will be discussed in section 5.4). Nevertheless, such an experiment may help to remedy possibly misguided conclusions regarding a causal role of visibility in categorical and semantic priming tasks.

Although the present results clearly show that semantic priming effects can be independent of visibility, thus indicating that semantic access can in principle occur without conscious control, these results do not imply that high-level semantic access to words is automatically triggered whenever words are processed under normal viewing conditions. Semantic processing of masked stimuli requires attention, unless the stimulus energy is high (Ansorge et al., 2014; Kouider & Dehaene, 2007; Van den Bussche et al., 2010) and depends on the active task set (Ansorge et al., 2014), which implies that stimuli are not by default processed up to semantic levels but semantic processing needs to be actively engaged. Instead, the current data demonstrate that masked words influence reactions to associated target words irrespective of prime visibility, indicating that a fast semantic access to masked words can in principle occur independent of consciousness.

5.1.2. Backward masks do not interfere with priming effects

Neither backward metacontrast (Chapter 2 and Chapter 4) nor backward pattern masks (Chapter 3 and Chapter 4) interfered with priming effects. This pattern of results was observed in a set of seven experiments that are reported in this thesis, across a range of three different priming tasks. The strength of masks was increased either by minimizing the contour proximity between masked stimuli and surround masks (paracontrast and metacontrast masks) or by increasing the amount of overlapping contours in the case of pattern masking. Although strong backward masks reduced the likelihood of successful discriminations of words, arrow orientations and font colors, they did not decrease priming effects compared to weaker masks. These result support previous findings that primes can influence behavior independent of conscious visibility (Schmidt, 2002; Schmidt et al., 2006; Vorberg et al., 2003), and extend these findings to semantic priming in the LDT. The current findings support theories of visual masking suggesting that backward masks selectively interfere with information processing underlying conscious awareness of the stimuli, but do not disturb information processing required for the access of perceptual and semantic stimulus properties (Chapter 1.3.3.1). However, an alternative interpretation is possible: Because backward masks were always presented simultaneously to the targets in the current experiments, possible interferences of masks were limited to processes that occur simultaneously to or after the time of target presentation. If the target by itself disrupts priming relevant processes, possible effects of masks on priming effects would be concealed (for a more detailed account of this interpretation, see the discussion sections in Chapters 2 and 3).

5.1.3. The suppression effect: Forward masks reduce priming effects

In a set of five experiments, we show that forward masks reduce priming of oriented arrows (Chapter 4). Although detrimental effects of forward masks on behavioral measures of stimulus processing have been shown before (Breitmeyer, Öğmen, et al., 2004; Deplancke et al., 2016) this is the first time that forward masks have been consistently shown to reduce priming of shapes. Breitmeyer et al. (2004) observed that colored paracontrast masks reduced color priming in two experiments, but shape priming was not affected under similar masking conditions. They concluded that their results “demonstrate that the information processing responsible for unconscious form priming during metacontrast masking is immune to the effects of paracontrast” (p. 155). This conclusion can be remedied based on the current data that clearly show a reduction of form priming effects through paracontrast masks – even down to complete annihilation of priming in Experiments 4.1 and 4.5 of Chapter 4. More than that, we mapped the time course of the suppression effect, and found that the impact of the forward masks depended both on the duration and the temporal delay of the forward masks (Experiments 4.3 and 4.4). Based on these data, it is unlikely that suppression effects of forward masks can be obtained with 10-ms-masks and an ISI of 80 ms between forward mask and prime as was intended by Breitmeyer and colleagues. In our study, the suppression effects of 10-ms forward masks ceased already after about 20 to 30 ms ISI. Interestingly, Breitmeyer and colleagues *did* observe an effect of colored paracontrast with an ISI of 90 ms, so the suppression effect of forward masks may behave different for the processing of colors.

The detrimental effect of forward masks on priming effects may have important implications for the study of masked processing and may help to explain divergent results in priming paradigms beyond priming of shapes. In priming paradigms that resort to the use of forward masks, including many categorical and semantic priming studies, priming effects normally decrease under masking (for an overview, see the introduction in Chapters 2 and 3).

Possible implications of this suppression effect have been exemplified for two semantic priming studies in a previous section of this chapter (Chapter 5.1.1). More than that, reduced priming in other masking paradigms such as CFS that also include forward masks may – at least in parts – also be explained by suppression due to forward masks (Faivre et al., 2012; Fogelson et al., 2014; Izatt et al., 2014; Peremen & Lamy, 2014). Knowledge about the suppression effect of forward masks may be helpful for masking studies in more than one way: First, it helps to avoid wrong conclusions regarding the role of visibility for stimulus processing when these conclusions build on comparisons in which the strength of the forward masks is not balanced (for an example, see the previous section 5.1.1). Second, it may help to get around false negative findings of masked stimulus processing that may have turned out differently if forward masks had been avoided. Of course, omitting forward masks is not always possible without increasing the visibility of the prime. Possible compromises will be discussed in section 5.4.

Third and finally, the suppression effect is by itself an interesting phenomenon that can be utilized to investigate the effects of forward masking. Based on the findings that have been collected so far, it can be assumed that the suppression effect is produced by more complex mechanisms than just lateral inhibition at spatial edges that have been proposed as mechanisms for forward masking (Enns, 2004; Hermens et al., 2008; Macknik & Martinez-Conde, 2007). Note that previous theories of forward masking were not based on effects of forward masks on priming effects, but prime visibility or neuronal activations. Still, masking theories propose general mechanisms of mask interference that may also explain the suppression of priming effects. Forward masking is strongest with close spatial distances between the mask and the prime contours (Macknik & Martinez-Conde, 2007), and no temporal delay (Alpern, 1953; Macknik & Martinez-Conde, 2007; Schiller, 1966; Schiller & Smith, 1965) or alternatively, very brief optimal delay between forward mask and prime

(Breitmeyer et al., 2006). By and large, the suppression effect showed a similar temporal course and was strongest at short ISIs and with close contour proximities of the forward mask. On the other hand, the interference of forward masks with priming effects diverged in a number of ways from its effect on visibility, suggesting that different mechanisms contribute to reductions of priming effects and prime visibility. The suppression effect also exhibits characteristics that are not covered by current forward masking theories. The suppression of priming effects was best described by the duration and ISI between forward mask and primes (Experiment 4.3). Previously, it has been argued that the effects of mask should be optimal at a specific ISI and SOA (Macknik & Martinez-Conde, 2007) which is not compatible with the temporal dynamics of the suppression effect. Because the suppression effect may be less prone to strategical use of prime information than prime visibility, it may be a more sensitive measure of prime processing than prime visibility. In this way, the suppression effect may be used to investigate the plausibility of masking mechanisms such as lateral inhibition that have been proposed for forward masking. The relation of priming effects and visibility under forward masking will be discussed in greater depth in the following Chapter 5.2.1. In addition, the suppression effect can be utilized to investigate the properties of early stimulus processes underlying priming effects. The suppression effect may provide a new way to dissociate prime visibility and priming effects and could thus be used to control early stimulus activity associated with priming effects. The potential of the suppression effect as a new tool to control specific stages of stimulus processing will be discussed in Chapter 5.2.2. In the final section of Chapter 5.2, an accumulator model of priming is used to describe the suppression of priming effects by forward masks (Chapter 5.2.3).

5.2. Implications of the suppression effect for theories of stimulus processing

It has been suggested that processes associated with conscious awareness involve different pathways (Breitmeyer, 2014) or stages of processing (Dehaene & Changeux, 2011; Lamme & Roelfsema, 2000) than nonconscious processes. A holistic understanding of stimulus processing requires knowing how the processing of conscious and nonconscious information is related (Dehaene, 2011; Tapia & Breitmeyer, 2011). In the current and the next chapter it will be discussed how the effects of forward masks on priming effects and visibility could be used to investigate these two processing modes. Therefore, the characteristics of the suppression effect that have been observed in Chapter 4 will be related to selected theories of forward masking (Chapter 5.2.1), theories of consciousness (5.2.2), and an accumulator model of priming (Chapter 5.2.3).

5.2.1. Implications of the suppression effect for theories of forward masking

Previous accounts of forward masking are based on studies that investigate the effects of masks on neurophysiological or psychophysical measures of stimulus processing. To what extent can the findings from these previous masking studies be generalized to explain the suppression effect?

Single-cell recordings suggest that forward masks disrupt an early part of the neuronal response to the masked stimulus (Judge et al., 1980; Kondo & Komatsu, 2000; Macknik & Livingstone, 1998). A disruption of early stimulus information could explain both reduced visibility and reduced priming effects when forward masks are being used. Both stimulus visibility (Breitmeyer & Öğmen, 2006; Macknik & Livingstone, 1998) and priming effects (Breitmeyer & Öğmen, 2006; Lamme & Roelfsema, 2000; Schmidt et al., 2006; VanRullen,

2007) have been related to an early phase of feedforward processing. It is therefore possible that masking mechanisms that have been proposed for the reduction of feedforward activity are also responsible for the suppression effect of priming effects.

Some findings argue against the view that a common process is responsible for the reduction of visibility and priming effects in forward masking. In Chapter 4, the influence of forward masks on priming effects and visibility was often not consistent, which led us to conclude that both processes are independent. This independence was evident in several ways: First, there were conditions in which the forward masks reduced priming effects, but not, or even positively, affected the visibility of the prime (weak forward masks in Experiments 4.1 and 4.2). Vice versa, there were conditions where the forward masks impacted on visibility, but only weakly on priming effects (strong forward masks versus weak forward masks in Experiment 4.2). In some cases, the effects of forward masks on visibility and priming effects can be completely dissociated. Individual performance of subjects in Experiment 4.4 indicate that priming effects were severely reduced at short ISIs between forward mask and prime, and progressively recovered at longer ISIs. Surprisingly, some subjects showed completely opposite visibility functions, being able to identify the primes at minimal ISIs between forward mask and prime, but less so at long ISIs where priming was intact. As a possible explanation, some subjects may have used perceptual strategies that relied on a merged percept of strong forward masks and primes and this percept was more likely at short ISIs.

These results suggest that forward masks affect visibility and priming effects differently. For example, positive effects of forward masks on visibility could be explained by interactions of the forward mask with the backward mask. The SOA-function of weak backward masks fits classical findings of type-B functions for masks with low masking energy (Kolers, 1962), replicating previous findings using these stimuli (Mattler & Palmer, 2012). The presence of forward masks abolished this characteristic type-B function that was present for weak metacontrast masks, thereby slightly increasing the visibility with weak forward masks. So one possibility is that weak forward masks did interfere with the processing of the prime, thereby reducing priming effects, but at the same time also interfered with the backward mask, thereby increasing prime visibility. Along this line, various explanations for independent effects of forward masks on priming effects and visibility are conceivable. This example also illustrates the complexity of comparing visibility and priming effects as measures of prime processing. Even in the case of a potential double dissociation of visibility and priming effects with weak masks, this does not exclude the possibility that masks affect both visibility and priming effects through a common mechanism like, for example, disruption of onset signals. The differences merely indicate that the two measures involve different information, and masking theories based on visibility data may be ill-suited to make predictions about the suppression effect.

Despite the aforementioned discrepancies between priming effects and visibility, there are also parallels between the results of previous masking studies and characteristics of the suppression effect. In Chapter 4, two processes were identified that contribute to the suppression effect of the forward mask: One process decreases exponentially with ISI between forward mask and prime, producing strongest suppression at short ISIs, and another process instead increases with ISI. As outlined in Chapter 4, the first of these processes may be caused by transients associated with the offset of the forward mask, explaining why this process is time-locked to the offset of forward masks independent of its duration. The second suppression process, on the other hand, seems to increase with ISI, suggesting that this ‘sustained’ suppression may operate with a certain delay.

Similar mechanisms have already been discussed in masking models. For example, in the RECOD model, paracontrast masking in short SOAs is explained by short-latency center-surround inhibition in the P-pathway, which is complemented by a slower cortical inhibition at longer SOAs (Breitmeyer et al., 2006; Breitmeyer & Öğmen, 2006). These two processes are reminiscent of the two processes that have been identified for the suppression effect in Chapter 4. However, the time course of the sustained forward masking effect has been modeled to peak at around 144 ms SOA (Breitmeyer & Öğmen, 2006, p. 191 f.). Therefore, this effect can probably not be equated with the sustained effect of long forward masks that appeared to peak at a rather brief ISI below 50 ms (Experiment 4.4). The transient forward masking effect on the other hand fits well with the transient process identified for the suppression effect. Considering that the authors linked priming effects to activation in the P-pathway, and forward masking occurs mainly as consequence of intra-channel inhibition in the P-pathway according to the RECOD-model, fast inhibition in this pathway could also explain why priming is reduced (Breitmeyer, 2014; Breitmeyer & Öğmen, 2006).

In another account of forward masking, Macknik and Livingstone (2007) assume that a unitary process is responsible for forward masking, namely, lateral inhibition at the spatio-temporal edges. Thus, these authors are able to explain why paracontrast masking is often strongest at short ISIs. Remarkably, their data also show that the peak of paracontrast masking shifts to larger ISIs when the forward mask is longer (Macknik & Livingstone, 1998; but see Macknik & Martinez-Conde, 2007, for a better description of this data). A very similar pattern has been observed for the ‘sustained’ part of the suppression effect: Long forward masks also seemed to exert additional suppression at longer ISIs. While the current experiments were not designed to examine such an effect at long ISIs, and more data is clearly needed, the dynamics of the suppression effect seem to bear an interesting parallel to the masking functions observed by Macknik and Livingstone (1998), raising the possibility that both measures may be affected by a common process. Unfortunately, the authors do not comment on the role of the duration of forward masks – possibly because this effect cannot be explained by inhibition at the spatio-temporal edges alone.

Although both theories of forward masking differ slightly in terms of their temporal predictions, they agree that lateral inhibition is a central mechanism of forward masking. However, lateral inhibition at the spatio-temporal edges as envisioned by Macknik and Martinez-Conde (2007) cannot fully account for the data. Such a mechanism implies, as explained by the authors, that a variation of the temporal or the spatial distance between prime and forward mask both affect a common process, namely, lateral inhibition. Based on the current data, it can be assumed that variations of the temporal and spatial distance tap into different processes. For example, in Experiment 4.2 strong forward masks with close contours considerably reduced the prime visibility, whereby weak forward masks did not. This is in line with Macknik and Livingstone (1998) who assume that forward masks reduce the onset activation of the prime and “there is something about the target’s onset that is important to its visibility” (p. 148). But the suppression of priming effects in this experiment was only somewhat larger for strong than weak forward masks. This indicates that contour proximity is not the determining factor for the suppression effect when the prime lasts at least 30 ms. However, a temporal delay between forward masks and primes in an otherwise identical experimental setup has a large impact on the suppression effect (Experiment 4.3). This does not fit well with the assumption that the spatial and temporal distance between prime and forward masks affects the same mechanism, namely, lateral inhibition at the spatio-temporal edges.

Although the considered theories of forward masking point to interesting parallels between the suppression effect and masking functions, including strong inhibition at short ISIs (Breitmeyer & Öğmen, 2006) or a shifted masking peak with long forward masks (Macknik & Martinez-Conde, 2007), the proposed mechanisms of forward masking cannot explain certain other characteristics of the suppression effect. Open questions include the different roles of contour proximity with short and long primes, as well as the role of the forward mask duration, which has not yet been addressed in previous theories. In addition, forward masks differentially affect priming effects and visibility in some conditions which requires additional assumptions. The suppression effect may help to extend existing masking theories by enabling a new window into the effects of forward masks on stimulus processing. The existing parallels between stimulus visibility, priming effects and the single-cell activations recorded by Macknik and Livingstone (1998) suggest that these measures may be influenced at least in part by a common mechanism.

5.2.2. Implications of the suppression effect for theories of consciousness

Theories of consciousness try to delimit processes that are associated with conscious perception from those that aren’t (Dehaene & Naccache, 2001). A recurring theme in these theories is that priming rests on early, feedforward activation that is potentially restricted to the ventral pathway, whereas visibility relies on recurrent activity in a later time window (e.g., Breitmeyer, 2014; Dehaene, 2011; Lamme & Roelfsema, 2000). This is an interesting working hypothesis and illustrates that priming can not only be used to define the processing limits of subliminal stimuli, but more, could be used to investigate specific stages or pathways of information processing. The results of Chapter 4 suggest that forward masks may be another way to experimentally isolate these processes, complementary to advances by previous studies using backward masks.

In the past, Vorberg et al. (2003) have shown that experimental manipulations of visibility using backward masks do not influence priming effects of arrows. Vorberg et al. (2003) proposed that priming effects in the arrow paradigm reflect processing in the ‘action system’ which is independent of processing in the ‘perception system’ underlying stimulus awareness. If priming in this paradigm generally reflects processing in an awareness-independent action system, priming of visible and invisible stimuli both index the same sort of ‘nonconscious processing’ in the action system. In this sense, processing in the perception and action system matches with the dichotomy of “Conscious and Nonconscious Processes” (title of Dehaene, 2011) discussed elsewhere. The current findings confirm that backward masks that are presented simultaneously with the target are well suited to compare processing in the action and perception system, to stay with the terminology of Vorberg et al. (2003), because backward masks do not interfere with the action system. Backward masks have been frequently used before to investigate properties of the perceptual system (e.g., Fahrenfort et al., 2007; Francken et al., 2011; Haynes et al., 2005; Lamme et al., 2002; Macknik & Livingstone, 1998; Schmidt et al., 2006; Vorberg et al., 2003). The data of Vorberg et al. (2003), and the current results with different types of backward masks and different priming tasks support the notion that backward masks can be used to selectively control processing in the ‘perception system’, while leaving different ‘action systems’ underlying perceptual and semantic priming undisturbed.

Here, we show that the reverse can be achieved with forward masks: Forward masks can be used to experimentally manipulate priming effects without systematically influencing prime visibility. Weak forward masks reduce early stimulus processing underlying priming effects, but less so (Chapter 4, Experiment 4.1 & 4.2), or even not at all (Experiment 4.2) reduce processes underlying conscious awareness. A similar dissociation can be achieved for individual subjects using only strong masks (Experiment 4.4). Therefore, weak forward masks provide a new way to dissociate priming effects and visibility.

These dissociations could, for example, be exploited to isolate neurophysiological correlates of early, stimulus driven processes that underlie priming, without measuring correlates of stimulus visibility: By adding a weak forward mask, controlling its temporal delay, or possibly increasing its contrast (cf., Izatt et al., 2014), the priming effects may be experimentally manipulated without affecting stimulus visibility. Manipulating priming effects with forward masks could be superior to manipulating priming effects by adapting the prime-target SOA, because even with complete masking, which is difficult to achieve, priming effects in a backward masking paradigm are still confounded with prime detection, i.e. the ability to detect the presence of the stimulus (Vorberg et al., 2003). Even though prime detection was not measured in the current experiments, it is not plausible that priming effects were confounded with prime detectability in the current studies, because the ability to detect a stimulus is unlikely to suffer while its discriminability is constant or increases. Thus forward masks could be a new way to control priming effects independent of stimulus visibility, including detection.

It has been argued that forward masks are another way to manipulate priming effects independent of visibility and this independence could be used to study the proposed dichotomy of an action and perception system outlined above. As a concluding note, it could be asked how such an independent action system could be realized according to the framework of current theories of consciousness.

The simplest solution for the differential effects of weak and strong forward masks on priming and visibility is a version of a dual channel model. For example, Breitmeyer (2014) proposed that priming is linked to feedforward activity in the ventral pathway, whereas stimulus visibility is linked to feedback activity in the ventral pathway. If backward masks only interfere with feedback activity, the feedforward-feedback dichotomy can explain why priming effects are independent of visibility in studies using backward masking (e.g., Vorberg, 2003). The effects of forward masks could also be explained in the framework proposed by Breitmeyer and Öğmen (Breitmeyer, 2014; Breitmeyer & Öğmen, 2006). For example, forward masks could interfere with the feedforward activity in both the ventral and the dorsal stream. In the RECOD model, interferences of forward masks with both ventral and dorsal activity have been modeled (Breitmeyer & Öğmen, 2006). Interferences with the ventral stream activity could thereby explain reduced priming effects. Because activations in the dorsal pathway indirectly also contribute to ventral feedback activity (Breitmeyer, 2014), forward masks that disturb activations in the dorsal pathway may interfere with visibility in a mere feedforward-way without necessarily reducing priming effects. The reduction of stimulus processing in these two channels could depend on different characteristics of the forward masks. In this way, a dual channel explanation is one way to account for the considerably strong reductions of prime visibility for strong but not weak forward masks, even though priming effects are similarly affected. At the same time, this explanation is compatible with the general notion that forward masks reduce visibility by reducing feedforward activation and priming effects reflect feedforward activation in the ventral pathway.

In the framework of the GNW theory (Dehaene & Changeux, 2011; Dehaene & Naccache, 2001), a similar proposition can be made. Dehaene (2011) proposes that processing in the absence of consciousness can be viewed as evidence accumulation within multiple local networks across the brain. Again, these networks can be engaged by feedforward processing of stimulus information. Only when the information in these local networks is linked via a global fronto-parietal network, conscious access to the processed stimuli is granted. This notion emphasizes the dynamic nature of prime processing over time and may explain why information that is sampled at different time points – early in the case of priming and late during the discrimination task – can reveal different results. Strong forward masks may interfere with prime visibility in this framework either by interfering with a late stage of access or by interfering with prime information in another localized network that is relevant for prime visibility but not priming effects. This latter possibility corresponds to a modified version of a dual channel model.

Theories of Breitmeyer (2014), Dehaene (2011) and others discuss in what way nonconscious processes underlying priming effects may differ from those that are associated with conscious perception of stimuli. The suppression effect of the forward masks provides new possibilities two control these processes, and may thus serve as an additional tool to contrast the properties of the two processing modes.

5.2.3. Implications of the suppression effect for accumulation models of priming

Vorberg et al. (2003) explained how priming effects can be modeled by an ongoing accumulation process of sensory information that is first fed by the prime and then by the target. In Chapter 4, it was observed that forward masks reduced the slope of priming effects across prime-target SOAs (henceforth only "slope of priming effects"), conceivably because forward masks reduce the accumulation rate of prime information. However, the spatial layout of the forward masks had different effects on priming depending on the duration of the prime and this difference cannot easily be explained by a reduced processing rate of the prime. In this section, it will be outlined how evidence accumulation processes of existing models of priming could be used to describe the detailed effects of forward masks on priming effects (primarily relating to the accumulation model proposed by Vorberg et al., 2003). Clearly, the following is just one possible perspective and solely intended to explore one possible (post-hoc) interpretation of the data.

Reaction times in a motor priming paradigm can be modeled as a decision process by a central decision unit that collects evidence in favor of the response alternatives and triggers motor reactions when a certain response threshold is reached (Dehaene 2011, Vorberg et al., 2003). Priming occurs because evidence in favor of the response associated with the prime is collected as soon as the prime is presented. This evidence sums up until the target is presented and the accumulated evidence at the time of the target presentation provides a new starting point for the accumulation process of the target evidence. In line with the portrayed theories of fast feedforward categorizations, most – though not all – of this evidence may be carried by the very first neuronal responses elicited by the prime. This general interpretation is compatible with the fact that stimulus duration of prime and target are not included in the model by Vorberg et al. (2003), and accumulation continues after stimulus offsets, which suggests that that the accumulation process can viewed as continuous sampling of buffered sensory prime information, similar to the model by Dehaene (2011).

Because prime evidence in this model constantly accumulates across SOA, priming effects increase for larger SOAs between prime and target. The slope of priming effects is not constant, but depends on the amount of available evidence. With the parameters used in the study by Vorberg et al. (2003), the slope was about 1. However, the slope of priming effects can also be smaller or larger than 1, probably depending on the energy of the prime (e.g., in Experiment 4.2, the rate was about 1.3; see Mattler & Palmer, 2012, for different examples). Because the priming effect depended on the duration of the prime in the current experiments, it is assumed that most, but not all evidence is transported by the first spikes of the prime. Note that the accumulation rate of prime and target was assumed to be equal in the model by Vorberg et al. (2003), so this version of the model is not designed to address such changes of prime accumulation rate.

How do the effects of forward masks fit into an accumulator model of priming? In the model by Vorberg et al. (2003), priming effects are independent of the rate of the accumulators. The slope of the priming effect does instead depend on a decay parameter v that determines the ‘forgetting rate’ of the accumulators. However, their model rests on the assumption that the accumulation rate of the prime and target is equal. Once this assumption is avoided, the difference between processing rates of prime and target also influences the slope of priming effects. An according two-stage accumulator model is currently developed by Schmidt and Schmidt (2018).

One possibility is that when a forward mask is inserted, this forward mask reduces the available evidence for the prime. Thus, the processing rate of the prime is reduced, resulting in a flatter slope of priming effects. In Experiments 4.1 and 4.2, the rate was reduced by approximately 50% with weak forward masks. Similar to weak forward masks, reduced priming slopes were also present with strong forward masks, except that strong forward masks produced an additional strong suppression with brief 13 ms primes but only a small additional suppression when primes lasted 30 ms. Here, the priming effects with strong forward masks were consistently reduced by about 10 ms when compared with the weak forward masks (at short SOAs priming effects cannot be reduced below zero). Importantly, this difference did not increase linearly with SOA, but appeared to be constant across the long SOAs. As a tentative explanation, strong forward masks may have exerted an additional strong suppression on the first spikes of the primes. If the prime is short, this will completely block the prime’s onset response, and no evidence is available for the priming effects (and probably, awareness of the primes, see Experiment 4.1). If the prime is sufficiently long, the prime activation can recover and the same amount of evidence will be available as for weak forward masks. However, this recovery process takes a brief moment while the initial prime response is still suppressed and the accumulation process will be delayed for the appropriate duration. Functionally, such a process would be equal to reducing the SOA between prime and target.

Summing up, different processes have been discussed that may contribute to the suppression effect of forward masks: A duration-dependent delayed suppression, and an ISI-dependent transient process, that – hypothetically – splits into a contour-dependent process that affects the available time of prime processing and a contour-independent process that affects the rate of prime processing. An implementation of the results of Chapter 4 in the framework of a modified version of the accumulator model proposed by Vorberg et al. (2003) could provide potential explanations (i) why the accumulation rate is generally lower with forward masks (because prime evidence is reduced), (ii) why the prime-rate depends on the duration of the prime (because prime evidence ramps up in a brief time window), (iii) and why the rate with weak and strong forward masks is identical for long primes, but priming effects are reduced by a constant with strong forward masks (because the evidence-sampling process is delayed with strong forward masks). The model makes the strong assumption that the evidence available to the accumulator is identical with weak and strong forward masks after a short buffer time, but the visibility is particularly reduced under strong forward masks. Another open issue is the suppression effect of forward masks in other priming paradigms than the response priming paradigm reported in this thesis. Since similar effects have been reported before in a color priming (Breitmeyer, Öğmen, et al., 2004) and a spatial priming paradigm (Deplancke et al., 2016), and semantic priming effects are reduced by sandwich masks which involve forward masks (Wernicke, 2014), it seems reasonable that forward masks also interfere with stimulus processing in other tasks. As indicated by the findings of Breitmeyer et al. (2004), forward masks may interfere with prime processing according to a different temporal dynamic in other tasks. Some of these open questions, along with predictions derived from this working model, could be further tested with experiments that are outlined in section 5.4 of the discussion.

5.3. Limitations

5.3.1. Is semantic priming possible without awareness of stimuli?

In the previous chapters, it was argued that semantic and perceptual priming effects do not depend on prime visibility, based on the fact that priming effects were not moderated by the experimentally controlled strength of backward masks. Generally, this finding is compatible with the notion that semantic priming is also possible under null visibility, i.e., when no task-relevant features are available. Here, visibility of task relevant features was defined as the ability to classify the prime as either word or nonword. Although the current data favor the prediction that processing of semantic content does not require awareness of task relevant prime features, there are important limitations for this interpretation.

The prime visibility was never zero in the reported experiments and some residual stimulus awareness was present for most participants even with the strong masks. It is possible that priming effects afford a certain minimal prime visibility and do not change unless visibility is lower than this minimal level. Even the strongest masks might not have been enough to reach this level. Of course, this possibility is equally important for studies that employ only one masking condition. Such studies are vulnerable to residual visibility of task-relevant features during the experiment and require deliberate methodological care to exclude stimulus awareness (Dienes, 2015; Holender, 1986; Kouider & Dehaene, 2007; Schmidt & Vorberg, 2006; Shanks, 2017). In comparison, a parametric variation of visibility has certain advantages: Because a parametric variation of visibility does only require that the different masking strengths permit a different level of prime visibility, it avoids the difficult requirement of null visibility.

A generalization of the present findings to null levels of stimulus awareness requires that priming effects and prime awareness are related linearly when averaging across trials. This is not completely implausible if one assumes that strong masks have a higher chance that participants missed critical prime features in at least some of the trials. For example, assume that strong masks had a higher probability of occluding some prime letters than weak masks. With each occluded letter, subjects have a higher chance of failing the word-nonword decision required in the visibility session. If priming relied on the conscious reconstruction of words, priming effects should be reduced if more letters are occluded, and the difficulty of word reconstruction is increased. With this assumption, a parametric variation of visibility should provide good evidence of whether priming is tied to the recognizability of word parts or letters that allow for the reconstruction of words.

However, this interpretation is limited in cases where the visibility task is more sensitive to partial occlusion of prime words than the priming effect. Returning to the previous example, the occlusion of a single letter may prevent that subjects can any longer solve the visibility task. For example, the perceived letters *hone?* might correspond to *honey*, or *honed*, which are words, or to *honer* or any other pseudoword. In either case, the letters *hone* might still be sufficient to include the prime word *honey* in a set of consciously expected prime words and thus prime the target *bee*. In this case, the mask decreases the subjects' chance of passing the visibility test, but not the chance of observing priming effects, even though the priming effects are solely due to a conscious encoding of the prime. Note that such a criticism would be equally valid for null visibility in the present task (see Kouider & Dupoux, 2004, for a similar case). In principle, this is an example of a mismatch between the priming and visibility task, because both tasks refer to different features (Schmidt & Vorberg, 2006). However, such a mismatch is difficult to avoid in the LDT, and the visibility task employed in the present studies is widely accepted in the literature of the LDT (e.g., Kiefer, 2002). This criticism rests on the assumption that the visibility task (indicating the lexicality of the prime) is more difficult than guessing possible prime words that may aid priming effects. This may be a strong assumption considering that the words and pseudowords typically differed by more than one letter in the current studies, so the performance in the visibility task does not so much depend on single letters and it may be equally difficult to assess the lexicality and identity of prime words. Whether both tasks are comparable is ultimately an empirical question.

Another possible, diametrical objection to the parametric visibility variation that was pursued in this thesis refers to differences between the task requirements in the priming and the identification session. Since the prime was never predictive for the target, the subjects may either have not noticed the primes in the priming task because they were attending to the target, or even purposely have ignored the primes if they were perceived as distracting. Therefore, it may be objected that the visibility of the prime was equally low across masks for the duration of the priming session, and the parametric visibility manipulation was not really effective. Consequently, it would be not surprising that the priming effects did not differ between masks. In the identification task, where the subjects had to attend to the prime, they were able to exploit the evidence of the primes optimally, which leads to an overall high prime visibility, especially with the weak masks. Contrary to this hypothesis, it can be inferred that subjects noticed the prime at least in part of the priming trials, presumably those with weak masks, based on the follow-up interviews held after each session. Further, a systematic overestimation of prime visibility should not undermine the conclusion that priming is independent of prime awareness.

All in all, although the present data show that priming effects are intact in conditions when prime identifications are reduced by masking, the present experiments were not designed to investigate prime processing under null visibility, but identify the role of different masks for priming effects. By showing that priming effects do not depend on the strength of masks, the present data disprove a common observation in the literature and provide a new foundation to study the role of prime visibility for semantic priming effects. A direct relation of priming effects and prime visibility in the current studies is difficult owing to limitations of the visibility task. However, each visibility task comes with its own limitations and a comprehensive picture of the relation of priming effects and awareness probably requires more than one visibility task.

5.3.2. No semantic priming at the short SOA?

The present results were ambiguous with regard to the role of the SOA for semantic priming effects. We tested two SOAs (40 and 80 ms) between prime and target/mask. According to a Bayesian analysis of semantic priming effects, the data in both semantic priming studies (Experiment 2.2 and 3.2) did not allow a clear statement whether priming effects increased with SOA. Because a significant effect of SOA could affect the interpretation of the results, and a significant three-way interaction was present in Experiment 3.2 indicating that the priming effect interacted with SOA and masking strength, additional analyses were performed in Experiment 3.2 with the goal to test semantic priming at each SOA. When the data were split according to SOA, a significant priming effect was only obtained at the long SOA, in line with numerically larger priming effects at the long SOA (11 vs. 4 ms at the short SOA). A similar pattern of results is obtained when the data of the metacontrast and pattern masking experiment are combined in a joint analysis (12 vs. 4 ms semantic priming effect in the long and short SOA, respectively). This pattern of results is not optimal for the purpose of the present experiments because it indicates that semantic priming effects are overall very small and noisy, and semantic priming effects may be especially small or even absent at the short SOA. Because the effects of the masks on prime visibility were strongest at the short SOA, the fact that priming effects are difficult to determine at the short SOA makes it more difficult to interpret the results. In a worst case scenario, priming effects were insensitive to masking only because (i) at long SOAs, the masks were not effective (in reducing prime visibility) and (ii) at short SOAs, a floor effect of priming prevented a moderation of priming effects by the masks. This worst case scenario can be remedied at least in part based on the current data: First, the masks were always effective in reducing stimulus visibility, including at the long SOA. However, it is not clear how rather small differences in masking can be interpreted with regard to the efficacy of the mask, which makes this point a version of the objection discussed in the previous section 5.3.1. Second, priming effects were numerically positive in the short SOAs, and Bayes ANOVAs indicate that more evidence is needed to conclude about the presence of priming effects. Overall, the evidence for priming effects is much better than for a moderating effect of SOA, so it may be overly cautious to adjust interpretations at this time point. Third, regarding the relation of priming effects and masks, priming effects were not sorted according to masking strength in a meaningful order, neither at the short nor at the long SOA. This is consistent with findings obtained in the perceptual task that showed robust priming also in the short SOA. The Bayes analyses provided in the appendices of each chapter revealed that based on the given data, substantial evidence is available that an effect of prime congruency is present and not moderated by the masking strength. These analyses contradict a possible objection that the non-significant interaction of priming effects and masking strength is merely due to lack of power.

In closing, small semantic priming effects at short SOAs may limit the interpretability of the current findings. In the current thesis, the obtained results were carefully scrutinized, and effort was taken to identify all possible implications of our findings. What can be concluded is that the evidence for semantic priming effects is generally larger than evidence in favor of mediating effects of SOA or the strength of the mask. As with every non-significant effect it cannot be concluded that non-significant effects are absent, but only that these effects are probably not meaningful since they are too small to be detected in typical experiments. Bayesian analyses that are capable of identifying evidence in favor of the null indicate that overall strong evidence is present to reject an influence of the strength of the masks on semantic priming across both SOAs, but more data would be needed to maintain this claim for each of the two SOAs separately.

5.4. Open Questions

While the main implications have been summarized in the previous section 5.1., what are open questions and possible research directions that arise from the present data? First, the present results support the assumption that semantic concepts can be activated independently of stimulus awareness. This assumption is anchored in current theories of consciousness (see Chapter 1.2.4) and semantic processing (Kiefer & Pulvermüller, 2012). The parametric variation of prime visibility that was pursued in the present studies is an important supplement to subliminal priming studies because it does not rest on the strong assumption of null visibility. In the future, the combination of both approaches could be desirable by including even stronger masking conditions. However, it may be difficult to create total masking without reducing the prime energy below a required minimum, or resorting to masking techniques that distort the priming effects. A few ideas to solve this dilemma will be addressed alongside the following paragraphs.

Second, the present results indicate that backward masks that are presented simultaneously with the target do not interfere with semantic and perceptual priming effects. Interestingly, this pattern was observed both with surrounding and overlapping backward masks. Based on these results, backward masks are well suited to investigate stimulus processing when visibility is reduced. Unfortunately, the effect of backward masks on stimulus visibility decreases with larger delays between prime and mask that favor perceptual and, possibly, semantic priming effects, limiting potential areas of application. One solution may be to present interposed masks immediately after the prime. These backward masks would strongly affect prime visibility, whereas the delayed presentation of the target may create sufficient time for prime processing. The influence of interposed masks between prime and target has not yet been covered by the current studies. Interposed masks can sometimes produce negative priming effects, especially in priming of perceptual features (Mattler, 2006; Sumner, 2007). Nevertheless, interposed masks have frequently been used in categorical and semantic priming studies that yield positive priming effects. Therefore, it could be an interesting next step to investigate the effects of interposed masks on categorical or semantic priming in a three-stimulus-paradigm where the mask is inserted in between the prime and target. Such an experiment has important implications for many studies of semantic priming that employ three-stimulus-paradigms. Furthermore, as has been discussed in the previous chapters, priming effects may have been immune to masking in the current studies because backward masks that are presented together with the target may come too late to affect interactions between prime and target. However, this need not be the case when the mask is presented before the target. In such a case it is still conceivable that priming effects are disturbed by subsequent masks. More so, this interference may also depend on the spatial layout of the masks (for reasons detailed in Chapter 3) and the SOA between prime and mask. Finally, if interposed masks should turn out not to interfere with semantic priming effects, such a three-stimulus-paradigm may be a valuable tool for future parametric visibility variations, combining the benefits of little prime suppression with strong masking.

Third, we show that forward masks lead to a remarkable suppression of shape priming effects. A comparison with the literature (e.g., Wernicke, 2014) suggests that this finding is not restricted to priming of shapes, but may explain reduced priming in a number of paradigms that employ forward masks. This finding has important implications. For one, it raises the possibility that previous findings implementing forward masks unintentionally reduced indirect measures of prime processing (e.g., de Wit & Kinoshita, 2015; Kouider & Dupoux, 2004). A replication of these findings without forward masks may reveal completely different results. To validate the generalization of the suppression effect in semantic priming paradigms, a direct comparison of categorical and semantic priming could be attempted using different strengths of forward masks. Generally, the type of forward mask that is being used is another interesting issue that has only briefly been touched in the present studies. In Chapter 4, we show that strong pattern forward masks have the same strong impact on brief primes than paracontrasts do, whereas weak patterns that apparently produce reduce stimulus visibility when applied as backward masks do not interfere with priming effects when applied as forward masks. These findings are just the beginning of an in-depth study of the effects regarding the spatial layout of forward masks.

In this context, it is of interest whether the suppression by the forward masks is located at precortical or cortical levels, which would help to narrow down responsible mechanisms of the suppression effect. This could most directly be achieved by comparing the suppression effect of forward masks in a dichoptic and a monoptic masking paradigm[3]. If the suppression of priming effects ceases when forward masks are presented to a different eye than the prime, it can be concluded that the suppression effects is to be located at precortical processing levels. A different approach to pinpoint the locus of the suppression effect is by varying the appearance of the forward mask to find out if and how the suppression effect depends on contour proximity and, especially when using words as primes, whether the suppression effect depends on a similar appearance or content of prime and mask. If forward masks that share features with the prime or target stimuli exert additional suppression, this would not only help to understand the mechanisms of the suppression effect, but also have implications for numerous semantic and categorical priming studies that use strings as forward masks.

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[3] This idea has been developed together with Bruno Breitmeyer when discussing the present findings.

Fourth, we are just beginning to understand the complex characteristics of the suppression effect. Understanding the suppression effect will not only guide a competent use of forward masks as a tool to reduce stimulus awareness, but is also valuable in its own right. The exploration of priming-effects under masking provides a new window into the interplay of brief stimuli, yielding insights into processes underlying priming effects and visual awareness. For example, it has been discussed how processes underlying priming effects and awareness are related (see Chapters 1.2.4 and 5.2.2). This question could be further explored in a dual task paradigm. In a dual task paradigm, subjects have to judge the visibility of the prime after each trial of the priming task. Such a procedure avoids differences in attention between the priming and the identification task, which may facilitate a comparison of these measures (e.g., Izatt et al., 2014). It also, however, invites other problems such as task interference. With semantic or categorical tasks, it has been reported that when subjects are explicitly instructed to process the prime semantically, semantic priming effects can also invert, though probably only at comparably long SOAs (reviewed in Ansorge et al., 2014).

In Chapter 4, two potential processes have been identified that shape the temporal dynamics of the suppression effect. These findings can be expanded in several ways: First, it is of interest whether the same two processes can be identified for weak forward masks. A comparison of weak and strong forward masks will also help to identify contour-dependent mechanisms that may contribute to the two processes. Second, it was hypothesized that with long primes, strong forward masks have a similar impact on the prime than weak forward masks do, but strong forward masks additionally delay prime processing by about 10 ms (Chapter 5.2.3). This is a strong prediction that can be tested easily by comparing priming effects with weak and strong forward masks at longer prime-target SOAs than those that have been tested so far. If the previous prediction is correct, priming effects with strong forward masks should be lower by about 10 ms independent of SOA. Third, a duration-dependent effect has been identified that seems to increase with ISI. This effect can be further explored by examining the effects of long forward masks with longer ISIs than 20 ms. According to an exploratory analysis of single subjects (Experiment 4.4), this additional suppression at intermediate ISIs seems to be relatively brief and pointed. Moreover, if this effect is shifted for different people, as indicated by these data, averaging is not a good way to locate the peak and size of this effect. In Chapter 4, possible neurophysiological causes have been discussed as to why long forward masks exert a stronger suppression than short forward masks. In psychophysiological terms, long forward masks have larger stimulus energy than short forward masks. According to Bloch's law, luminance information is accumulated over time and the perceived intensity is defined as the product of presentation time and intensity. If the suppression effect is solely defined by the energy of the forward mask, a contrast reduction of forward mask should yield the same results as shorter forward masks, which would contradict a specific role of stimulus onset or offset events[4].

Finally, the temporal dynamics of the forward masks suggest that forward masks can still be used as a masking tool in priming paradigms without disturbing priming effects if certain conditions are met. The suppression effect wears off at larger ISIs, especially for short forward masks. However, forward masks are still efficient in masking stimuli at intermediate ISIs (Macknik & Martinez-Conde, 2007) and long ISIs (see Experiment 4.4) even with very brief forward masks (Breitmeyer et al., 2007). If forward masks reduce stimulus visibility in a time window when the suppression effect is not active anymore, forward masks may thus still be a viable tool to decrease visibility without compromising priming effects. This creates exciting new avenues for the study of subliminal stimulus processing, and will ideally enable researchers to use forward and backward masks as efficient tools to reduce stimulus awareness while keeping interference of masks with priming effects at a minimum.

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[4] This idea has also been developed together with Bruno Breitmeyer when discussing the present findings.

5.5. Outlook and Conclusion

The current results have implications for three related branches of research: Research on masked priming investigating how processing unfolds in the absence of conscious perception, masking theories that describe how masks interfere with the processing of masked stimuli, and third, theories of consciousness that aim to identify functions of stimulus processing and neurophysiological activations that are unique to consciously processed stimuli.

First, investigating the effects of visual masks on priming effects has important implications for research on subliminal priming. Even though Marcel's (1983) original experiments may have methodological flaws (Holender, 1986), our results altogether support the interpretation of Marcel (1983) and others (see Chapter 1.3.4 and 1.4) that priming effects depend on the masking technique that is used to reduce prime visibility. While Marcel concluded that subliminal semantic priming is only possible under central (dichoptic backward structure masking), but not peripheral masking (monoptic backward noise masking), the present results provide a more detailed view of the effects of visual masks on priming, showing that the spatial layout of the backward masks is less important than the order of stimulus presentation. As pointed out by Holender and Duscherer (2004), it is important to know whether and how masks interfere with priming effects because else, researchers would "be licensed to degrade the stimulus by any means, which is pretty much what most researchers do, anyway" (p. 873). Our results show that the choice of masking technique does indeed affect priming effects and allow clear recommendations on which and how masks should be used to investigate priming. Whereas backward metacontrast and pattern masks do not interfere with perceptual and semantic priming effects, forward masks reduce perceptual priming effects and may also account for reduced semantic priming effects under sandwich masking that is observed in the literature. Our experiments suggest that the effect of forward masks on priming effects are transient, and may be avoided if forward masks last brief and are presented with a certain delay to the prime. However, the temporal dynamics of forward masks have not yet been investigated in a semantic priming paradigm, so this assumption is yet to be confirmed empirically.

Besides the practical implications for the priming literature, the current results can be embedded in priming theories along two alternative lines of argumentation. Across a range of different masks and tasks, backward masks never interfered with priming effects. Two possible interpretations emerge: First, backward masks never interfere with priming because they interfere with a late stage of processing that is not relevant for priming effects (recurrent processing has been discussed as a candidate, see below). This possibility is in line with previous theories of priming stating that priming effects depend on an early fast feedforward sweep that evades interference by after-coming masks (Schmidt et al., 2006, 2011; VanRullen, 2007), but may be reduced by forward masks (Breitmeyer, Öğmen, et al., 2004). As a possible exception to this rule, masks that are presented very briefly after the onset of the prime may still be able to interfere with feedforward sweep of the prime (Bacon-Macé et al., 2005; Schmidt et al., 2006). Nevertheless, no such interferences of backward masks were observed in the current studies.

As an alternative interpretation for our findings, backwards may indeed interfere with priming-relevant processes even if they are presented with a delay after the prime. However, interferences by backward masks may be irrelevant as long as the mask is presented simultaneously to the target. This possibility would apply if prime and target are processed serially and the target replaces the ongoing processing of the prime. In this case, potential effects of masks on priming effects would be concealed because the prime processing is terminated by the target anyway. Corresponding models have been proposed for response priming of perceptual features (Schmidt, 2002; Schmidt et al., 2006; Vorberg et al., 2003), but theories are less consistent when it comes to semantic priming. If one assumes that semantic priming is independent of masking because the target replaces the processing the prime, our findings indicate that non-serial semantic priming mechanisms such as post-lexical matching did either not contribute to semantic priming effects or were not affected by masking. The possibility that backward masks do not interfere with processes underlying priming effects and the possibility that interferences by the target stimuli conceal such effects of backward masks on priming effects cannot be discerned based on the current data, and their underlying assumptions are also not mutually exclusive. To obtain a complete picture of the effects of masking in semantic priming paradigms and to distinguish the two possible interpretations of the current data, the current results could be replicated in a three-stimulus paradigm.

We also varied the SOA between primes and targets, which can provide additional insight into the processes underlying priming. Priming of perceptual features increased linearly with SOA between prime and target, which fits into accumulator models of priming that assume that priming relevant processes are time-locked to the onset of the prime and disrupted by the processing of the target (Schmidt, 2002; Schmidt et al., 2006; Vorberg et al., 2003). Still, current versions of this accumulator model do not cover the effect of prime duration on the suppression effect and slope of priming across SOA, providing new starting points for accumulation models of priming that allow for a free estimation of the rate of primes and targets (e.g., Schmidt & Schmidt, 2018). Furthermore, the fact that priming of shapes depended on the duration of the prime and the suppression effect also interacts with the duration of the prime underscores the dynamic effects of prime processing time. The rate of prime processing appears to be variable, suggesting that the prime is not encoded as a momentary event but rather dynamically over a critical time span.

Although the role of SOA for semantic priming was unclear, the data hinted at a similar effect of SOA in the semantic task. Masked priming effects that increase with SOA would be theoretically interesting, as they suggest a variant of evidence accumulation over time that does not depend on conscious strategies. A similar effect has already been implemented in models of semantic priming, albeit on larger timescales (Lerner et al., 2012; Plaut, 1995). The role of prime-target and prime-mask SOAs in semantic priming paradigms did not receive much attention in the past, especially in the short time windows that are commonly employed in masked semantic priming studies and may be worthy of systematic exploration.

Summarizing the main implication of the current results for theories of priming, the effects of visual masks on priming effects can be successfully integrated into existing models of prime processing. Even though priming in perceptual and semantic tasks probably involves very different mechanisms, both tasks showed a similar pattern: Priming effects in both tasks was independent of masks presented simultaneously with the target, which indicates that processes relevant for priming are either completed or disrupted by the time the target is presented, and that simultaneous masks no longer have any possibilities to disturb these processes. Because prime awareness is affected by backward masks, but priming effects are not, both of these interpretations suggest that an early stage of feature extraction underlying priming effects is not affected by prime awareness.

The current results fit well with previous masking theories that distinguish between an early stage of stimulus processing that is reduced by forward masks (Breitmeyer, Öğmen, et al., 2004; Kondo & Komatsu, 2000; Macknik & Livingstone, 1998) and a late, possibly recurrent, phase that is affected by backward masks (Breitmeyer, 2014; Haynes et al., 2005; Lamme & Roelfsema, 2000; Macknik & Livingstone, 1998). On the other hand, our results are difficult to reconcile with theories that propose a peripheral locus of pattern masking due to integration of mask and prime stimuli at early processing levels (Breitmeyer & Öğmen, 2006; Enns, 2004). If integration is responsible for backward pattern masking, the question arises why priming effects are not affected by such integration at early levels of visual processing (Experiments 3.1, 3.2, and 4.5). However, because masks and targets were always presented simultaneously, the current studies only analyzed the effects of masks on prime processing that occurs after the target is processed. Different results may be obtained in a three-stimulus paradigm where masks are inserted before the target, so the possibility of functional differences between overlapping and surround masks should not yet be discarded. The relevance of investigating such effects becomes particularly clear when considering the broad variety of interposed masks that are used in current lexical priming studies.

The finding that forward masks reduce priming of perceptual features and this suppression effect depends on the ISI between prime and forward mask, its duration and its contour proximity provide new material for theories of forward masking. Considering priming effects as measures of stimulus processing creates new avenues to investigate the effects of masking on stimulus processing, especially since priming effects are a hitherto rarely used measure to determine the effects of masks. In line with findings of visibility reductions by forward masks (Breitmeyer et al., 2006, 2007; Macknik & Martinez-Conde, 2007), it has been shown that the suppression effect depends on the duration and temporal delay of forward masks. On the other hand, our results reveal different effects of forward masks on priming effects and visibility. These differences may be confusing because both priming effects and visibility reductions under forward masking have been linked to onset activation of the primes, suggesting a common mechanism of visibility and priming reductions by forward masks (Breitmeyer & Öğmen, 2006; Macknik & Livingstone, 1998; Macknik & Martinez-Conde, 2007). The divergent effect of forward masks on visibility and priming effects calls for a general theory of stimulus processing under forward masking that can explain both effects. For example, one possible solution that adheres to reductions of early stimulus processing as common cause for reduced priming effects and visibility postulates feedforward activity in multiple processing channels (Chapter 5.2): Whereas activity in one channel is sufficient for priming, activity in another channel is important for stimulus visibility. If both channels are differentially affected by experimental variables such as contour proximity, it is possible to explain why contour proximity affects priming effects to a lesser extent than prime visibility (Chapter 4). Alternatively, it could be speculated that weak and strong forward masks have a comparable effect on early activation underlying priming effects, but strong masks additionally influence sustained activations that are relevant for prime visibility. In this case, priming effects and visibility are dissociated not because they rely on different processing channels, but rather, different processing stages. Even though a general theory of stimulus processing under forward masking is pending, the results of the current thesis generally concur with masking theories that posit differential effects of forward and backward masks on early and late stimulus activity, respectively.

Finally, the current results provide evidence that the processing of complex features such as meaning of words can be dissociated from consciousness. Semantic priming effects that are independent of consciousness could be explained by automatic prime-processing mechanisms like spreading activation or part-activations of distributed memory patterns that have been previously used to explain semantic priming when the processing of the prime is limited by brief prime-target SOAs (de Groot, 1984; McNamara, 2005) and reduced visibility due to masking (Kiefer, 2002; Ulrich et al., 2013). The possibility that semantic concepts can be activated independent of consciousness is compatible with current theories of consciousness suggesting that a feedforward phase of information processing can reach large parts of the brain independent of conscious awareness (Lamme, 2015; Lamme & Roelfsema, 2000; Schmidt et al., 2006; van Gaal & Lamme, 2012; VanRullen, 2007; VanRullen & Koch, 2003). It has been suggested that this feedforward processing activates local networks that can operate without becoming part of an awareness-associated global network (Dehaene, 2011; Dehaene & Naccache, 2001; Oizumi et al., 2014). Although early neuronal feedforward activity may be sufficient to analyze complex features, a conscious perception of stimuli appears to require an additional sustained phase of stimulus processing that can be disturbed by subsequent backward masks. As a potential merit of such delayed access to stimulus features, Dehaene (2011) has argued that by pooling evidence over time and across multiple parallel local processing networks, the system is less susceptible to errors that should inevitably arise when performing multistep calculations in noisy environments like the brain. According to Dehaene (2011), pooling of evidence in order to form a coherent interpretation of the signal, and then distributing this interpretation back to the local processing units, may be a core function of the "conscious workspace" (p. 163).

Visual masking is a useful tool to reduce the awareness of stimuli. Yet, it is largely unknown whether masks also affect processing levels underlying priming. We show that the effects of masks on stimulus processing depend on the order of stimulus presentation: Whereas priming of perceptual features was strongly reduced by forward masks, backward masks did not reduce priming effects, neither of perceptual features nor of semantic word contents. This finding is consistent with previous reports that forward masks interfere with stimulus processing at a very early stage of processing, which has been linked to priming effects, whereas backward masks interfere with a later stage of information processing that has been linked to stimulus visibility. The contrastive effect of forward and backward masks helps to put previous research on masked processing into perspective, drawing attention to the fact that specific masks like forward masks may have limited the behavioral and neurophysiological effects in a great number of studies. Knowing the effects of masks on priming effects has practical implications for future masking studies: An informed use of forward masks will help to avoid false negative results of unconscious stimulus processing, and creates new opportunities to purposefully target specific processing stages underlying priming effects. Finally, the antagonism of forward and backward masks is in good agreement with neurophysiological theories that conscious extraction of stimulus features depends on a complex, relatively time-consuming process, whereas priming effects demonstrate that these same features are available early on and deeply processed.

6. References

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Appendix A

Appendix A contains the Bayesian Analyses and conventional ANOVA tables of the results of Chapter 2.

Results based on Bayesian Analysis – Experiment 2.1 (Color Priming)

Bayesian within-subject ANOVAs were performed using the BayesFactor package in R (Morey & Rouder, 2015; Rouder et al., 2017). Bayesian modeling allows to quantify evidence in favor of the alternative or null hypothesis and is thus superior to classical inferential statistics that only tests for evidence against the null (Dienes, 2015). All tested models include random intercepts for participants. In the RT and error analysis, the null and all alternative models include main effects of SOA, Mask, and an interaction between SOA and Mask. These factors may by themselves influence RTs, but are not theoretically important for the congruency effects studied in this experiment and are therefore by default included in the null model. Models that include interactions of a factor are tested against a model that includes the main effect of this factor, unless reported otherwise. Our verbal descriptions of the Bayes factors were adopted from Jeffreys (1961).

RTs. A JZS Bayes factor ANOVA (Rouder et al., 2017) with default prior scales revealed that the congruency model was preferred to the null model by a Bayes factor (BF) of 2.0×10^{69}. There was strong evidence that the priming effects were not moderated by the masking strength (*BF* = 15.8 in favor of the Congruency-only model against a model that also includes an interaction of Congruency and Masking Strength). Decisive evidence was found in favor of an interaction of Congruency and SOA (*BF* = 1.9×10^{26}), mirroring increased priming effects in the long (*PE* = 73 ms) versus short SOA (*PE* = 27 ms).

Errors. Priming effects for errors paralleled the priming effects for the reaction times. Errors were fewer in congruent (3%) than in incongruent trials (11%), as confirmed by a large Bayes factor in favor of the Congruency over the null model ($BF = 1.1 \text{ x } 10^{50}$). There was strong evidence that the priming effects were not moderated by the masking strength ($BF = 13.9$ against a model with an interaction between Congruency and Masking Strength). Similar to the priming effects in RTs, priming effects rose with SOA ($BF = 6.2 \text{ x } 10^{16}$ in favor of a model with interaction between Congruency and SOA).

Visibility. A Bayes factor ANOVA with wide prior scales ($r = .707$) revealed decisive evidence that visibility was influenced by the masking strength, SOA and an interaction between masking strength and SOA ($BF = 1.1 \text{ x } 10^{16}$ against the null model with only subjects). The best model was preferable to a model without the interaction by a Bayes Factor of 370. The interaction of masking strength and SOA indicated that the slope of the visibility functions differed across masks. To see whether masks also affected prime visibility at the late SOA, a subsequent analysis was performed including only the 80-ms-SOA, revealing less, but still very strong evidence for an effect of the masking strength ($BF = 45.9$).

Results based on Bayesian Analysis – Experiment 2.2 (Semantic Priming)

RTs. The Bayes factor ANOVA revealed that the Congruency model was preferred to the null model by a Bayes factor of 36.1. The Congruency model had the largest Bayes factor among the compared models. There was substantial evidence that the priming effects were not moderated by the masking strength ($BF = 8.6$ against a model with interaction between Congruency and Masking Strength). The evidence was not clear as to whether the priming effects interacted with SOA ($BF = 1.2$ against a model with interaction between Congruency and SOA).

Errors. Priming effects for errors pointed in the same direction as the priming effects for the reaction times. Errors were fewer in congruent than in incongruent trials, as indicated by substantial evidence for the Congruency model over the null model (*BF* = 3.9). There was substantial evidence that priming effects for errors did not increase with masking strength (*BF* = 6.7 in favor of the model without an interaction), or SOA (*BF* = 3.1 in favor of the model without an interaction).

Visibility. Bayes factors indicate decisive evidence that visibility was influenced by the Masking Strength, SOA and an interaction between Masking Strength and SOA (*BF* = 1.4×10^{14} against the null model with only subjects). The best model was preferable to a model without the interaction by a Bayes Factor of 275. These results confirm that the masks successfully reduced the visibility of the prime (*d'* for the weak, medium and strong masks was 1.9, 1.3 and 1.2, respectively). Prime visibility was higher in the long SOA (mean *d'* of 1.8 versus 1.1). The interaction of masking strength and SOA indicated that the slope of the visibility functions differed across masks. To see whether masks also affected prime visibility at the late SOA, a subsequent analysis was performed including only the 80ms-SOA, revealing weak evidence for an effect of the masking strength (*BF* = 2.7).

Appendix A

ANOVA tables of the results of Chapter 2

When necessary, *p*-values are based on Greenhouse-Geisser corrected degrees of freedom.

Table 2.1

ANOVA Table – RTs in Experiment 2.1

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	31122458.7	193186	2416.51	5.43E-18	.993	.99
Congruency	1	15	119512.0	13238	135.42	6.57E-09	.352	.90
Mask	2	30	64.1	2514	0.38	6.86E-01	.000	.02
SOA	1	15	1160.7	1236	14.08	1.92E-03	.005	.48
Congruency : Mask	2	30	89.6	2443	0.55	5.83E-01	.000	.04
Congruency : SOA	1	15	24572.7	3497	105.41	3.53E-08	.101	.88
Mask : SOA	2	30	61.1	1530	0.60	5.56E-01	.000	.04
Congruency : Mask : SOA	2	30	134.9	2033	1.00	3.82E-01	.001	.06

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared.*

Table 2.2

ANOVA Table – Errors in Experiment 2.1

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_p^2
(Intercept)	1	15	10.992	0.600	274.62	4.72E-11	.904	.95
Congruency	1	15	1.315	0.175	112.43	2.30E-08	.529	.88
Mask	2	30	0.002	0.072	0.50	6.09E-01	.002	.03
SOA	1	15	0.166	0.037	67.50	6.19E-07	.124	.82
Congruency : Mask	2	30	0.003	0.081	0.53	5.96E-01	.002	.03
Congruency : SOA	1	15	0.294	0.087	50.77	3.48E-06	.201	.77
Mask : SOA	2	30	0.012	0.063	2.85	7.38E-02	.010	.16
Congruency : Mask : SOA	2	30	0.003	0.055	0.75	4.80E-01	.002	.05

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared.*

Table 2.3

ANOVA Table – d' in Experiment 2.1

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_p^2
(Intercept)	1	15	508.577	92.752	82.25	1.78E-07	.820	.85
Mask	2	30	23.602	8.408	42.11	3.07E-07	.175	.74
SOA	1	15	17.603	5.892	44.82	7.17E-06	.136	.75
Mask : SOA	2	30	5.635	4.425	19.10	4.46E-06	.048	.56

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared.*

Table 2.4

ANOVA Table – d' in Experiment 2.1 (only SOA = 80 ms)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	357.708	54.054	99.26	5.25E-08	.859	.87
Mask	2	30	3.093	4.858	9.55	6.17E-04	.050	.39

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 2.5

ANOVA Table – RTs in Experiment 2.2

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	53474047.3	323656	2478.28	4.50E-18	.993	.99
Congruency	1	15	3542.6	4154	12.79	2.75E-03	.009	.46
Mask	2	30	134.2	8564	0.24	7.92E-01	.000	.02
SOA	1	15	188.2	7696	0.37	5.54E-01	.001	.02
Congruency : Mask	2	30	169.4	6711	0.38	6.88E-01	.000	.02
Congruency : SOA	1	15	957.8	4205	3.42	8.44E-02	.003	.19
Mask:SOA	2	30	444.3	8097	0.82	4.49E-01	.001	.05
Congruency : Mask : SOA	2	30	1360.9	9889	2.06	1.64E-01	.004	.12

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 2.6

ANOVA Table – Errors in Experiment 2.2

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	13.254	0.970	204.86	3.76E-10	.849	.93
Congruency	1	15	0.056	0.264	3.20	9.39E-02	.023	.18
Mask	2	30	0.003	0.216	0.22	8.06E-01	.001	.01
SOA	1	15	0.000	0.193	0.00	9.47E-01	.000	.00
Congruency : Mask	2	30	0.010	0.168	0.86	4.32E-01	.004	.05
Congruency : SOA	1	15	0.007	0.148	0.74	4.03E-01	.003	.05
Mask : SOA	2	30	0.004	0.227	0.29	7.52E-01	.002	.02
Congruency : Mask : SOA	2	30	0.013	0.173	1.14	3.33E-01	.006	.07

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared.*

Table 2.7

ANOVA Table – d' in Experiment 2.2

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	203.423	42.336	72.10	4.11E-07	.790	.83
Mask	2	30	9.850	6.018	24.60	2.10E-05	.154	.62
SOA	1	15	11.104	1.630	102.20	4.34E-08	.171	.87
Mask : SOA	2	30	3.339	3.956	12.70	1.03E-04	.058	.46

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared.*

Table 2.8

ANOVA Table – d' in Experiment 2.2 (only SOA = 80 ms)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	154.7916	22.598	102.75	4.18E-08	.859	.87
Mask	2	30	0.8988	2.884	4.68	1.71E-02	.034	.24

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Appendix B

Appendix B contains the Bayesian Analyses and conventional ANOVA tables of the results of Chapter 3.

Results based on Bayesian Analysis – Experiment 3.1 (Color Priming)

RTs. A JZS Bayes factor ANOVA (Rouder et al., 2017) with default prior scales revealed that the congruency model was preferred to the null model by a Bayes factor of 2.6×10^{33}. There was substantial evidence that the priming effects were not moderated by the masking strength (*BF* = 7.8 in favor of the Congruency-only model against a model that also includes an interaction of Congruency and Masking Strength). Decisive evidence was found in favor of an interaction of Congruency and SOA (*BF* = 1.3×10^{16}).

Errors. Error priming effects were confirmed by a large Bayes factor in favor of the Congruency model over the null model (*BF* = 2.6×10^{33}). There was substantial evidence that the priming effects were not moderated by the masking strength (*BF* = 7.8 against a model with an interaction between Congruency and Masking Strength). Similar to the priming effects in RTs, priming effects rose with SOA (*BF* = 1.3×10^{16} in favor of a model with interaction between Congruency and SOA).

Visibility. A Bayes factor ANOVA with wide prior scales ($r = .707$) revealed decisive evidence that visibility was influenced by the masking strength and SOA (*BF* = 9.8×10^{4} against the null model with only subjects). The best model was preferable to a model with an interaction between SOA and Masking Strength by a Bayes Factor of 3.2, indicating substantial evidence against an interaction.

Results based on Bayesian Analysis – Experiment 3.2 (Semantic Priming)

RTs. The Bayes factor ANOVA revealed that the Congruency model was preferred to the null model by a Bayes factor of 11.5. The Congruency model had the largest Bayes factor among the compared models. There was substantial evidence that the priming effects were not moderated by the masking strength (*BF* = 6.9 against a model with interaction between Congruency and Masking Strength). The evidence was not clear as to whether the priming effects interacted with SOA (*BF* = 1.7 against a model with interaction between Congruency and SOA). The evidence was also inconclusive with regard to the three-way interaction (*BF* = 0.8 in favor of a model that includes both two-way interactions but no three-way interaction).

Errors. The Bayes analysis indicates that the data are inconclusive with regard to error priming effects (*BF* = 0.5 in favor of a model that includes Congruency).

Visibility. Bayes factors indicate decisive evidence that visibility was influenced by the Masking Strength, SOA and an interaction between Masking Strength and SOA (*BF* = 6.7×10^{13} against the null model with only subjects). The best model was preferable to a model without the interaction by a Bayes Factor of 12.4. To see whether masks also affected prime visibility at the late SOA, a subsequent analysis was performed including only the 80-ms-SOA, revealing substantial evidence for an effect of the masking strength (*BF* = 8.5).

ANOVA tables of the results of Chapter 3

When necessary, *p*-values are based on Greenhouse-Geisser corrected degrees of freedom.

Table 3.1

ANOVA Table – RTs in Experiment 3.1

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	33136709.0	320712	1549.83	1.48E-16	.990	.99
Congruency	1	15	64102.9	12846	74.85	3.24E-07	.155	.83
Mask	2	30	1651.0	3467	7.14	2.90E-03	.005	.32
SOA	1	15	938.0	2450	5.74	3.00E-02	.003	.28
Congruency : Mask	2	30	395.2	2562	2.31	1.16E-01	.001	.13
Congruency : SOA	1	15	17012.5	3179	80.28	2.08E-07	.046	.84
Mask : SOA	2	30	38.7	1874	0.31	7.36E-01	.020	.00
Congruency : Mask : SOA	2	30	25.9	2578	0.15	8.61E-01	.010	.00

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 3.2

ANOVA Table – Errors in Experiment 3.1

Effect	DFn	DFd	SSn	SSd	F	p	η_G^2	η_P^2
(Intercept)	1	15	15.296	1.258	182.38	8.47E-10	.895	.92
Congruency	1	15	0.817	0.195	62.85	9.63E-07	.314	.81
Mask	2	30	0.059	0.074	12.07	1.43E-04	.032	.45
SOA	1	15	0.130	0.022	87.42	1.20E-07	.068	.85
Congruency : Mask	2	30	0.008	0.079	1.60	2.18E-01	.005	.10
Congruency : SOA	1	15	0.294	0.065	67.58	6.15E-07	.141	.82
Mask : SOA	2	30	0.022	0.059	5.52	9.09E-03	.012	.27
Congruency : Mask : SOA	2	30	0.006	0.036	2.40	1.08E-01	.003	.14

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 3.3

ANOVA Table – d' in Experiment 3.1

Effect	DFn	DFd	SSn	SSd	F	p	η_G^2	η_P^2
(Intercept)	1	15	44.731	47.781	14.04	1.94E-03	.426	.48
Mask	2	30	3.831	7.250	7.93	8.98E-03	.060	.35
SOA	1	15	3.616	2.882	18.82	5.85E-04	.057	.56
Mask : SOA	2	30	0.506	2.310	3.29	5.13E-02	.008	.18

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 3.4

ANOVA Table – d' in Experiment 3.1 (only SOA = 80 ms)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	36.8919	30.967	17.87	7.31E-04	.524	.54
Mask	2	30	0.7968	2.517	4.75	3.13E-02	.023	.24

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 3.5

ANOVA Table – RTs in Experiment 3.2

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	52925292.7	570041	1392.67	3.28E-16	.988	.99
Congruency	1	15	2782.4	4681	8.92	9.23E-03	.004	.37
Mask	2	30	69.8	6187	0.17	8.45E-01	.000	.01
SOA	1	15	637.7	7366	1.30	2.72E-01	.001	.08
Congruency : Mask	2	30	314.6	10766	0.44	6.49E-01	.001	.03
Congruency : SOA	1	15	680.7	7511	1.36	2.62E-01	.001	.08
Mask : SOA	2	30	121.1	7913	0.23	7.96E-01	.000	.02
Congruency : Mask : SOA	2	30	1288.4	4869	3.97	2.96E-02	.002	.21

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 3.6

ANOVA Table – RTs in Experiment 3.2 (only SOA = 40 ms)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	26646678.6	280898	1422.94	2.80E-16	.989	.99
Congruency	1	15	355.34	7492	0.71	4.12E-01	.001	.05
Mask	2	30	98.84	5486	0.27	7.65E-01	.000	.02
Congruency : Mask	2	30	727.03	8086	1.35	2.75E-01	.002	.08

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 3.7

ANOVA Table – RTs in Experiment 3.2 (only SOA = 80 ms)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	26279251.8	296509	1329.43	4.63E-16	.988	.99
Congruency	1	15	3107.74	4701	9.92	6.62E-03	.010	.40
Mask	2	30	92.01	8614	0.16	8.53E-01	.000	.01
Congruency : Mask	2	30	875.89	7549	1.74	1.93E-01	.003	.10

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 3.8

ANOVA Table – Errors in Experiment 3.2

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	12.244	0.392	468.67	9.98E-13	.867	.97
Congruency	1	15	0.020	0.153	1.96	1.82E-01	.011	.12
Mask	2	30	0.023	0.266	1.27	2.94E-01	.012	.08
SOA	1	15	0.001	0.122	0.07	7.94E-01	.000	.00
Congruency : Mask	2	30	0.005	0.347	0.23	7.95E-01	.003	.02
Congruency : SOA	1	15	0.000	0.165	0.02	8.90E-01	.000	.00
Mask : SOA	2	30	0.014	0.309	0.66	5.27E-01	.007	.04
Congruency : Mask : SOA	2	30	0.004	0.122	0.47	6.30E-01	.002	.03

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 3.9

ANOVA Table – d' in Experiment 3.2

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	199.811	80.124	37.41	1.97E-05	.690	.71
Mask	2	30	7.799	6.223	18.80	1.09E-04	.080	.56
SOA	1	15	9.845	1.547	95.47	6.77E-08	.099	.86
Mask : SOA	2	30	1.640	1.822	13.50	6.03E-04	.018	.47

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Table 3.10

ANOVA Table – d' in Experiment 3.2 (only SOA = 80 ms)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
(Intercept)	1	15	149.181	43.579	51.35	3.25E-06	.764	.77
Mask	2	30	1.143	2.626	6.53	4.42E-03	.024	.30

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared.*

Appendix C

This appendix contains ANOVA tables of the main results of Chapter 4. When necessary, *p*-values are based on Greenhouse-Geisser corrected degrees of freedom.

Table 4.1

ANOVA Table – RTs in Experiment 4.1

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	13	57957564.2	216903	3473.66	3.57E-17	.996	1.00
Congruency	1	13	85847	3451	323.35	1.45E-10	.247	.96
M-Type	1	13	35960	4017	116.38	7.41E-08	.121	.90
M-Strength	1	13	1773.5	1329	17.35	1.11E-03	.007	.57
SOA	3	39	1513.6	4459	4.41	9.15E-03	.006	.25
Congruency : M-Type	1	13	27180.5	3365	105.02	1.35E-07	.094	.89
Congruency : M-Strength	1	13	3356.2	1377	31.68	8.23E-05	.013	.71
M-Type : M-Strength	1	13	291.5	1022	3.71	7.63E-02	.001	.22
Congruency : SOA	3	39	41899.4	6187	88.04	2.05E-17	.138	.87
M-Type : SOA	3	39	446.6	3551	1.64	1.97E-01	.002	.11
M-Strength : SOA	3	39	126.5	3552	0.46	7.10E-01	.000	.03
Congruency : M-Type : M-Strength	1	13	2716.7	2187	16.15	1.46E-03	.010	.55
Congruency : M-Type : SOA	3	39	18388.6	3408	70.14	9.03E-16	.066	.84
Congruency : M-Strength : SOA	3	39	354.8	2683	1.72	1.79E-01	.001	.12
M-Type : M-Strength : SOA	3	39	767.2	1565	6.37	1.28E-03	.003	.33
Congruency : M-Type : M-Strength : SOA	3	39	1331.4	2028	8.53	1.76E-04	.005	.40

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared; M-Strength = Masking Strength; M-Type = Masking Type*

Appendix C

Table 4.2

ANOVA Table – Errors in Experiment 4.1

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	13	16.412593	2.31523	92.16	2.88E-07	.739	.88
Congruency	1	13	1.923181	0.20424	122.41	5.50E-08	.249	.90
M-Type	1	13	0.766318	0.65914	15.11	1.87E-03	.117	.54
M-Strength	1	13	0.022541	0.08397	3.49	8.44E-02	.004	.21
SOA	3	39	1.987646	0.45715	56.52	2.91E-14	.255	.81
Congruency : M-Type	1	13	0.796759	0.14891	69.56	1.41E-06	.121	.84
Congruency : M-Strength	1	13	0.088621	0.10364	11.12	5.38E-03	.015	.46
M-Type : M-Strength	1	13	0.003278	0.05386	0.79	3.90E-01	.001	.06
Congruency : SOA	3	39	1.212251	0.26566	59.32	1.35E-14	.173	.82
M-Type : SOA	3	39	0.153516	0.21907	9.11	1.07E-04	.026	.41
M-Strength : SOA	3	39	0.003914	0.20717	0.25	8.64E-01	.001	.02
Congruency : M-Type : M-Strength	1	13	0.032615	0.09586	4.42	5.55E-02	.006	.25
Congruency : M-Type : SOA	3	39	0.458164	0.27273	21.84	1.83E-08	.073	.63
Congruency : M-Strength : SOA	3	39	0.039928	0.26608	1.95	1.37E-01	.007	.13
M-Type : M-Strength : SOA	3	39	0.039917	0.18761	2.77	5.46E-02	.007	.18
Congruency : M-Type : M-Strength : SOA	3	39	0.039061	0.25356	2.00	1.29E-01	.007	.13

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared; M-Strength = Masking Strength; M-Type = Masking Type*

Table 4.3

ANOVA Table – Visibility in Experiment 4.1

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	13	691.5851	37.384	240.50	9.15E-10	.865	.95
M-Type	1	13	2.5244	10.455	3.14	9.99E-02	.023	.19
M-Strength	1	13	590.0693	31.828	241.01	9.03E-10	.845	.95
SOA	3	39	1.0288	8.388	1.60	2.06E-01	.009	.11
M-Type : M-Strength	1	13	5.9671	4.219	18.38	8.83E-04	.052	.59
M-Type : SOA	3	39	0.5824	4.66	1.63	1.99E-01	.005	.11
M-Strength : SOA	3	39	9.3814	6.419	19.00	9.35E-08	.080	.59
M-Type : M-Strength : SOA	3	39	6.9448	4.575	19.73	5.20E-06	.060	.60

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared; M-Strength = Masking Strength; M-Type = Masking Type*

Table 4.4

ANOVA Table – RTs in Experiment 4.2

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	13	77819548	442226	2287.64	5.32E-16	.993	.99
Congruency	1	13	231598.223	22975	131.05	3.67E-08	.300	.91
Postmask	1	13	8589.41346	3352	33.31	6.47E-05	.016	.72
Premask	2	26	43371.7292	4887	115.38	1.18E-13	.074	.90
SOA	3	39	3494.80816	10453	4.35	3.62E-02	.006	.25
Congruency : Postmask	1	13	0.01439	2073	0.00	9.93E-01	.000	.00
Congruency : Premask	2	26	32151.6284	3932	106.31	3.05E-13	.056	.89
Postmask : Premask	2	26	177.18865	1939	1.19	3.21E-01	.000	.08
Congruency : SOA	3	39	92887.1199	9140	132.12	7.53E-11	.146	.91
Postmask : SOA	3	39	1231.17373	4109	3.90	1.58E-02	.002	.23
Premask : SOA	6	78	1378.98725	8044	2.23	4.89E-02	.003	.15
Congruency : Postmask : Premask	2	26	150.70322	2423	0.81	4.56E-01	.000	.06
Congruency : Postmask : SOA	3	39	488.85236	2657	2.39	8.32E-02	.001	.16
Congruency : Premask : SOA	6	78	8057.91351	9598	10.91	8.60E-09	.015	.46
Postmask : Premask : SOA	6	78	804.67052	7525	1.39	2.61E-01	.001	.10
Congruency : Postmask : Premask : SOA	6	78	1036.37006	6249	2.16	5.62E-02	.002	.14

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared; Postmask = Strength of the Backward Mask; Premask = Strength of the Forward Mask*

Table 4.5

ANOVA Table – RTs in Experiment 4.2 (only weak and strong forward masks)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	13	50164949.8	297169	2194.52	6.97E-16	.993	.99
Congruency	1	13	84928.07	13859	79.66	6.62E-07	.190	.86
Postmask	1	13	5319.45	2909	23.77	3.03E-04	.014	.65
Premask	1	13	146.95	2234	0.86	3.72E-01	.000	.06
SOA	3	39	3039.56	9642	4.10	3.28E-02	.008	.24
Congruency : Postmask	1	13	21.84	2109	0.13	7.20E-01	.000	.01
Congruency : Premask	1	13	1237.6	1594	10.09	7.29E-03	.003	.44
Postmask : Premask	1	13	154.71	1183	1.70	2.15E-01	.000	.12
Congruency : SOA	3	39	40302.7	7615	68.80	5.78E-09	.100	.84
Postmask : SOA	3	39	736.44	3989	2.40	8.25E-02	.002	.16
Premask : SOA	3	39	195.98	3317	0.77	5.19E-01	.001	.06
Congruency : Postmask : Premask	1	13	82.42	1366	0.78	3.92E-01	.000	.06
Congruency : Postmask : SOA	3	39	291.46	2741	1.38	2.62E-01	.001	.10
Congruency : Premask : SOA	3	39	403.16	5988	0.88	4.62E-01	.001	.06
Postmask : Premask : SOA	3	39	404.16	3922	1.34	2.76E-01	.001	.09
Congruency : Postmask : Premask : SOA	3	39	41.63	3382	0.16	9.23E-01	.000	.01

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared; Postmask = Strength of the Backward Mask; Premask = Strength of the Forward Mask*

Table 4.6

ANOVA Table – Errors in Experiment 4.2

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	13	32.5935522	6.5762	64.43	2.16E-06	.726	.83
Congruency	1	13	5.2418977	0.7388	92.24	2.87E-07	.299	.88
Postmask	1	13	0.090893	0.086	13.74	2.64E-03	.007	.51
Premask	2	26	0.4244668	0.4631	11.92	2.12E-04	.033	.48
SOA	3	39	3.5489115	0.4272	107.99	6.18E-19	.224	.89
Congruency : Postmask	1	13	0.0065598	0.1017	0.84	3.77E-01	.001	.06
Congruency : Premask	2	26	0.7061221	0.252	36.43	2.88E-08	.054	.74
Postmask : Premask	2	26	0.019976	0.1843	1.41	2.62E-01	.002	.10
Congruency : SOA	3	39	2.6076638	0.4524	74.93	3.05E-16	.175	.85
Postmask : SOA	3	39	0.0376251	0.3304	1.48	2.35E-01	.003	.10
Premask : SOA	6	78	0.1461165	0.4566	4.16	1.12E-03	.012	.24
Congruency : Postmask : Premask	2	26	0.0337845	0.1865	2.36	1.15E-01	.003	.15
Congruency : Postmask : SOA	3	39	0.0008977	0.3053	0.04	9.90E-01	.000	.00
Congruency : Premask : SOA	6	78	0.5206632	0.5567	12.16	1.33E-09	.041	.48
Postmask : Premask : SOA	6	78	0.0267265	0.465	0.75	6.13E-01	.002	.05
Congruency : Postmask : Premask : SOA	6	78	0.0484019	0.6922	0.91	4.93E-01	.004	.07

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared; Postmask = Strength of the Backward Mask; Premask = Strength of the Forward Mask*

Table 4.7

ANOVA Table – Errors in Experiment 4.2 (only weak and strong forward masks)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	13	24.54553	5.08346	62.77	2.49E-06	.740	.83
Congruency	1	13	2.046051	0.32306	82.33	5.49E-07	.192	.86
Postmask	1	13	0.053375	0.0982	7.07	1.97E-02	.006	.35
Premask	1	13	0.16709	0.12832	16.93	1.22E-03	.019	.57
SOA	3	39	1.757039	0.37676	60.63	9.56E-15	.169	.82
Congruency : Postmask	1	13	0.002066	0.12477	0.22	6.50E-01	.000	.02
Congruency : Premask	1	13	0.128006	0.09885	16.83	1.25E-03	.015	.56
Postmask : Premask	1	13	0.019289	0.07429	3.38	8.91E-02	.002	.21
Congruency : SOA	3	39	0.857116	0.44874	24.83	3.75E-09	.090	.66
Postmask : SOA	3	39	0.042213	0.36496	1.50	2.29E-01	.005	.10
Premask : SOA	3	39	0.006435	0.24693	0.34	7.97E-01	.001	.03
Congruency : Postmask : Premask	1	13	0.032501	0.0886	4.77	4.79E-02	.004	.27
Congruency : Postmask : SOA	3	39	0.010481	0.3349	0.41	7.49E-01	.001	.03
Congruency : Premask : SOA	3	39	0.039943	0.20705	2.51	7.30E-02	.005	.16
Postmask : Premask : SOA	3	39	0.010962	0.20441	0.70	5.59E-01	.001	.05
Congruency : Postmask : Premask : SOA	3	39	0.019551	0.41334	0.61	6.09E-01	.002	.05

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared; Postmask = Strength of the Backward Mask; Premask = Strength of the Forward Mask*

Table 4.8

ANOVA Table – Visibility in Experiment 4.2

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	13	1209.017	150.995	104.09	1.43E-07	.796	.89
Postmask	1	13	437.82	47.843	118.97	6.51E-08	.585	.90
Premask	2	26	22.908	42.009	7.09	1.45E-02	.069	.35
SOA	3	39	20.887	14.948	18.17	8.61E-05	.063	.58
Postmask : Premask	2	26	8.557	13.547	8.21	1.72E-03	.027	.39
Postmask : SOA	3	39	34.363	9.073	49.24	1.02E-08	.100	.79
Premask : SOA	6	78	7.172	15.462	6.03	3.22E-05	.023	.32
Postmask : Premask : SOA	6	78	5.101	16.172	4.10	1.25E-03	.016	.24

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 = generalized eta squared; η_p^2 = partial eta squared; M-Strength = Masking Strength; M-Type = Masking Type

Table 4.9

ANOVA Table – Reaction times in Experiment 4.4

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	7	27599217.7	106869.9	1807.76	1.04E-09	1.00	1.00
Congruency	1	7	55962.8	2537.6	154.38	5.03E-06	.31	.96
Mask Duration	1	7	134.6	205.4	4.59	6.95E-02	.00	.40
ISI	7	49	1671.1	4102.3	2.85	1.41E-02	.01	.29
Congruency : Mask Duration	1	7	1358.4	174.5	54.50	1.52E-04	.01	.89
Congruency : ISI	7	49	12698.6	4896.5	18.15	1.20E-11	.09	.72
Mask Duration : ISI	7	49	562.8	2876.3	1.37	2.39E-01	.00	.16
Congruency : Mask Duration : ISI	7	49	822.2	3780.6	1.52	2.43E-01	.01	.18

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 = generalized eta squared; η_p^2 = partial eta squared

Table 4.10

ANOVA Table – Errors in Experiment 4.4

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	7	17.9724	0.3216	391.19	2.11E-07	.91	.98
Congruency	1	7	1.4919	0.18172	57.47	1.28E-04	.45	.89
Mask Duration	1	7	0.06285	0.07313	6.02	4.39E-02	.03	.46
ISI	7	49	0.79722	0.38137	14.63	4.14E-10	.30	.68
Congruency : Mask Duration	1	7	0.01772	0.04843	2.56	1.54E-01	.01	.27
Congruency : ISI	7	49	0.39184	0.32752	8.37	1.07E-06	.18	.54
Mask Duration : ISI	7	49	0.05262	0.3061	1.20	3.19E-01	.03	.15
Congruency : Mask Duration : ISI	7	49	0.02595	0.1858	0.98	4.58E-01	.01	.12

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared*

Table 4.11

ANOVA Table – Visibility in Experiment 4.4

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	7	124.961918	81.248	10.77	1.35E-02	.49	.61
Mask Duration	1	7	0.001658	1.089	0.01	9.21E-01	.00	.00
ISI	7	49	11.073367	39.39	1.97	7.88E-02	.08	.22
Mask Duration : ISI	7	49	0.988164	6.507	1.06	4.01E-01	.01	.13

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared*

Table 4.12

ANOVA Table – RTs in Experiment 4.5

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	9	51067472.9	58367	7874.43	1.49E-14	1.00	1.00
Congruency	1	9	84015.1	3647	207.33	1.61E-07	.422	.96
Postmask	1	9	1774.0	1890	8.45	1.74E-02	.015	.48
Premask	2	18	32582.1	7086	41.39	1.85E-07	.221	.82
SOA	3	27	5970.9	6243	8.61	6.06E-03	.049	.49
Congruency : Postmask	1	9	0.6	1895	0.00	9.57E-01	.000	.00
Congruency : Premask	2	18	39433.6	2756	128.79	2.16E-11	.255	.93
Postmask : Premask	2	18	519.8	1576	2.97	7.68E-02	.004	.25
Congruency : SOA	3	27	40354.3	4392	82.70	1.47E-07	.260	.90
Postmask : SOA	3	27	460.7	1959	2.12	1.21E-01	.004	.19
Premask : SOA	6	54	3005.2	5526	4.89	4.64E-04	.025	.35
Congruency : Postmask : Premask	2	18	8.7	1518	0.05	9.50E-01	.000	.01
Congruency : Postmask : SOA	3	27	411.2	2087	1.77	1.76E-01	.004	.16
Congruency : Premask : SOA	6	54	21469.9	6615	29.21	2.69E-15	.157	.76
Postmask : Premask : SOA	6	54	247.2	4720	0.47	8.27E-01	.002	.05
Congruency : Postmask : Premask : SOA	6	54	402.4	4806	0.75	6.09E-01	.003	.08

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared; Postmask = Strength of the Backward Mask; Premask = Strength of the Forward Mask*

Table 4.13

ANOVA Table – RTs in Experiment 4.5 (only weak and strong forward masks)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	9	35085046.3	50488.8	6254.16	4.18E-14	.998	1.00
Congruency	1	9	122531.3	4584.9	240.52	8.44E-08	.597	.96
Postmask	1	9	489.9	1419.2	3.11	1.12E-01	.006	.26
Premask	1	9	9109.0	2995.2	27.37	5.41E-04	.099	.75
SOA	3	27	1605.6	3831.9	3.77	4.34E-02	.019	.30
Congruency : Postmask	1	9	0.8	1269.4	0.01	9.40E-01	.000	.00
Congruency : Premask	1	9	868.4	710.6	11.00	8.99E-03	.010	.55
Postmask : Premask	1	9	69.1	699.6	0.89	3.70E-01	.001	.09
Congruency : SOA	3	27	60440.2	3856.9	141.03	1.32E-16	.422	.94
Postmask : SOA	3	27	389.8	1942.5	1.81	1.70E-01	.005	.17
Premask : SOA	3	27	51.9	2922.1	0.16	9.22E-01	.001	.02
Congruency : Postmask : Premask	1	9	1.3	372.2	0.03	8.62E-01	.000	.00
Congruency : Postmask : SOA	3	27	573.3	935.3	5.52	4.36E-03	.007	.38
Congruency : Premask : SOA	3	27	1245.7	3682.2	3.04	4.59E-02	.015	.25
Postmask : Premask : SOA	3	27	160.3	1627.6	0.89	4.61E-01	.002	.09
Congruency : Postmask : Premask : SOA	3	27	89.2	1436.3	0.56	6.47E-01	.001	.06

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared; Postmask = Strength of the Backward Mask; Premask = Strength of the Forward Mask*

Table 4.14

ANOVA Table – Errors in Experiment 4.5

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	9	34.8	3.37687	92.73	4.89E-06	.831	.91
Congruency	1	9	2.6	0.22486	103.79	3.06E-06	.269	.92
Postmask	1	9	0.0	0.0458	0.68	4.32E-01	.000	.07
Premask	2	18	1.3	0.3121	36.38	4.74E-07	.152	.80
SOA	3	27	2.8	0.24325	104.60	5.59E-15	.286	.92
Congruency : Postmask	1	9	0.0	0.07309	0.01	9.43E-01	.000	.00
Congruency : Premask	2	18	1.6	0.19129	73.77	2.12E-09	.182	.89
Postmask : Premask	2	18	0.0	0.23483	0.47	6.30E-01	.002	.05
Congruency : SOA	3	27	1.5	0.25237	55.03	1.24E-11	.179	.86
Postmask : SOA	3	27	0.0	0.23855	0.30	8.28E-01	.001	.03
Premask : SOA	6	54	0.1	0.28284	3.67	3.97E-03	.016	.29
Congruency : Postmask : Premask	2	18	0.0	0.16511	1.87	1.83E-01	.005	.17
Congruency : Postmask : SOA	3	27	0.0	0.34179	0.67	5.81E-01	.004	.07
Congruency : Premask : SOA	6	54	0.7	0.42034	14.28	4.38E-06	.086	.61
Postmask : Premask : SOA	6	54	0.1	0.31908	1.67	1.45E-01	.008	.16
Congruency : Postmask : Premask : SOA	6	54	0.0	0.3419	1.10	3.77E-01	.006	.11

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared; Postmask = Strength of the Backward Mask; Premask = Strength of the Forward Mask*

Table 4.15

ANOVA Table – Errors in Experiment 4.5 (only weak and strong forward masks)

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	9	18.6	2.34784	71.13	1.45E-05	.791	.89
Congruency	1	9	4.1	0.29285	127.47	1.29E-06	.459	.93
Postmask	1	9	0.0	0.0967	1.17	3.08E-01	.003	.11
Premask	1	9	0.5	0.12221	35.78	2.07E-04	.090	.80
SOA	3	27	1.9	0.2077	82.42	4.17E-08	.280	.90
Congruency : Postmask	1	9	0.0	0.07947	0.43	5.29E-01	.001	.05
Congruency : Premask	1	9	0.0	0.0723	0.63	4.47E-01	.001	.07
Postmask : Premask	1	9	0.0	0.11044	0.00	9.93E-01	.000	.00
Congruency : SOA	3	27	2.1	0.35936	53.65	1.67E-11	.305	.86
Postmask : SOA	3	27	0.0	0.18057	1.32	2.87E-01	.005	.13
Premask : SOA	3	27	0.1	0.16467	4.12	1.57E-02	.015	.31
Congruency : Postmask : Premask	1	9	0.0	0.0303	7.37	2.38E-02	.005	.45
Congruency : Postmask : SOA	3	27	0.1	0.27644	1.72	1.86E-01	.011	.16
Congruency : Premask : SOA	3	27	0.0	0.17999	1.21	3.17E-01	.005	.12
Postmask : Premask : SOA	3	27	0.0	0.19117	0.45	7.16E-01	.002	.05
Congruency : Postmask : Premask : SOA	3	27	0.0	0.17841	0.05	9.85E-01	.000	.01

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_P^2 *= partial eta squared; Postmask = Strength of the Backward Mask; Premask = Strength of the Forward Mask*

Table 4.16

ANOVA Table – Visibility in Experiment 4.5

Effect	DFn	DFd	SSn	SSd	*F*	*p*	η_G^2	η_P^2
Intercept	1	9	105.412	95.956	9.89	1.18E-02	.300	.52
Postmask	1	9	27.514	23.336	10.61	9.88E-03	.100	.54
Premask	2	18	58.641	71.628	7.37	2.08E-02	.192	.45
SOA	3	27	5.427	8.124	6.01	1.68E-02	.022	.40
Postmask : Premask	2	18	11.809	17.452	6.09	9.55E-03	.046	.40
Postmask : SOA	3	27	3.135	8.719	3.24	8.88E-02	.013	.26
Premask : SOA	6	54	4.872	12.141	3.61	4.40E-03	.019	.29
Postmask : Premask : SOA	6	54	1.319	9.191	1.29	2.77E-01	.005	.13

Note. DFn = degrees of freedom numerator; DFd = degrees of freedom denominator; SSn = Sums of Square numerator; SSd = Sums of Square denominator; η_G^2 *= generalized eta squared;* η_p^2 *= partial eta squared; M-Strength = Masking Strength; M-Type = Masking Type*

List of Abbreviations

ANOVA	Analysis of variance
BF	Bayes Factor
BIC	Bayesian information criterion
CFF	Continuous flicker fusion
CFS	Continuous flash suppression
GNW	Global Neuronal Workspace
IIT	Integrated information theory
ISI	Inter-stimulus interval
ITI	Inter-trial interval
LDT	Lexical Decision Task
N	Sample size
PE	Priming effect
RECOD	Retino-cortical dynamics model
RT	Reaction Time
SOA	Stimulus onset asynchrony

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Chapter 2 – Semantic Priming Effects Using Metacontrast Masking

Chapter 3 – Semantic Priming Effects Using Metacontrast Masking

Chapter 4 – Forward Masks reduce Priming Effects

Eigenständigkeitserklärung

Declaration of Academic Honesty

Hiermit erkläre ich, dass die vorliegende Arbeit ohne unzulässige Hilfe und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt wurde und dass die aus fremden Quellen direkt oder indirekt übernommenen Gedanken in der Arbeit als solche kenntlich gemacht worden sind.

I hereby declare that this dissertation is my own work. Information derived from the published and unpublished work of others has been acknowledged in the text and a list of references is given in the bibliography.

Göttingen,

14.05.2018

Nicolas Becker