Effects of Visual Masking and Crowding on Stimulus Visibility and Processing

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Summary

The visibility of visual stimuli can be manipulated by various methods such as visual masking or crowding in such a way that the viewer can no longer identify the stimulus. Despite these circumstances, the stimuli can be processed in the brain to a certain degree, which is why these methods are also used to compare the information processing of conscious and unconscious visual stimuli. In this way, conclusions can be drawn about the limits of processing unconscious stimuli or the neuronal correlates of consciousness. This serves as a basis for a better understanding of the function of consciousness or the emergence of consciousness. However, there are indications that the processing depth of unconscious stimuli may depend significantly on the method used to manipulate visibility. The generalizability of individual study results would thus be strongly limited. A more detailed investigation of these relationships could be helpful to understand how stimulus processing is affected by different experimental methods and furthermore at least partially explain the multitude of contradictory study results in this research area. In this context, several masked priming experiments were developed in the present work. In the first study it was shown that the stepwise manipulation of visibility by spatiotemporal crowding had no effect on the processing of this stimulus. This conclusion can be attributed to the fact that priming effects (as a measure of processing) did not depend on the visibility of the prime. In a subsequent study, a direct comparison was made to determine whether the priming effects depended on different masking conditions (backward pattern masking, metacontrast masking, and spatiotemporal crowding). Under the tested conditions, no difference was found between these conditions and priming effects were as pronounced as with visible primes. Taken together, this suggests that these methods are well suited to study the processing of unconscious stimuli, since visibility was reduced regardless of the processing depth. This was shown in the processing of colors, semantic categories and arrow directions. Future studies should verify whether this conclusion can be applied to the processing of more complex visual stimuli. In the present work it will be discussed how different

ways of manipulating stimulus visibility differ in this feature in relation to the processing mechanisms that are possibly involved. As long as the mechanisms of individual methods to manipulate stimulus visibility are not sufficiently clarified, conclusions about the processing depth of unconscious stimuli and the neuronal correlates of consciousness should be interpreted in connection with the research methods. Further studies comparing the effects of different methods could improve our knowledge about the mechanisms of visual processing, which seems to be a necessary prerequisite for a better understanding of the mystery of consciousness.

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Zusammenfassung

Die Sichtbarkeit von visuellen Stimuli kann mit unterschiedlichen Methoden wie zum Beispiel visueller Maskierung oder Crowding so manipuliert werden, dass der Betrachter den Reiz nicht mehr identifizieren kann. Trotz dieser Umstände können die Reize im Gehirn bis zu einem gewissen Grad verarbeitet werden, weshalb diese Methoden auch genutzt werden, um die Informationsverarbeitung von bewussten und unbewussten visuellen Stimuli miteinander zu vergleichen. Auf diese Weise können Schlussfolgerungen über die Grenzen der Verarbeitung unbewusster Reize oder über die neuronalen Korrelate des Bewusstseins gezogen werden. Dies dient als Grundlage um die Funktion von Bewusstsein beziehungsweise die Entstehung von Bewusstsein besser verstehen zu können. Allerdings gibt es Hinweise darauf, dass die Verarbeitungstiefe unbewusster Reize maßgeblich von der Methode abhängen könnte, die verwendet wurde, um die Sichtbarkeit zu manipulieren. Die Generalisierbarkeit von einzelnen Studienergebnissen wäre damit stark eingeschränkt. Eine genauere Untersuchung dieser Zusammenhänge könnte außerdem hilfreich sein, um die Vielzahl widersprüchlicher Studienergebnisse in diesem Bereich zumindest teilweise zu erklären. In diesem Zusammenhang wurden im Rahmen der vorliegenden Arbeit verschiedene maskierte Priming Experimente entwickelt. In der ersten Studie zeigte sich, dass die stufenweise Manipulation der Sichtbarkeit durch räumlich-zeitliches Crowding keine Auswirkung auf die Verarbeitung dieses Reizes hatte. Diese Schlussfolgerung lässt sich darauf zurückführen, dass Priming Effekte (als Maß für die Verarbeitung) nicht von der Sichtbarkeit des Primes abhängig waren. In einer darauffolgenden Studie wurde dann direkt verglichen, ob sich die Priming Effekte zwischen unterschiedlichen Arten der Maskierung (Mustermaskierung, Metakontrastmaskierung und räumlich-zeitliches Crowding) unterscheiden. Unter den getesteten Bedingungen zeigte sich kein Unterschied zwischen diesen Methoden. Priming-Effekte waren genauso stark ausgeprägt wie in der Bedingung mit sichtbaren Primes. Zusammen genommen deutet dies darauf hin, dass die verwendeten Methoden gut geeignet sind, um die Verarbeitung von unbewussten Stimuli zu untersuchen, da die

Sichtbarkeit unabhängig von der Verarbeitungstiefe eingeschränkt wird. Dies zeigte sich für die Unterscheidung von Farben, semantischen Kategorien und Pfeilrichtungen. Zukünftige Studien sollten überprüfen, ob diese Schlussfolgerung auch auf die Verarbeitung von komplexeren visuellen Stimuli übertragbar ist. In der vorliegenden Arbeit darauf eingegangen wie sich unterschiedliche Arten die Sichtbarkeit zu manipulieren in diesem Merkmal unterscheiden und welche Verarbeitungsmechanismen daran möglicherweise beteiligt sind. Solange die Wirkungsmechanismen einzelner Methoden zur Manipulation der Sichtbarkeit nicht hinreichend geklärt sind, sollten Schlussfolgerung über die Verarbeitungstiefe unbewusster Stimuli und die neuronalen Korrelate des Bewusstseins im Zusammenhang mit den Maskierungsmethoden interpretiert werden. Weitere Studien, die die Effekte unterschiedlicher Methoden unter ähnlichen Bedingungen vergleichen, könnten unser Wissen über die Mechanismen der visuellen Verarbeitung erweitern. Dies scheint eine notwendige Voraussetzung zu sein, um das Mysterium Bewusstsein besser verstehen zu können.

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1 General Introduction

1.1 Consciousness as a research field

Questions concerning the nature of consciousness have been the subject of philosophical debates for a long time. Why are we conscious? What exactly is consciousness and how does it emerge? Does consciousness fulfill a function? Related deliberations consider whether consciousness is specific to human beings or whether it can be attributed to animals or machines as well. Although these questions "…seem to have been around forever, […] neither science nor philosophy has been able to provide an answer" (Lamme, 2010, p. 204). The investigation of consciousness strongly relies on introspection, because of the subjective nature of conscious experience. We cannot simply ask an animal what it is like to experience a certain situation. Although human beings can answer these kinds of questions easily, internal representations do not necessarily mirror an objective reality. This complicates the implementation of objective measures that are the basis of most scientific research methods. However, in the last 30 years, consciousness has become a rapidly growing research topic in psychology and neuroscience (Aru & Bachmann, 2015). This development has been linked to technological advances in brain imaging techniques and computational power, accompanied by progress in the understanding of the neuronal mechanisms underlying cognitive functions, like attention and working memory (Dehaene & Naccache, 2001). Under these conditions the seemingly impenetrable nature of consciousness becomes explorable by identifying patterns of neuronal activity associated with mental states related to reports of subjective experience. Along these lines, it has been suggested that finding the differences between processing of conscious and unconscious visual information is one step towards a more fundamental understanding of consciousness (Lamme, 2015). For this purpose, it is necessary to specify properties of both conditions and - within that framework - identify vision related processes that require consciousness and those that function in the absence of consciousness. In doing so, it should be possible to identify the neuronal correlates of consciousness (NCC) that should be closely related to the origin of consciousness. Moreover, in ascertaining the limit of processes that can take place unconsciously, it is possible to approach the function of consciousness. Although this approach appears to be the most expedient solution to unravel the mystery of consciousness we can currently come up with, “it has been surprisingly hard to find fundamental differences in the workings of many visual functions in the two conditions” (Lamme, 2015, p. 20). There are considerable difficulties in consolidating the variety of different findings into a coherent understanding of unconscious visual processing (Dehaene et al., 2006; Dehaene & Naccache, 2001) or the neuronal correlates of consciousness (NCC, Aru & Bachman, 2015). But why is it so difficult?

Rothkirch and Hesselmann (2017) attributed the difficulty to compare results from different studies in this research field to the variety of methods used to manipulate visibility, different measures of visibility, different practices in statistical analysis and a lack of shared definitions. All these criteria, considered separately, can strongly influence the outcome of a study. Unfortunately, different studies often vary in so many aspects that comparisons become unreliable and pinpointing the factor that could explain different outcomes becomes nearly impossible.

The variety of different methods that can be used to experimentally suppress stimulus visibility is one of the aspects that will be addressed more thoroughly in the present work. Closely related to this aspect are differences in the way visual stimuli need to be presented for a specific method to be most effective. However, even if different studies use the same method to investigate the processing of unconscious stimuli, the applied experimental procedures can differ considerably. The choice of a method and related stimulus presentation parameters are often determined by applicability with respect to the research task at hand. This approach seems straightforward, because certain stimulus types, sizes, durations or presentation locations can more easily be manipulated by different methods (Kim & Blake, 2005). Similar approaches were adopted in the development of experimental designs that are designed for different measures of visibility and statistical analyses.

This strategy has led to a lack of standard practice in this research field (Rothkirch & Hesselmann, 2017), which is more and more recognized as problematic. For example, there are studies that demonstrate quite impressively that the neuronal processing of unconscious stimuli seems to depend on the method that is used to manipulate stimulus visibility (Fogelson et al., 2014). This is particularly problematic when it is not considered within the research field that aims at discovering the NNCs or a processing limit of unconscious stimuli, as it can result in misleading conclusions when generalizations about unconscious processing are based on one experimental method alone or lead to confusion about apparently contradictive findings. Even when this problem is recognized, disentangling the processing depth of unconscious stimuli or the NCCs from the effects of a specific method can be difficult. In an attempt to unify a variety of inconsistent findings different theories of consciousness were developed and it has been suggested to arrange different methods to manipulate stimulus visibility in a functional hierarchy regarding the processing depth they allow unconscious stimuli to reach (Breitmeyer, 2015). In the following paragraph different methods and the mechanisms by which they interfere with stimulus processing are discussed within these frameworks.

1.2 Theories of Consciousness

With the aim to disambiguate experimental findings regarding the processing mechanisms that are characteristic for either unconscious or conscious stimuli, it has been suggested to extend this distinction. Dehaene et al. (2006) consequently distinguished the processing of unconscious stimuli between subliminal and preconscious processing in contrast to processing that leads to conscious perception. In this context, the processing of conscious stimuli is associated with the ability to report about the stimulus, which is not possible in subliminal or preconscious conditions (Dehaene et al., 2006). This distinction is based on the interaction of two factors that govern stimulus processing: the bottom-up strength and top-down attention. Conscious perception relies on both sufficient stimulus strength and attention.

Subliminal stimuli are typically associated with a weak stimulus strength. For example, this is the case when visual backward masking is used to reduce the visibility of a briefly shown stimulus by a subsequently presented stimulus called mask (Breitmeyer & Öğmen, 2006). The processing of these stimuli can be very limited when they are unattended or when the processing is interrupted at an early stage. The important role of attention has for example been observed in the form of reduced or absent priming effects when subliminal stimuli were not attended temporally (Kiefer & Brendel, 2006; Naccache et al., 2002) or spatially (Lachter et al., 2004). Additionally, electrophysiological measures typically associated with masked and unmasked stimuli could not be observed when no spatial attention was directed at the stimuli (Koivisto et al., 2009). Furthermore, priming effects can be reduced when their processing is interrupted at an early stage. This has for example been observed when forward masks (Becker & Mattler, 2019) or continuous flash suppression (CFS) were used (Valuch & Mattler, 2019) to reduce prime visibility, because in these cases priming effects depend on prime visibility. This already indicates that some methods could affect stimulus processing at earlier stages than others.

In the distinction of unconscious stimulus processing by Dehaene and colleagues (2006), preconscious stimuli could potentially become conscious in contrast to subliminal stimuli. Preconscious stimuli are visible when they are attended, because their bottom-up strength would be sufficiently large for a conscious percept to emerge. However, preconscious stimuli cannot be reported, because top-down attention is limited. This mechanism is for example used in methods like change blindness, attentional blink or inattentional blindness.

Within the framework of the global neuronal workspace (GNW) hypothesis (Dehaene & Nacchache, 2001) the distinctions between subliminal, preconscious and conscious stimulus processing are associated with different neuronal mechanisms (Dehaene et al., 2006). First of all, the authors suggested that brain activity in early visual areas is a prerequisite for stimulus awareness, but not in itself sufficient. For example, the processing of subliminal stimuli remains weak and is only transient, but can, depending on attention and task set, reach higher level processing as indicated by priming effects. The neuronal activation evoked by preconscious stimuli is stronger and more durable but restricted to sensory-motor areas when stimuli are unattended. In contrast, the processing of conscious stimuli is associated with attention that amplifies brain activation, which then extends to fronto-parietal areas creating a network between distinct and distant brain regions. This global network can maintain stimulus information for longer durations and makes it available for other processes including verbal report. The transition from preconscious to conscious stimulus processing is supposed to occur sharply (in a nonlinear way) when a certain threshold activity is overcome, which has been described as “ignition” (Dehaene et al., 2006, p. 206).

In contrast to this GNW theory Lamme (2006; 2010) proposed that the neuronal correlate of consciousness is not related to brain activity in a fronto-parietal network, but to recurrent processing more generally. This recurrent or re-entrant processing is characterized by an interaction of neurons in higher- and lower-level (visual) brain regions via horizontal and feedback connections, promoting the distribution and exchange of information. In contrast, processing of unconscious stimuli is associated with a fast feedforward sweep of visual information to progressively higher levels of processing, so that after only 100 to 150 ms motor responses to a variety of different and even complex stimulus features can be prepared (Lamme, 2006). Just like the GNW theory, this recurrent processing (RP) hypothesis (Lamme 2006; 2010; 2015) is also based on the motivation to clarify the heterogenous findings regarding the NCCs and the definition of a boundary that separates the processing of unconscious and conscious visual stimuli. Lamme pointed out that the behavioral measures of conscious experience and the cognitive functions involved in those measures differ considerably between the methods used. This inevitably seems to result in contradictive conclusions about the NCCs that Lamme summarized in table 1 of his paper from 2006. Thus, Lamme suggested that the true NCC should be independent from other cognitive functions like attention, working memory and reportability.

In this context Lamme (2010) proposed four stages of visual processing that differ in the depth of stimulus processing. Analogous to the distinction made by Dehaene et al. (2006) there are two orthogonal factors that determine the processing depth, defined on the one hand by attention (unattended versus attended stimuli) and on the other hand by feedforward versus feedback processing. Stimulus processing in stage 1 is very short-lived and limited to feedforward processing when stimuli are unattended and additionally masked. In this case prime visibility and priming effects are reduced or absent, because the processing depth of the prime is only low. In contrast, stimulus processing in stage 2 refers to the case where stimuli are attended to and masked. Prime processing is still characterized by a feedforward sweep; thus, prime visibility is still low or absent, but the processing depth is strong enough to produce priming effects. Stage 3 is characterized by recurrent processing that is, however, only superficial, because stimuli are not attended. This is the case when stimulus visibility is for example affected by inattentional blindness, change blindness or attentional blink. Under these conditions unconscious stimuli are supposed to evoke large effects or rather larger effects as observed with visual masking (e.g., Kouider & Dehaene, 2007). In turn, Stage 4 processing characterizes the widespread recurrent processing of attended stimuli that are visible and therefore consciously accessible comparable to the ignition in the GNW theory. According to this approach all stimuli that undergo solely feedforward processing (stage 1 and 2) are unconscious, but in case of stage 2 can reach even prefrontal areas (Lau & Passingham, 2007). At first, this distinction of stimulus processing seems very similar to the distinction made by Dehaene et al. (2006) within the GNW theory of consciousness (Naccache & Dehaene, 2001). The main difference is that Lamme suggests recurrent processing as NCC, which is associated with stage 3 and stage 4 (Lamme, 2010). According to Lamme (2006, 2010) recurrent processing can account for the experience of phenomenality in conscious visual perception. This is for example because it enables the integration of information, which in turn is essential for perceptual organization that determines how the environment appears to the viewer (Lamme, 2010). In this regard he relates to another theory of consciousness, the information integration theory (ITT, Tononi, 2004; 2008). According to the ITT consciousness can be understood as integration of information, and the amount of integrated information a system can reach at different states of processing is measured by phi. This measure has certain characteristics. For example, as integration of information generates new information, this includes that earlier states of the system can be ruled out and that various complexes with different values of phi can occur simultaneously. Feedforward networks seem to generate lower values of phi than those that allow recurrent processing (Tononi, 2004). Although this measure cannot be directly transferred to information processing in the brain, the ITT is a helpful way to investigate the characteristics of information processing in different systems. Lamme (2010) related feedforward processing associated with unconscious stimuli in stages 1 and 2 to a system with lower values of phi (less information integration) and recurrent processing associated with conscious stimuli in stage 4 with a system with higher values of phi (large amount of information integration). The interesting point Lamme (2010) made is that there is no fundamental difference in processing between stage 3 and 4 (as both are associated with recurrent processing) as compared to stages 1 and 2 (associated with feedforward processing). With this background and from the neuronal perspective that Lamme advocates (2006; 2010), he raised the interesting suggestion that stage 3 processing can be sufficient to account for the phenomenality associated with consciousness, with the difference that it cannot be accessed as in stage 4. According to this point of view there could have been a conscious experience of stimuli when for example change blindness is used to manipulate their visibility, that is simply overwritten by a following one. During inattentional blindness or attentional blink it is possible that there was a conscious experience of the stimulus as it appeared but is forgotten afterwards. Thus, Lamme (2010; 2015) argues that stimuli in these conditions could be seen, but not reported. In this regard the RP hypothesis (Lamme 2010) diverges from the GNW hypothesis (Dehaene et al., 2006) most by placing the boundary between unconscious versus conscious stimulus processing between stages 1 and 2 versus 3 and 4, while according to the GNW theory the boundary lies between processing stages 1, 2 and 3 versus 4. According to Lamme consciousness is confounded with attention and cognitive control in the

GNW theory, while consciousness is orthogonal to these cognitive functions in the context of the RP theory (illustrated in figure 4 in Lamme, 2010). Lamme (2010) promotes the idea that this distinction of consciousness from other cognitive functions is essential in understanding visual consciousness and emphasizes the explanatory power of a neuronal perspective in addition to (or relying less on) introspection. However, this point of view is not quite uncontroversial because without introspection or report it cannot be determined whether a visual stimulus was indeed consciously perceived. The phenomenality associated with the awareness of a visual stimulus seems to be closely related to its accessibility (Kouider et al., 2010), although there is also the notion that phenomenal experience is richer than what can be reported, which is also referred to as "overflow argument" (Block, 2011). This is however related to a much more far-reaching debate that will not be further discussed at this point.

In summary, what can be learned from these considerations so far is that the boundary between the processing of unconscious and conscious stimulus remains difficult to determine and that it varies from different theoretical perspectives. However, these theoretical perspectives include important considerations about the methods that are used to manipulate visibility and how they could differently affect stimulus processing. On the one hand there seem to be methods that interrupt stimulus processing at an early level (stage 1) which can be related to reduced or absent priming effects, as for example in forward masking (Becker & Mattler, 2019) or CFS (Valuch & Mattler, 2019). On the other hand, different types of visual masking were associated with far-reaching effects of subliminal stimuli (e.g., Lau & Passingham, 2007) associated with stage 2. In contrast to that there are methods that affect stimulus visibility by manipulating the top-down attention (change blindness, attentional blindness or inattentional blink), which was associated with allowing for large effects (e.g., Kouider & Dehaene, 2007) of these preconscious (or stage 3) stimuli. This summary is already closely related to the functional hierarchy Breitmeyer (2015) proposed.

1.3 Functional hierarchy of blinding techniques

Breitmeyer (2015) suggested hierarchically ordering different "blinding techniques" according to the amount of residual processing that is preserved for visually suppressed stimuli. One possibility to address the functional level at which different blinding techniques affect stimulus processing, in contrast to the considerations made above, is to investigate how different blinding techniques interact with each other. This approach assumes that one technique A can prevent the effect from another technique B if A affects stimulus processing at a level earlier than B. The conclusion for this observation is that the processing depth of a stimulus must be more limited when it is affected by A compared to B. Thus, the relative functional level of technique A and B can be determined.

In one of these studies, Breitmeyer et al. (2008) investigated the interaction of binocular rivalry and metacontrast masking. In binocular rivalry different stimuli are presented to each eye and only one stimulus can be perceived at a time while the other one is intraocularly suppressed. In such a rivalrous condition the target stimulus was presented to the non-suppressed eye, and the metacontrast mask to the suppressed eye after a short delay. Consequently, the target stimulus was clearly visible while the visibility of the mask was impaired. Conversely, in the non-rivalrous control condition the typical effect of metacontrast masking was observed: Target visibility was suppressed by the metacontrast mask while the mask itself was clearly visible. The authors concluded that binocular rivalry became effective before the mechanism of metacontrast masking could emerge. Therefore, binocular rivalry seems to affect stimulus processing on a functionally earlier level than metacontrast masking.

In another study, Chakravarthi and Cavanagh (2009) reduced the visibility of a peripherally presented target stimulus by simultaneously presenting four flankers, one to each side. This so-called crowding effect impairs the ability to distinguish a stimulus that would be easy to identify without nearby flankers. Interestingly, they used three other blinding techniques to suppress the visibility of these flankers and compared the target discrimination performance to crowded and non-crowded conditions.

When they presented a mask with an overlapping noise pattern at the position of each flanker after the flanker disappeared, target discrimination performance was restored to uncrowded levels. Presenting a metacontrast mask instead, consisting of a ring that would fit around each flanker, target discrimination also improved, but not to non-crowed levels. However, when object substitution masking (OSM) was used, target discrimination did not recover from crowding. In OSM four dots were presented simultaneously with each flanker, more specifically at the corners of an imaginary rectangle around it and remained after flanker offset. They concluded that the effect of crowding must have occurred before OSM becomes effective. In contrast, visual masking by noise or metacontrast seemed to interfere with stimulus processing before the effect of crowding. Consolidating the findings from both studies, binocular rivalry would be placed at the lowest level of a functional hierarchy of blinding techniques followed by backward pattern masking, metacontrast masking, crowding and OSM, in this order (Breitmeyer, 2015). This is in accordance with the view postulated by the object substitution theory (Enns, 2004) stating that backward masking affects stimulus processing at an early stage (0 - 100 ms between target and mask) by interfering with “object formation”, while OSM unfolds its effect stimulus at a later “object substitution” stage when attention is not focused on the stimulus.

Another possibility to determine the depth of unconscious processing in relation to different blinding techniques is to directly compare the neuronal activity between them. For example, Fogelson and colleagues (2014) used multivariate pattern analysis to recover stimulus category information (faces versus tools) from neuroimaging data generated under three different viewing conditions. The stimuli were presented either fully visible or rendered invisible by chromatic flicker fusion (CFF) or CFS. They showed that information about stimulus categories could be found throughout the brain when stimuli were visible, but that different brain regions were used to distinguish between faces and tools when stimuli were invisible, depending on which blinding technique was used. When CFS was used information about stimulus categories was restricted to the occipital cortex, while neuronal activity under CFF propagated to occipital, temporal and frontal brain regions. This suggested that stimulus information does not reach higher level processing when CFS is used, while at least some higher-level processing was preserved during CFF.

Other studies inferred the amount of residual processing by comparing priming effects that stimuli can elicit although they are suppressed from visibility by different methods (e.g., Faivre et al., 2012; Izatt et al., 2014; Peremen & Lamy, 2014). For example, Faivre et al. (2012) observed that emotional faces could bias preference judgements (pleasant or unpleasant) on a subsequently presented neutral stimulus when crowding was used to suppress their visibility. These findings could not be replicated with sandwich noise masking and CFS. This is in accordance with the functional hierarchy of blinding techniques (Breitmeyer, 2015) described earlier. Because sandwich noise masking combines the effect of a forward mask with a backward mask, it is suggested to suppress stimulus processing early on (Wernicke & Mattler, 2019; Becker & Mattler, 2019). As the mechanism of interocular suppression is also used in CFS, where a stream of salient patterns is presented to one eye to suppress the visibility of the stimulus to the other eye (Tsuchiya & Koch, 2005), it could also affect stimulus processing at an earlier level than crowding.

Similar findings were reported by Izatt et al. (2014) comparing the processing of faces between sandwich noise masking and CFS conditions. In both cases, repetition priming effects depended on the visibility of the primes in a fame categorization task, indicating that these methods do not only reduce the visibility of the prime, but also its residual processing. Others have recently observed that the priming effects depend on prime visibility when CFS is used to suppress prime visibility (Valuch & Mattler, 2019). Likewise, Peremen and Lamy (2014) compared the processing of arrows that were reduced in their visibility by CFS and metacontrast masking in a masked priming experiment and found that the processing of those stimuli was only preserved when metacontrast masking was used.

However, it should be noted that Faivre et al. (2012) found priming effects in a repetition priming experiment (prime and target face where either the identical face or different faces showing the same emotion) when sandwich noise masking and CFS were used, concluding that some lower-level residual processing was maintained despite these manipulations. This seems to be in conflict with the findings described above and is difficult to interpret in the given context. Nevertheless, this example demonstrates clearly how methodological differences can potentially lead to different conclusions even between experiments using similar methods to manipulate stimulus visibility and thus dramatically complicate comparisons between different studies. Additionally, these observations point out that the differences in the detrimental effect of blinding techniques on stimulus processing could be revealed by additionally regarding the stimulus complexity and requirements of the task under investigation. It could well be that a method applied to limit the processing of complex stimulus information does not affect the processing of simpler stimuli.

Such a hierarchy can be useful in unifying a variety of different, partially contradicting findings and at the same time provides testable assumptions. Moreover, it illustrates that it could be misleading to rely on blinding techniques as a mere research tool to make inferences about the depth of unconscious processing: The mechanisms by which blinding techniques suppress stimulus visibility vary considerably and are themselves not completely understood. Blinding techniques are a worthwhile research topic, because they allow us to investigate visual processing from a different point of view.

In the endeavor to analyze whether there are preferences regarding blinding techniques in the investigation of unconscious visual processing Lamme (2015) reviewed findings based on different methods that can be used to experimentally manipulate the visibility of a stimulus. Proceeding from the available methods (for an overview see e.g., Breitmeyer, 2015; Kim & Blake, 2005) he suggested that visual masking, CFS and dichoptic color fusion could be most suitable. This is because these techniques can reliably render a stimulus invisible and, despite being based on different mechanisms, involve only mechanisms related to visual processing. In visual masking a visual stimulus can be rendered invisible by presenting it only briefly and showing a second stimulus (called mask) after a short delay (Breitmeyer & Öğmen, 2000). In contrast, CFS is based on interocular suppression, and in dichoptic color fusion a stimulus with an opposite color contrast is shown to each eye and becomes invisible when visual information from both eyes is combined (Moutoussis & Zeki, 2002). Other blinding techniques seem less suitable for studying the processing of unconscious visual stimuli, because the mechanisms by which they achieve invisibility are related to various other cognitive functions like attention or memory, including for example inattentional blindness, change blindness or attentional blink (2015).

However, the cumulated evidence from above would suggest that CFS or methods based on interocular suppression could be less reliable in this field of research, because they seem to affect stimulus processing at an early stage, which is for example related to the observation of priming effects that depend on visibility even for simple stimuli like arrows (Peremen & Lamy, 2014; Valuch & Mattler, 2019). Although processing of stimuli manipulated in their visibility by CFS was initially observed to be unaffected for stimuli in complex contexts (e.g., Bahrami et al., 2010; Mudrik, et al., 2011; Sklar et al., 2012) these effects were critically reflected on methodological terms by others (e.g., Hesselmann et al., 2018; Moors, Hesselmann et al., 2017; Yang & Blake, 2012).

This leaves visual masking as a reliable candidate for the investigation of unconscious visual processing. Similarly, visual crowding seems to allow for uninterrupted stimulus processing for a wide range of different stimuli (Manassi & Whitney, 2018). For this reason, and because the effects of both methods are compared in the two studies presented in the following chapters, visual masking and crowding are discussed in more detail in the following.

1.4 Blinding Techniques

1.4.1 Visual masking

In visual masking the visibility of a target stimulus is reduced by presenting another stimulus referred to as mask. Different types of masking can be distinguished depending on the spatial composition and temporal sequence of the mask relative to a target stimulus (Breitmeyer & Öğmen, 2006). First, when the mask consists of a pattern spatially overlapping with the target stimulus, this pattern can either be structurally unrelated to the target stimulus (masking by noise) or share figural characteristics with the target stimulus (masking by structure). Moreover, the mask can either be presented prior to a target stimulus (forward masking) or after a target stimulus (backward masking). This sequence usually takes a few tens to hundreds of milliseconds in which the mask interferes with target processing. When the stimulus-onset-asynchrony (SOA), which describes the time interval from the onset of the mask to the onset of the target stimulus, is varied, the magnitude of masking changes. This temporal dynamic of the interaction between mask and target stimulus provides information about how stimulus processing unfolds regarding different stimulus properties.

Metacontrast masking can be regarded as a special case of masking by structure (Breitmeyer & Öğmen, 2006, p. 34). The main characteristic of metacontrast masking is that there is no spatial overlap between the target and mask. Instead, the outer contours of the target stimulus fit closely to the inner contours of the mask thereby creating spatial continuity between both stimuli. The metacontrast mask is typically presented after the target stimulus. When the stimulus sequence is the other way around it is referred to as paracontrast.

1.4.1.1 Mechanisms

What usually can be observed when masking is depicted as a function of SOA, is a monotonic increase in target stimulus visibility with larger SOAs, which is referred to as type A function. This can be observed for masking by noise or structure. Masking by structure and metacontrast (as well as paracontrast) can also produce different masking functions, which are referred to as type B functions. They are U-shaped with the strongest masking effect at intermediate SOAs. Whether type A or type B masking functions are observed with masking by structure (in the following referred to as pattern masks) has been related to the relative energy of mask and target stimuli (Breitmeyer, 2014). The energy of a stimulus is determined by its duration and luminance. When the mask-target energy ratio is larger than 1, type A masking is more frequently observed, while type B masking has been associated with a mask-target energy ratio smaller than 1. Thus, stronger pattern masks reduce target visibility most strongly at short SOAs, while the strongest masking effect with weaker pattern masks can shift to intermediate SOAs.

Interestingly, monotonic increasing functions with backward pattern masking have been associated with an integration process that occurs primarily on a paracortical level, while the process associated with type B masking functions is related to interruption that occurs at cortical levels. (Breitmeyer & Öğmen, 2006). These considerations date back to Turvey (1973), who observed that under dichoptic viewing conditions (target and pattern mask are presented to different eyes), monotonic pattern masking effects decreased substantially (even for large mask-target energy ratios). As information from both eyes is combined at the cortical level, it has been concluded that different processes are involved in masking by pattern revealed by the viewing conditions. There are a variety of different models used to explain visual masking. For example, the dual-channel inhibition model (e.g., Breitmeyer & Öğmen, 2000) describes the interruption process in visual masking in more detail. According to this model, the onset of a stimulus evokes a transient and a sustained response. The transient response is characterized by a short latency and short duration and carries positional information about a stimulus (“where”-signal). The sustained response has a longer latency and a longer duration and contains information about the characteristics of the stimulus (“what”-signal). Consequently, interruption of transient signals can impair the ability to locate a stimulus, while interruption of sustained signals can impair the ability to identify a stimulus. This model suggests two mechanisms by which the ability to identify a target is affected by a successively presented mask: interchannel inhibition and intrachannel inhibition. The mechanism of interchannel inhibition occurs when the transient response of the mask interferes with the sustained response of the previously presented target, given that they are presented with a specific SOA. The mechanism of intrachannel inhibition occurs when the sustained responses of the mask interfere with the sustained response of the previously presented target, which is possible because sustained responses of both stimuli persist for a longer duration.

The experimental parameters and the task play an important role in visual masking. It determines the criterion content, which is the stimulus dimension that is task relevant, or which is used by the observer to solve the task. This affects the performance which is reflected in the masking function. Moreover, masking can also be influenced by higher-level processes such as perceptual grouping, figure-ground segmentation and attention (Breitmeyer, 2014).

1.4.1.2 Processing despite visual masking

Visual masking is also well suited to investigate the processing of unconscious stimuli, which is typically realized in masked priming experiments (Scharlau & Ansorge, 2003). In these experiments the prime stimulus is shortly presented and followed by a mask after a variable SOA. For example, in metacontrast masking, the mask can be designed in such a way that it reduces the visibility of the prime and simultaneously serves as a target stimulus. This can be achieved by creating a mask stimulus with an inner cutout that closely fits around the (previously presented) prime contours without overlap. This mask stimulus can have different outer contours defining the target feature. This has for example been done by Vorberg et al. (2003) using prime arrows and target arrows (that at the same time worked as metacontrast masks). Within one trial both stimuli are subsequently presented and could either point left or right. By asking participants to react as fast as possible to the pointing direction of the clearly visible target stimulus, it is possible to observe the effect of an invisible prime stimulus on the response to the visible target. It is assumed that it must be the residual processing that affected target processing when the prime is invisible. This can be revealed by contrasting conditions in which prime and target arrows pointed in different directions (incongruent trials) with conditions in which both stimuli pointed in same direction (congruent trials). In incongruent conditions responses are usually slowed down in comparison to congruent conditions. The difference in reaction times between those conditions yields the priming effect, which can be regarded as a measure of unconscious processing. Additionally, the variation of SOA allows to observe the changes in the magnitude of priming effects, that usually increase with longer SOA between prime and mask/target stimulus (Vorberg et al., 2003). When participants are instead asked to identify the pointing direction of the prime stimulus, this reveals how prime visibility chances with SOA. In the study of Vorberg and colleagues (2003) participants were not able to distinguish the pointing direction of the prime arrow above chance level over different SOAs. This criterion is usually used to conclude that the prime was invisible. However, even when type B masking is observed (in which prime visibility is lowest at intermediate SOAs) it still indicates that prime processing and processing related to the visibility of the prime are dissociable processes (Neumann & Klotz, 1999).

Nonconscious processing has been observed over different levels of stimulus processing including visuo-motor priming (e.g., Dehaene et al., 1998; Neumann & Klotz, 1994; Vorberg et al., 2003), perceptual priming (e.g., Scharlau & Ansorge, 2003), semantic priming (e.g., Kiefer, 2002; 2012) and priming of execute control (e.g., Ansorge et al., 2002; Mattler, 2003). Moreover, it has been suggested that categorization of unconscious stimuli seems not to be limited (Lamme, 2015).

This could for example be explained by the direct parameter specification (DPS) hypothesis (Scharlau & Ansorge, 2003). According to this theory unconscious stimuli can affect sensori-motor control, when they share features with response relevant stimuli. This requires that an action is planned in relation to those features. And this can, depending on task and stimulus material, be extended to many features.

1.4.2 Crowding

Crowding is an effect that is ubiquitous in visual perception. It describes how the ability to recognize an object depends on its distance to other similar objects (Whitney & Levi, 2011). This means that an object that could be easily identified when viewed in isolation, cannot be distinguished from other objects anymore when they occur in proximity. In foveal vision this distance between objects would have to be very small to experience the crowding effect. Therefore, we rarely notice it in everyday situations. However, the crowding effect is especially strong in the visual periphery: even with large distances between objects, they cannot be identified anymore. This is what makes this effect so remarkable. Frequently, the detrimental effect of crowding on object recognition is compared with a reduction of visual acuity, because both become stronger in the visual periphery. Although this comparison is not as straightforward as it might seem at the first glance, crowding represents a much larger constraint to object recognition than acuity, even in the fovea (Strasburger, 2020).

However, this “mysterious process named crowding” (Whitney & Levi, 2011, p. 160) is still much less popular and has in fact for a long time mainly been investigated in the context of reading research and visual acuity (Pelli, 2008). The number of characters that could be identified within one fixation was primarily associated with the letter size (acuity) until the important role of the spacing between the letters (crowding) had gained attention (Levi, 2008, p. 648). Earlier investigations described the phenomenon under different names including for example lateral masking (Townsend et al., 1971; Wolford & Chambers, 1983), interaction effects (Bouma, 1970) and contour interaction (Flom et al., 1963). Only since the late nineties did research on crowding became more popular (Strasburger, 2020) and is more recently regarded as “fundamental limit on conscious visual perception and object recognition” (Whitney & Levi, 2011, p. 160), a development that is referred to as paradigm shift in visual perception (Herzog et al., 2016; Strasburger, 2020). The important role crowding plays in the perception of our environment and goal-oriented behavior is well illustrated by an example from Whitney and Levi (2011). When we drive a car down a street, our gaze is typically directed in front of us and consequently, what occurs at the roadside is subject to peripheral vision. When a person suddenly appears at the edge of the street with the intention to cross, we can quickly assess the situation and react accordingly by slowing down the car without having to look at the person directly. However, when multiple road signs are added to the scene because of a construction site, it can be difficult to perceive a person about to cross the street among them and our ability to react accordingly would be impaired.

Crowding is a worthwhile research topic, because it can be studied to gain insight into mechanisms related to object recognition and visual perception more generally. For this purpose, crowding can be used to experimentally suppress the visibility of a stimulus up to a point where it cannot be recognized any better than chance level. Stimuli under these conditions are still processed up to a certain degree, which allows the investigation of unconscious stimulus processing, a topic discussed in chapter 1.4.2.2. Moreover, crowding is especially strong in clinical conditions like amblyopia, a developmental disorder resulting in a reduced visual acuity (Hariharan et al., 2005), whereas an increased extent of crowding has been associated with dyslexia (Bouma & Legein, 1977; Gori & Facoetti, 2015; Martelli et al., 2009).

1.4.2.1 Characteristics of the crowding effect

What does the crowding effect look like? A simple demonstration illustrates that a peripherally viewed letter can be easily identified when viewed in isolation. However, when other letters are placed next to it, its recognition is impaired. Even increasing the viewing time does not seem to break the effect. Also, directly looking at the middle letter on the right helps only to identify it if it is directly fixated. When the gaze is returned to the fixation cross, we are still faced with the crowding effect: all letters on the right appear sharp in contrast but the central letter still cannot be recognized as an individual character.

This reflects the jumbled appearance observers typically use to describe the percept of the crowded area and it illustrates another important characteristic of crowding: the target object usually can be detected, but its identification is impaired (Pelli et al., 2004).

Other characteristics of the crowding effect are described in the following, including the spatial extent of crowding and its dependence on eccentricity. Crowding has been extensively investigated with respect to the area around a target in which other objects, frequently called flankers, affect target recognition. In general, smaller target-flanker separations lead to a stronger impairment of target recognition performance. Additionally, it has been observed that this target-flanker separation systematically increases with target eccentricity, the distance at which the target is presented from fixation. In an influential study from 1970, Bouma compared how the recognition performance of letters that were presented for 200ms depended on eccentricity when they appeared in isolation, flanked by two other letters or flanked by one letter. As expected, according to the reduction of visual acuity with increasing eccentricity, recognition performance for isolated letters decreased. However, recognition performance for letters flanked with one letter at each side decreased much steeper. Following this, Bouma more closely investigated different spacings between the target letter and the two flankers until recognition performances equaled those for isolated letters. Interestingly, he found this target-flanker spacing to be much larger than expected. More specifically he formulated that “for complete visual isolation of a letter presented at an eccentricity of φ°, it follows that no other letters should be presented within (roughly) 0.5 φ° distance” (Bouma, 1970, p. 178). In other words, the so called “critical spacing” between target and flanker needs to be larger than half the target eccentricity to allow for unimpaired target identification; lower values lead to a decline in performance. These interaction effects are now referred to as crowding.

Moreover, Bouma found that the detrimental effect of one flanker is larger when it is presented at the peripheral compared to the foveal side relative to the target, suggesting that the “area of interaction” (p. 178) around a target is not symmetric. A systematical investigation of this area or interaction was conducted by Toet and Levi in 1992, who used the term “spatial interaction zones” to describe their results. For this purpose, they presented an array of three stimuli at different eccentricities (0°, 2,5°, 5° and 10°) and three retinal locations (lower vertical meridian, nasal horizontal meridian and nasal 45° diagonal meridian). This array was presented in several orientations (horizontally, vertically, left diagonal and right diagonal) at each location for 150ms. It consisted of three times the letter T, which was randomly either turned upward or downward. Participants had to report the orientation of the middle T. The authors varied the distance between target and flanker (measured from center to center) and estimated the critical spacing for 75% correct target recognition. Additionally, acuity thresholds have been measured for an isolated T by determining the size at which 75% correct recognition performance is achieved at a given eccentricity. They found that the sizes of spatial interaction zones increased with eccentricity to a much larger extent than acuity threshold sizes. Most remarkably however, Toet and Levi (1992) showed that the interaction zones in the periphery had an elliptical shape. This shape reflects that the spatial interaction zones are indeed not symmetrical but extend longer in the radial direction from the center of the visual field than in the tangential direction. This finding, while interesting in itself, has implications for the experimental usage of flankers. When a target is presented below fixation, flankers positioned above and below have a larger effect than flankers positioned left and right to the target. However, when a target is presented for example left to fixation, flankers positioned above and below the target would have a smaller effect than horizontally arranged ones. Bouma (1970) presented his stimuli radially, which is why the critical spacing he reported fits well with the observation of Toet and Levi (1992), showing that the spatial zone of interaction at 10° was about 0.5 * eccentricity in the radial direction. However, according to Toet and Levi (1992) the zone of interaction would be much smaller (with about 0.1 * eccentricity) when the flankers were presented tangentially. In 2007, Pelli and colleagues reported a similar anisotropy as observed by Toet and Levi (1992).

Following the observations by Bouma in 1970, a similar relationship between target-flanker spacing and eccentricity has been observed with a wide range of different stimuli and stimulus dimensions. For example, Van den Berg et al. (2007) reported that critical spacing was about half the target eccentricity for orientation, size, saturation and hue judgements. Kooi et al. (1994) used the letter T as target stimulus, flanked by four other T stimuli, one at each side. Target and flanker were randomly either turned upward, downward, left or right and the orientation of the target letter had to be reported. Targets were presented at 10° eccentricity in the lower visual field and average target-flanker separations that determined the crowding effect were 5.7° visual angle, about half the target eccentricity.

Along these lines, it has been suggested that this relationship between critical spacing and eccentricity should be a crucial criterion for crowding (Pelli et al., 2004; Whitney & Levi, 2011). On top of that, Pelli et al. (2004) proposed that the investigated effect should be independent of target size, a characteristic that distinguishes crowding from ordinary masking. This notion has been supported by Van den Berg et al. (2007) and other studies. Tripathy and Cavanagh (2002) showed that the extent of interaction for achromatic and chromatic stimuli presented in the visual periphery did not scale with target size. Similarly, Pelli et al. (2007) showed that the critical spacing at a given eccentricity was not affected by letter size.

The relationship between critical spacing and eccentricity reported by Bouma (1970) has become such a prominent feature of crowding that the value of 0.5 has been referred to as Bouma's proportionality constant b (Pelli, 2008; Whitney & Levi, 2011). In their review from 2008, Pelli and Tillmann emphasize the fundamental nature of this observation to object recognition by calling it the "Bouma law". They propose that the recognition of objects among similar objects "depends solely on the ratio of the object spacing to the observer's critical spacing at that location" (Pelli & Tillmann, 2008, p. 1131). An important characteristic of Bouma's observation is that it was based on experiments with similar target and flanker. It seems to hold especially well when this similarity is ensured.

In fact, there are a variety of different factors that affect the critical spacing and with it the target recognition performance at a given eccentricity. These factors include for example the similarity between target and flankers, grouping mechanisms, perceptual learning and presentation time. For example, it has been suggested that differences between targets and flankers make the target "pop-out", thereby facilitating target recognition (Kooi, et al., 1994; Whitney & Levi, 2011). A diminished crowding effect has been observed when target and flankers were dissimilar in stimulus dimension like contrast polarity (Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Tripaty et al., 2014), orientation (Andriessen & Bouma, 1976), shape (Kooi et al., 1994) and depth (Kooi et al., 1994), contrast (Kooi et al., 1994) and color (Kooi et al., 1994).

Moreover, it has been shown that even flankers that exceed the critical spacing of half the target eccentricity can affect target recognition (Manassi et al., 2013). By placing additional flankers in the periphery next to the ones close to the target, its recognition performance can improve. This has been associated with grouping mechanisms that play a role in pattern recognition more generally. In Gestalt theory different principles are formulated on how complex visual input is perceived. When similar flankers group separately from the target, the target can be more easily distinguished and thus the effect of crowding can be overcome (review by Herzog & Manassi, 2015). We frequently observed in our own experiments that training noticeably improved the ability to recognize a crowded target in most participants. Similarly, Tripathy and colleagues (2014) mentioned that the extent of crowding was substantially reduced by a highly trained observer. Chung (2007) systematically investigated the effect of training and found that after 6000 trials of practice to recognize the central target letter in a string of three letters with a specific target-flanker spacing, recognition performance improved substantially. The critical spacing decreased on average by 38%. Moreover, while there seems to be no upper limit in presentation time for crowded stimuli (He et al., 1996), it has been reported that short presentation times result in an increased area of interaction around a target (Chung & Mansfield, 2009; Tripathy & Cavanagh, 2002; Tripathy et al., 2014). On the one hand this means that the crowding effect becomes stronger at a given eccentricity and on the other hand that the area of interaction can exceed the extent of half the target eccentricity when presented as short as 27ms (Tripaty et al., 2014).

Acknowledging the variety of factors that can affect critical spacing in crowding makes the labeling of a law somewhat controversial, because there is considerable variance in the crowding effect to question the generality of the law. Therefore, crowding related findings have rather been discussed in the context of Bouma's rule (Pelli et al., 2004) or Bouma's rule of thumb (Whitney & Levi, 2011). Strasburger (2020) notes that Bouma's observation from 1970 should be treated as a rule, as it was likely intended. However, he also acknowledges that "[t]he amazing robustness and generality across configurations of that rule suggests there is something much more fundamental about it." (p.7). However, inconsistencies need to be clarified before it can be treated as a law. For example, while there is considerable variance in the factor that must be multiplied with target eccentricity to determine critical spacing, the relationship between eccentricity and critical spacing remains quite robust. In this regard Strasburger (2020) proposes that the factor 0.5 should not be considered as fixed but may be adjusted according to the requirements of the task. Furthermore, he points to another important issue regarding the investigation of the critical spacing in crowding. While Bouma (1970) defined the target flanker distance as empty space between the stimuli, other authors use the center-to-center distance (Pelli et al; 2004; Pelli et al., 2007; Tripathy & Cavanagh, 2002), which is the more convenient measure when the argument about target size invariance of the crowding effect is made (Strasburger, 2020). However, this difference becomes critical when crowding is investigated at small eccentricities, because the target flanker spacing is so small that the stimuli would overlap with the center-to-center definition. Because of this relationship, Strasburger (2020) pointed out that the empty space definition is more formally correct and thus, critical spacing increases linearly with eccentricity.

1.4.2.2 Processing despite crowding

Crowding can be used to experimentally suppress the visibility of a variety of different stimulus features. Regarding the processing limit of unconscious stimuli, the question arises to what extent crowding preserves the processing of stimuli that cannot be distinguished from their neighboring flankers. Visual adaptation and priming experiments provide information based on which inferences about the depth of processing can be made. Using stimuli and tasks that require different levels of processing, it is possible to determine which stages of processing are not affected by crowding and where information processing is limited. In the following, the observations made with visual adaptation and priming experiments are presented one after the other.

The method of visual adaptation can be used to investigate neuronal responses related to the properties of an adapting stimulus. When aftereffects are not reduced in their magnitude by suppressing the visibility of the adapting stimulus with a blinding technique, it can be inferred that the mechanism by which the blinding technique achieves suppression from awareness must occur at a later stage of processing than necessary to produce the aftereffect. There are several studies showing that the orientation of real lines (Bi et al., 2009; Blake et al., 2006; He et al., 1996) and illusory lines (Montaser-Kouhsari & Rajimehr, 2005; Rajimehr et al., 2003) is processed in the absence of stimulus awareness when crowding is used. The processing of line orientation and illusory line orientation has been associated with early visual areas V1 and V2 respectively. Furthermore, Rajimehr and Montaser-Kouhsari (2005) even observed an apparent motion after effect (MAE) despite crowding, which is associated with processing in V5. However, it should be noted that Blake et al. (2006) found that orientation-specific aftereffects were smaller when the contrast of the crowded adaptors was reduced, and they did not find a translational MAE.

In the following, studies investigating the orientation-specific threshold elevation after effect (TEAE) are briefly summarized. He et al. (1996) presented adapting gratings with different tilts either as a single grating or crowded by other gratings. Although the tilt of crowded grating could not be reported above chance level, they found that the extent of orientation-specific adaptation was similar in both conditions. Blake and colleagues (2006) investigated the role of the adapting contrast on the orientation specific TEAE and the translational MAE in binocular rivalry and crowding. The finding of orientation specific TEAEs (He et al., 1996) could be replicated, but only when the contrast of the adapting stimulus was strong enough. Reducing the contrast of the adapting grating weakened orientation-specific adaptation, which was then further diminished by crowding. Furthermore, they found no dynamic MAE with crowded adaptors even at high adaptor contrasts. Following these observations, Bi and colleagues (2009) studied the orientation selective TEAE in crowded and non-crowded conditions more closely. They used high and low adaptor contrasts (as used by Blake et al., 2006) in a behavioral experiment and an fMRI experiment. First, orientation discrimination thresholds were measured for crowded and non-crowded conditions. Thresholds were elevated in crowding conditions with both contrasts, which revealed the crowding effect. The effect of crowding on the TEAE was measured separately. The TEAE for high level adaptor contrasts was larger than for low level adaptor contrasts, replicating the findings of Blake et al. (2006). However, when the attention during the adaptation phase was controlled by engaging participants in a task performed at fixation, there was no difference between TEAEs in either contrast condition (figure 2B in Blake et al, 2006;). In the fMRI experiment they found that the orientation specific TEAE in V1 was not affected by crowding but that it was weaker in V2/V3. This was true for adaptation with high and low contrasts. Taken together, these results suggest that crowding occurs at a later processing stage than V1, where neurons respond selectively to line orientations. This is supported by fMRI results (Bi et al., 2009) and the observation of preserved orientation specific TEAE with crowded adaptors (Blake et al., 2006; He et al., 1996). Other studies found orientation-specific TEAE under crowded conditions with illusory lines (Montaser-Koushari & Rajimehr, 2005; Rajimehr et al., 2003), that are supposed to be processed even later in V2 (Von der Heydt et al., 1984). Furthermore, Rajimehr et al. (2004) showed evidence that crowding allows processing up to V5, as they found apparent motion aftereffects with crowded adaptors.

Priming effects for crowded stimuli have been observed for different stimulus features like orientation of tilts in gabor-patches (Faivre & Kouider, 2011a), directional symbols (Faivre & Kouider, 2011b), facial identity (Faivre & Kouider, 2011b), facial expressions (Faivre et al., 2012) and semantic information (Yeh et al., 2012). In a recent review Manassi and Whitney (2018) pointed out that although crowding can be used to effectively suppress the visibility of a variety of stimuli, the processing of those stimuli seems unaffected, which can be observed as aftereffects or priming effects. This indicates that crowded information is represented at various processing stages. On the one hand, this qualifies crowding as a method that is particularly well suited to study unconscious processing and the NCCs. On the other hand, this complicates the implementation of a model that explains all characteristics of crowding.

It is well established that crowding is a cortical phenomenon, because crowding still occurs when target and flankers are presented to different eyes. This has been observed in foveal vision (Flom et al., 1963) and in the visual periphery (Kooi et al., 1994; Tripathy & Levi, 1994). For this reason, it has been concluded that the effect crowding is not of retinal origin, but must occur in the cortex, where visual information from both eyes is combined. However, there is still considerable disagreement on the mechanisms underlying crowding. There are different theories that can largely be distinguished by accounting for crowding either as a bottom-up or a top-down process. Moreover, there is an increasing number of computational models that try to capture the characteristics of the crowding effect. In the following, some of these accounts will be discussed in more detail.

On the one hand, there are indications that some characteristics of the crowding effect are well captured by the anatomy of the pathways processing visual information, which speaks in favor of bottom-up accounts to explain crowding. For example, Toet and Levi (1992) investigated the size of the zone of interaction around a target for different eccentricities. In the periphery they found a strong anisotropy of these zones of interactions as they were shaped elliptically, extending more in radial compared to tangential directions. This could for example be related to the elongated form and radial orientation bias of receptive fields in the periphery. This is further supported by the observations that other tasks show similar effects with superiority in a radial direction. As outlined above in connection with Bouma's rule a main characteristic of crowding has become that the spatial extent of crowding (critical spacing) increases linearly with eccentricity. In this context it has been proposed that the critical distance in crowding is associated with a fixed cortical distance in retinotopically organized visual areas (Pelli, 2008). Neurons in the early visual cortex represent input from the visual field in an organized way. Adjacent neurons process adjacent areas of the visual field, which can be depicted in a so called retinotopic map. An important characteristic of this retinotopic map is its distortion. This distortion results from the fact that the cortical area representing the central part of the visual field is larger than the cortical areas representing the peripheral visual field. This can be quantified by the cortical magnification factor (M) describing how the number of neurons in the visual cortex changes in relation to the location of the visual field they represent. M can be expressed as millimeters of cortical surface per degree of visual angle. Values of M are highest in the fovea and decrease with larger eccentricities. This relationship can be described as a logarithmic function, which Pelli (2008) used to calculate the area of crowding for retinotopic visual areas with a fixed critical spacing.

On the other hand, other findings support the view that crowding can also be explained as a top-down related process. According to this view the crowding effect is suggested to be related to the limited spatial resolution of attention (He et al., 1996; Intriligator & Cavanagh, 2001). He et al., (1996) showed that the orientation specific TEAE was not diminished by crowding, although participants were unaware of the orientation of the crowded grating. Because the processing of orientation information was not influenced by crowding the authors concluded that the effect of crowding must unfold after visual area V1, where the processing of orientation information begins. Moreover, they suggested that limited attentional resolution could be a mechanism central to crowding, as crowding and other attention demanding tasks were subject to a visual field asymmetry in such a way that performance was worse in the upper compared to the lower visual field. Interestingly, there are more projections from early visual areas to parietal regions originating from the lower compared to the upper visual field. In accordance with these physiological findings the authors suggested that "dorsal parietal areas may control attentional resolution and the information entering our conscious vision" (He et al., 1996, p. 337). Strasburger (2005) suggested that crowding can also be explained by a combination of bottom-up and top-down processes.

A popular model for object recognition that is often referred to in crowding is a two-step model that incorporates a stage of feature detection and a stage of feature combination (Levi, 2008; Pelli et al., 2004; Pelli & Tillmann, 2008). In the first stage simple object features are detected independently by specific receptive fields of neurons in the primary visual cortex. In the second stage some of these features are combined to an object. Crowding is supposed to affect only the second stage. This view is supported by the observation that crowding does not affect stimulus detection and studies showing that although crowded objects are not consciously perceived, stimulus features are still processed up to a certain degree. However, while this model is suitable to embrace a variety of experimental results, it is not very specific about the mechanism underlying crowding (Pelli & Tillmann, 2008). Different mechanisms that fit into the framework of this second stage have been proposed like integration (Pelli et al., 2004), or pooling (Parkes et al., 2001).

An increasing number of computational models have been developed more recently reflecting that there is little agreement on the mechanisms underlying crowding. Although there are attempts to unify different accounts, as for example by the weighted feature model (Harrison & Bex, 2015) or the texture synthesis model (Keshvari & Rosenholtz, 2016), it seems to be difficult to describe different aspects of crowding by a single model (Agaoglu & Chung, 2016). For this reason, computational models are not discussed further at this point.

1.4.2.3 Temporal crowding

Although crowding has for most of its history been regarded as a spatial effect, more recent studies have also started to consider the influence of temporal variations on crowding. Consequently, it has been suggested that crowding should be regarded as a spatiotemporal phenomenon (Chung, 2016; Herzog et al., 2016; Lev et al., 2014).

However, what is understood by "temporal crowding" differs widely depending on the subject that is studied. For example, Pelli et al. (2004) distinguish spatial crowding from temporal crowding by emphasizing that spatial crowding depends on spatial proximity, independent of time pressure, while temporal crowding depends on time pressure, independent of spatial proximity. This temporal crowding occurs for example when more than one object must be recognized in a very short time. It seems to be related to the visual span of apprehension and Pelli et al. (2004) explain it within the framework of the feature integration theory (Treisman & Schmidt, 1982), which proposes a serial attentional process underlying object recognition. Thus, Pelli et al. (2004) further propose that temporal crowding reveals the maximum rate at which objects can be recognized, while spatial crowding reveals the minimum spacing at which objects can be recognized. In contrast, Yeshurun et al. (2015) refer to spatial crowding when the recognition of a target is reduced by other stimuli surrounding it in space, while in temporal crowding target recognition is reduced by other stimuli surrounding it in time.

Independent of these definitions, some effects of temporal variations in crowding are discussed in the following, including the stimulus duration and the temporally delayed presentation of flankers. One advantage of crowding over other blinding techniques is the notion that stimuli can be presented for relatively long (Faivre et al., 2014; Kim & Blake, 2005) or even unlimited viewing time (He et al., 1996) without breaking the effect. Especially in conditions with a strong crowding effect (e.g., large eccentricities and small target-flanker spacings), this seems to be the case. For example, He et al. (1996) presented gratings at 25° eccentricity above fixation, flanked by two other gratings at each side with 4° visual angle between each element. In this condition, they mentioned that participants were not aware of orientation of the target grating in the middle, even though the presentation time was not limited.

On the contrary, reducing the presentation time seems to increase the crowding effect. There are suggestions that the critical spacing (the distance between target and flanker below which the effect of crowding occurs at a certain eccentricity) is not fixed at half of the target eccentricity (Bouma, 1970), but dependent on the presentation time of the crowded stimuli. Several studies have shown that the critical spacing seems to be larger for shorter presentation times, which has been reported for foveal (Lev et al., 2014) and peripheral crowding (Chung & Mansfield, 2009; Tripathy & Cavanagh, 2002; Tripathy et al., 2014). More specifically, when Tripathy and Cavanagh (2002) investigated the relation between target size and the spatial extent of crowding, they varied the presentation duration to equate target visibility. In this way, they found that presentation duration systematically affected the spatial extent of crowding, since it was larger for a 13/ 27ms stimulus than for a 360ms stimulus. Chung and Mansfield (2009) presented the letter T (flanked by one T at each of the four sides) in the lower visual field at 10° eccentricity for different durations (53, 174 and 1000 ms) with similar and different target-flanker contrast polarities and found that the spatial extent of crowding was larger with shorter stimulus durations in both cases. Tripaty et al. (2014) investigated the influence of presentation time more systematically and found that the spatial extent of crowding was constant for presentation durations shorter than 27 ms and decreased systematically with stimulus durations of up to 427 ms (Experiment 1). Additionally, they pointed out that the spatial extent of stimuli presented for 27 ms was larger than half of the target eccentricity, the critical spacing observed by Bouma (1970).

Pelli et al. (2004) suggested that delaying the flanker onset relative to the target onset in crowding could affect target recognition performance in a similar way compared to metacontrast masking. Along these lines, Huckauf and Heller (2004) investigated the effect of flankers occurring before, simultaneously, or after the target in combination with a variation of target-flanker distance (0.4°, 1° and 2° in Experiment 1) and target eccentricity (1°, 4° and 7° in Experiment 2) and compared the recognition performance to visual masking. Target letters were shown along the horizontal meridian in the right or left visual field flanked by two other letters, one on the left and one on the right to the target. Target and flanker were presented for 50ms and the SOA between them could be 0, 50, 100 or 150 ms before or after the target. Huckauf and Heller (2004) found that the effect of target-flanker distance at different eccentricities decreased with longer SOAs (up to an SOA of 150 ms). As recognition performance for isolated letters was still better than in conditions with the largest SOA of 150 ms (Experiment 3), they concluded that even with an inter stimulus interval (ISI) of 100 ms between the stimuli, flankers seem to affect target recognition. Moreover, they observed that target recognition performance could be described by type A and type B masking functions, which are associated with different mechanisms in visual masking. This indicates that similar mechanisms could also play a role in crowding when flankers are presented with a delay. On the one hand, type A masking functions are characterized by a monotonic increase of recognition performance with increasing SOAs. This has for example been associated with an integration mechanism (Turvey, 1973) that is especially strong when target and mask appear close in time, because information from both stimuli cannot be processed separately and are thus combined. When the SOA between target and mask increases integration becomes less likely and target recognition improves. Integration is a mechanism that is often suggested to play a role in crowding, e.g., with respect to the two-step model approach (Parkes et al., 2001; Pelli et al., 2004). On the other hand, Type B masking functions are typically u-shaped, because target recognition performance is worst at intermediate SOAs. One mechanism that could be related to these behavioral results is described by the interactive activation account (Di Lollo et al., 2000). According to this account higher-level feedback processes can explain that target recognition performance is most strongly impaired at intermediate SOAs. While the target is still processed, the mask is presented and the timing between these events is such, that bottom-up information from the mask interferes with the top-down information from the target. Interestingly, Huckauf and Heller (2004) observed type A masking functions more frequently in conditions associated with a strong crowding effect (large eccentricities and small target-flanker separations), while type B masking functions were mainly observed in conditions associated with weak crowding (small eccentricities and large target-flanker spacings). This shows that the strongest crowding effect is not per se achieved with the simultaneous presentation of target and flankers. Instead, it depends on target-flanker spacing and eccentricity, while in relation to those parameters, different processes could affect target recognition performance. An integration process could play the main role in crowding at small target-flanker separations and large eccentricities, because features from all stimuli are combined to a jumbled percept. When in contrast, target eccentricity is small enough and target-flanker spacings are sufficiently large to allow for the computation of higher-level target information, the process that affects target recognition could be related to a mismatch between target feedback and flanker information. This could explain why, according to the interactive activation account, the delayed presentation of flankers would impair target recognition more strongly under these conditions.

Chung (2016) systematically investigated the spatiotemporal window for crowding, which was defined by the target-flanker spacing (0.8, 1, 1.25 and 2 x target width) and 13 different target-flanker SOAs (between -150 and 150ms in steps of 25ms). With these variations a target letter was presented at 0° and 10° eccentricity, flanked by two other flankers positioned on the left and right to the target. The crowding effect was measured as difference between the performance identifying the target letter in isolation versus flanked. In general, they found that there was a trade-off between temporal and spatial variations of the flanker presentation in crowding. While larger spatial and temporal distance lead to improved target recognition, a similar performance could be obtained with an increase in either dimension. Replicating the findings of Huckauf and Heller (2004), Chung (2016) also observed that target and flanker do not have to be presented simultaneously to induce the strongest crowding effect. For the largest target-flanker spacings (2* letter width) the strongest crowding effect occurred when flankers were presented with an SOA of 50ms. This was true for targets presented foveally and at 10° eccentricity in the lower visual field. These findings conflict with notions that in crowding simultaneous presentation of target and flankers produces the strongest effect, which has been suggested as a criterion to distinguish crowding from other forms of masking (Enns, 2004; Whitney & Levi, 2011).

Moreover, Chung (2016) suggested that the dual-channel model (Breitmeyer & Ganz, 1976; Breitmeyer & Öğmen, 2000) frequently used to explain the effects of visual masking is also well suited to describe their findings. With larger target-flanker separations, the strongest crowding effect shifted to more positive SOAs. Thus, type B masking effects were observed in conditions where the crowding effects were weaker. Although mechanisms associated with visual masking can account for these results, it is not clear to what extent these results are due to visual masking or crowding (Chung, 2016).

1.4.3 Comparison of visual masking and crowding

Various attempts have been made to distinguish crowding from visual masking. For example, Pelli et al. (2004) pointed out that a major difference between crowding and ordinary masking (when target and mask spatially overlap) is that crowding scales with eccentricity independent of size, while masking scales with size independent of eccentricity, suggesting that this characteristic should be a diagnostic criterion for crowding. Moreover, target detection is not affected by crowding (but recognition is impaired), while in ordinary masking the signal disappears (Parkes et al., 2001; Pelli et al., 2004; Whitney & Levi, 2011). Chung et al. (2001) found that masking and crowding share some properties (spatial frequency tuning and weaker effects for low-contrast masks) but argue that they are distinct phenomena, suggesting that in masking information is rather pooled over time, while in crowding information is pooled over space. Whitney and Levi (2011) suggested that crowding is especially strong for simultaneous presentation of target and flanker, what distinguishes the effect from metacontrast masking and OSM. However, depending on the conditions crowding and visual masking can share temporal characteristics (Lev & Polat, 2015). For example, Chung (2016) and Huckauf and Heller (2004) showed that the strongest masking effect with spatiotemporal crowding can also be found with positive SOAs. These type B masking functions were observed with large spacings and small eccentricities. The authors acknowledged that similar mechanisms as in metacontrast masking could account for these observations. Thus, especially in comparison to metacontrast masking, the observed effects can be very similar. Although the interaction of eccentricity and target flanker separation is much more investigated in crowding compared to metacontrast masking, stronger masking effects can be found for larger separations of target and mask when presented in the visual periphery (Breitmeyer & Öğmen, 2006). This is perhaps not surprising when the presentation conditions are similar, because the stimulus processing is affected by retinal eccentricity. Sometimes masks that are usually used as metacontrast are, perhaps unintentionally, applied to investigate crowding (Agaoglu & Chung, 2016; Harris & Bex, 2015), indicating that the differences between those methods can be very subtle. While crowding and visual masking have a different history associated with their own research practice that should be acknowledged, it could be helpful to unify different approaches for the benefit of an improved understanding of visual processing mechanisms more generally. As Francis and Cho (2008) pointed out, models of visual masking would profit from the integration of spatial information, and similarly, models of spatial vision (like crowding) could be improved by including temporal information.

2 Study 1

Priming effects of visual stimuli masked by spatiotemporal crowding do not depend on the strength of the mask

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2.1 Abstract

Crowding is a visual phenomenon that we experience as difficulties in distinguishing objects when they are spaced closely together. This effect is particularly strong in the visual periphery and goes beyond the reduction of visual acuity. Due to these properties crowding has been used to experimentally manipulate stimulus visibility for studying the NCCs. To this date, the origin of crowding is unclear, and it has largely been investigated in relation to spatial manipulations of the visual stimuli. However, in this paper we focused on the effects of temporal variations in crowding. This perspective allows us to compare the effects of different techniques used to reduce stimulus visibility and thus, draw conclusions about more general mechanisms that govern stimulus processing of stimuli that do not reach awareness.

We investigated the processing of color and categorical information in separate but otherwise identical priming experiments that differed only regarding the instruction. Prime visibility was reduced by crowding to different degrees as we varied flanker onsets and flanker contrasts.

In general, prime visibility improved with longer delays to flanker onsets and with weaker flanker contrasts. However, prime processing was only affected by variations in flanker onsets. More specifically, reaction time priming effects increased with longer flanker onset delays but were unaffected by flanker contrasts. We concluded that the processing of primes reduced in their visibility by crowding depended on uninterrupted prime processing times. The prime visibility per se does not seem to be a sufficient indicator of priming effect magnitude. In this aspect temporal crowding resembles masking.

A plethora of blinding techniques can be used to experimentally suppress stimulus visibility via different mechanisms. Breitmeyer (2015) proposed a functional hierarchy of blinding techniques based on the assumed depth of stimulus processing they allow. Along these lines, we suggest that not only the processing of a stimulus feature under different blinding techniques, but also the processing of different stimulus features within the same technique should be systematically investigated. We provide further evidence and discuss the importance of these reflections in the search of NCCs.

2.2 Introduction

A central issue of psychology is the extent to which unconscious information can affect cognitive processing (e.g., Chalmers, 1996; Dolan, 2002; Holender, 1986; Kouider & Dehaene, 2007; Sidis, 1898; Van den Bussche, Van den Noortgate, & Reynvoet, 2009). This issue has been investigated by various experimental studies that employed different methods to achieve conditions in which visual stimuli cannot be consciously perceived by the participants (e.g., Breitmeyer, 2015; Kim & Blake, 2005; Kouider & Dehaene, 2007). Several studies used metacontrast masking to prevent conscious perception of briefly presented prime stimuli which were followed by clearly visible targets to which participants had to respond in a speeded choice reaction time (RT) task (e.g., Ansorge et al., 2009; Ansorge et al., 2007; Ansorge et al., 1998; Breitmeyer et al., 2004; Klotz & Wolff, 1995; Lau & Passingham, 2007; Mattler, 2003; Neumann & Klotz, 1994; Schmidt, 2000; 2002; Vorberg et al., 2003).

One distinguished study employed small arrow stimuli as primes and larger arrows with an aperture in the size of the two prime alternatives that simultaneously severed as metacontrast masks and as targets (Vorberg et al., 2003). With primes of short stimulus durations and masks of long stimulus durations participants could not discriminate between left and right pointing prime stimuli. Nonetheless, reaction times (RTs) were facilitated on congruent trials on which prime and target pointed to the same direction as opposed to incongruent trials on where prime and target pointed to opposite directions. This priming effect increased monotonically when the SOA between the prime and the target was increased. Very similar priming effects over SOA were found when the duration of prime and mask stimuli was varied, and participants could discriminate left and right pointing primes. In conclusion, this study demonstrates action priming effects independent from the visibility of the effective stimuli. This finding was replicated and confirmed by several later action priming studies that employed metacontrast masking (e.g., Albrecht, Klapötke, & Mattler, 2010; Becker & Mattler, 2019; Mattler, 2003; 2005; 2006; Mattler & Palmer, 2012; Schmidt, 2000; 2002; Wernicke & Mattler, 2019).

In contrast to the acceptance of action priming by unconscious stimuli, there is some controversy regarding the effects of unconscious stimuli on higher level processing like semantic processing (e.g., Kouider & Dehaene, 2007; Holender, 1986). Semantic priming, for instance, has been reported by some studies as an effect of unconscious stimuli due to masking (e.g., Adams & Kiefer, 2012; Kiefer & Brendel, 2006) while other studies reported absence of semantic priming with masked stimuli (e.g., Duscherer & Holender, 2002; Nolan & Caramazza, 1982). The meta-analysis of Van den Bussche and colleagues (2009) suggested a positive relation between semantic priming effects and prime visibility which has been reported by some studies (e.g., Eckstein & Henson, 2012; Kouider & Dehaene, 2009; Naccache & Dehaene, 2001), while other studies reported more complex, non-linear relationships between semantic priming effects and conscious perception of the prime (e.g., Dagenbach, Carr, & Wilhelmsen, 1989; Fischler & Goodman, 1978; Sereno & Rayner, 1992).

This complexity of findings results from studies which employed a variety of procedures with abundant differences. The present study addresses only two of these procedural differences, namely the experimental task and the masking procedure used to prevent conscious perception of the effective stimuli. In a previous study, Wernicke and Mattler (2019) examined the role of masking methods for the occurrence of priming effects in categorical and action priming. In both tasks, priming effects were compared in conditions with different masking methods and experimentally varied masking strengths. With metacontrast masking, virtually the same priming effects occurred irrespective of masking strength. However, when primes were masked by preceding and following pattern masks (sandwich masking) of various strengths, priming effects correlated negatively with masking strength. Interestingly, this difference in masking methods occurred within a perceptual priming task where the color of prime stimuli modulated the response to the color of target stimuli, and also in a categorical priming task, where participants reported whether the target was a digit or a letter.

These findings suggest that priming effects can vary with masking methods: With metacontrast masking action priming and semantic priming are independent from prime visibility; with pattern masking or sandwich masking, however, priming effects depend on the visibility of the prime. To isolate the crucial aspect of the latter masking method, Becker and Mattler (2019) compared priming effects on trials with and without sandwich masking. When metacontrast masks were supplemented by an additional forward mask, priming effects could be severely reduced and even abolished. Similarly, when sandwich masking was employed with a forward and backward pattern mask, priming effects could be related to measures of prime visibility. In conclusion, this study suggests that forward masking suppresses priming effects with both metacontrast and pattern masks.

The role of the masking method for priming effects has recently been examined by Valuch and Mattler (2019) who employed CFS to prevent conscious perception of the prime (Tsuchiya & Koch, 2005; Tsuchiya, Koch, Gilroy, & Blake, 2006; Yang, Brascamp, Kang, & Blake, 2014). Initial studies that employed CFS reported impressive priming effects (e.g., Bahrami et al., 2010; Mudrik, Breska, Lamy, & Deouell, 2011; Sklar et al., 2012) that were disputed on methodological grounds later (e.g., Hesselmann, Darcy, Rothkirch, & Sterzer, 2018; Moors, Hesselmann, Wagemans & Van Ee, 2017; Yang & Blake, 2012). Valuch and Mattler took these methodological considerations into account and examined whether priming effects of simple stimuli like those used by Vorberg et al. (2003) produce priming effects with CFS. Small arrow stimuli were shown as primes to one eye while a dynamically changing stimulus sequence of randomly positioned overlapping filled circles was shown to the other eye. Prime visibility was varied by the contrast of the circles and the contrast of the prime. While choice-RTs and error rates to visible target arrows (that were shown to both eyes) were influenced by the congruency of the primes, these action priming effects depended on the visibility of the primes. These findings demonstrate that CFS affects both conscious perception of the prime’s identity and the effects of the stimuli on the processing of the targets.

Taken together, these studies provide evidence for the view that masking methods modulate the relation between priming effects and conscious perception of visual primes. On the one hand, Metacontrast masking seems to suppress visual perception without disturbing the stimuli's effect on other types of processing as reflected in the stimuli's priming effects. On the other hand, CFS and forward masking seems to affect both visual perception and priming effects of stimuli. These findings are consistent with the distinction suggested by Breitmeyer (2015) that different masking procedures modulate visual processing at different levels in the visual hierarchy. The present study examined the effects of another masking method regarding the relation between priming and prime perception, which presents another type of masking procedure within this hierarchy: visual crowding.

Visual crowding causes the recognition performance of an object to decrease significantly as soon as there are other similar objects in the vicinity. In contrast to other masking procedures crowding is a phenomenon that is ubiquitous in vision (Levi, 2008) and its importance is emphasized by Whitney and Levi referring to crowding as "fundamental limit on conscious visual perception" (2011, p. 161). A crowded object can still be detected but is not distinguishable from nearby similar objects (Pelli et al., 2004), often described as a percept in which different object parts appear "jumbled together" (Levi, 2008, p. 637). The effect of crowding is especially strong in the visual periphery, since the distance between objects needs to be surprisingly large to ensure unimpaired recognition performance.

Crowding is well studied regarding the area around a target at which flankers limit its recognition performance. The strength of crowding is reflected by the performance at a specific target-flanker spacing. The target-flanker spacing at which flankers begin to affect target processing is called "critical spacing" (Levi, 2008) and it reflects the spatial extent of crowding.

The spatial extent of crowding strongly depends on eccentricity, reaching up to half of the eccentricity at which the target is presented (Bouma, 1970). More specifically, it has been found that the shape of "spatial interaction zones" in crowding is elliptical in the visual periphery, extending more in the radial direction (0.5 x eccentricity) than tangential direction (0.1 x eccentricity) relative to the center of the visual field (Toet & Levi, 1992). Another characteristic property of the crowding effect is that it does not depend on the size of the target, which distinguishes crowding from ordinary visual masking (Pelli et al., 2004). This notion is supported by studies that found that the spatial extent of crowding did not scale with target size (Pelli et al., 2007; Tripathy & Cavanagh, 2002; van den Berg et al., 2007).

The critical spacing found with a variety of different stimuli and tasks has been compared to Bouma's observations, either because it was remarkably similar to half of the target eccentricity or because it deviated substantially. For this reason, it seems not surprising that the critical spacing of about 0.5 has been referred to as Bouma's proportionality constant b (Pelli, 2008) or Bouma's rule (Pelli et al, 2004; Whitney & Levi, 2011). On the one hand, critical spacings of about half the target eccentricity have been found in relation to different stimulus properties including orientation, size, saturation and hue judgements (van den Berg et al., 2007). Likewise, Kooi et al. (1994) reported a critical spacing of 5.7° for the ability to recognize the orientation of the letter T (upward, downward, left or right), when flanked by similar stimuli. On the other hand, it has been observed that the critical spacing in crowding can be modulated by different factors. Typically, the effect of crowding is strong when target and flankers are similar. The crowding effect was reduced, when target and flankers differed in properties like contrast polarity (Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Tripaty et al., 2014), orientation (Andriessen & Bouma, 1976), shape (Kooi et al., 1994) depth (Kooi et al., 1994), contrast (Kooi et al., 1994) and color (Kooi et al., 1994). Moreover, grouping mechanisms also seem to interact with crowding (reviewed by Herzog & Manassi, 2015). Adding additional flankers, even when they appear outside the critical spacing, can reduce the crowding effect, because flankers appear grouped separately from the target (Manassi, Sayim, & Herzog, 2013). Additionally, it has been pointed out, that the strength of crowding can be reduced by perceptual learning (Chung, 2007; Tripathy et al., 2014), which is what we also observed in our experiments with highly trained observers. While crowded stimuli can be presented for relatively long presentation times without breaking the suppressive effect (He et al, 1996; Faivre et al., 2014; Kim & Blake, 2005), short presentation times increased the extent of crowding (Chung & Mansfield, 2009; Tripathy & Cavanagh, 2002; Tripathy et al., 2014) and critical spacings larger than 0.5 have been observed with stimuli as short as 27ms (Tripathy et al., 2014).

Although crowding is mainly regarded as a spatial effect, it has been pointed out that temporal variations between target and flankers can affect crowding (Whitney & Levi, 2011). More recently, it has been suggested to consider crowding as a spatiotemporal phenomenon (Chung, 2016; Herzog et al., 2016; Lev et al., 2014). However, it is less clear, what exactly is meant by "temporal crowding". For example, Pelli et al. (2004) refer to temporal crowding as the maximum rate at which objects can be identified (related to the visual span of apprehension) in contrast to spatial crowding which is the minimum spacing at which objects can be identified (at a given eccentricity). On the contrary, Yeshurun et al. (2015) referred to temporal crowding when the visibility of target stimulus is suppressed by flankers occurring before and after the target in time.

There are some studies that investigated the effect of temporarily delaying the flanker onset relative to the target onset on crowding (Chung, 2016; Huckauf & Heller, 2004). First, there seems to be a tradeoff between spatial and temporal distance in crowding, in such a way that smaller target-flanker spacings can be compensated by larger target-flanker SOAs (and vice versa) to achieve a similar target recognition performance (Chung, 2016). Huckauf and Heller (2004) found that the influence of target-flanker spacings at different eccentricities decreased with longer SOAs (up to an SOA of 150 ms). As recognition performance for isolated letters was still better than in conditions with the largest SOA of 150 ms, they concluded that even with an ISI of 100 ms between the target and flankers, target recognition seemed to be impaired. Interestingly, Huckauf and Heller (2004) observed that recognition performance increased monotonically with SOA more frequently in conditions associated with a strong crowding effect (large eccentricities and small target-flanker separations, while the strongest crowding effect occurred more frequently at intermediate SOAs in conditions associated with a weak crowding effect (small eccentricities and large target-flanker spacings). Based on the similarity to type A and type B masking functions they suggested that similar mechanisms as in visual masking could be contributing to crowding. Similarly, Chung (2016) found that the maximal crowding effect shifted to positive SOAs when target-flanker spacings were large. Taken together, these observations indicate that the strongest crowding effect is not per se achieved with the simultaneous presentation of target and flankers. Instead, depending on target-flanker spacing at a given eccentricity, different processes could affect target recognition performance.

Crowding still occurs when target and flankers are presented to different eyes (Flom et al., 1963; Kooi et al., 1994; Tripathy & Levi, 1994). For this reason, it is well established that the crowding effect emerges in the cortex, where visual information from both eyes is combined. Other than that, there is still considerable disagreement on the mechanisms underlying crowding.

A popular model of object recognition is the two-stage model that incorporates a stage of feature detection and a stage of feature integration (Levi, 2008; Pelli et al., 2004; Pelli & Tillmann, 2008). In the first stage simple object features are detected independently presumably by receptive fields of neurons in the primary visual cortex. In the second stage some of these features are combined to an object. Crowding is supposed to affect only the second stage, probably somewhere after V1. This view is supported by the observation that crowding does not impair stimulus detection and studies showing that although crowded objects are not consciously perceived, stimulus features are still processed up to a certain degree. However, neither the neuronal locus of crowding, nor the mechanisms associated with the feature integration stage are further specified.

Additionally, there are different theories that can largely be distinguished by accounting for crowding either as a bottom-up or a top-down process. On the one hand, the effect of crowding has been related to limitations in the physiology of the visual system. For example, it has been suggested that the extent of crowding (about half the target eccentricity in radial direction) corresponds to a fixed spacing in the primary visual cortex (Pelli, 2008). Thus, objects can only be identified when the distance in the cortical representation of these objects is large enough (6 mm radially in V1). Interestingly, Tripathy and Levi (1994) observed crowding even when flankers were presented around the blind spot of one eye and the target to the corresponding region of the other eye. As it has been reported that the cortical representation of the blind spot is monocular, they suggested that horizontal connections of neurons in V1 could account for their results. The average extent of crowding at the blind spot was about 8°, which they estimated to correspond to a mean distance of 6.4 mm in the human visual cortex. This seems to be in good agreement with the length of long-range horizontal connections in V1.

On the other hand, it has been proposed that crowding occurs because the isolation of target and flanker features is limited by the "attentional resolution" (He et al., 1996; Intriligator & Cavanagh, 2001). There is some indirect evidence that attention contributes to the crowding effect. He et al. (1996) showed that the orientation-specific aftereffect was not diminished by crowding, although participants were unaware of the orientation of the crowded grating. Because the processing of orientation information remained unaffected by crowding the authors concluded that the effect of crowding must unfold after visual area V1, where the processing of orientation information occurs. They suggested that the conscious perception of crowded stimuli could be impaired due to interference with information processing in dorsal parietal areas associated with the control of attentional resolution. This is supported by the finding that crowding and other attention demanding tasks were subject to a visual field asymmetry in such a way that performance was worse in the upper compared to the lower visual field (He et al., 1996). In this context they pointed out that there are more projections from early visual areas to parietal regions originating from the lower compared to the upper visual field. The involvement of attention in the crowding effect is supported by findings of Chakravarthi and Cavanagh (2007) who observed that the polarity advantage effect (crowding is reduced when target and flanker differ in contrast polarity) follows a similar temporal resolution as attention.

In a recent article, Manassi and Whitney (2018) reviewed different experiments showing that information at different levels of processing is preserved although the access to crowded stimuli is impaired. This view is supported by evidence showing that crowded information seems not to be lost, but neuronally represented in such a way that it can affect processing of subsequent stimuli. As crowding seems to occur at different levels of visual processing any account that focuses on mechanisms in an early stage of processing can explain crowding only insufficiently (Manassi & Whitney, 2018). The locus of crowding does not seem to be specific, as it can occur at different stages depending on the stimulus information that is crowded.

Additionally, some priming studies provide evidence that even under crowding conditions, prime information can be processed. In these experiments a crowded prime stimulus is usually followed by a target stimulus, that can either be different (incongruent) or similar (congruent) with respect to the task relevant feature. The task that has to be performed on the target usually requires discrimination. Reaction times and error rates measured in incongruent minus congruent conditions provide information about prime processing in the form of priming effects. Priming effects larger than zero indicate that the prime stimulus affected target processing. Thus, although the crowded prime was not consciously perceived, it can be concluded that it was processed up to a certain degree. With simple orientation stimuli presented at an average eccentricity of 17° for 200 ms, Faivre and Kouider (2011b) found 52 ms priming effects in the crowded condition. Even complex stimuli consisting of multiple features can produce priming effects under crowding conditions. Faivre and Kouider (2011a) found an 11.5 ms action priming effect with directional arrow symbols and a repetition priming effect of 19 ms with famous faces with crowded primes presented for 200-1400 ms at 15° eccentricity. Moreover, it has been shown that even semantic information seems to be preserved by crowding. Yeh, He and Cavanagh (2012) found semantic priming effects of Chinese single character words that did not statistically differ between crowded and non-crowded conditions.

In the present study we used a priming paradigm similar to Wernicke and Mattler (2018), who investigated the processing of primes gradually reduced in their visibility by sandwich pattern masking and metacontrast masking respectively. In the same manner, we reduced the visibility of primes with crowding. The flankers that induced crowding were presented simultaneously with the target at four prime-target SOAs (30, 60, 90 and 120 ms) and with three contrasts (weak, medium, strong). We used similar green and red letters and digits as prime and target stimuli, and in two different experiments asked the participants to do a color discrimination (red or green) or a semantic categorical discrimination (letter or digit).

The purpose of this study was twofold. First, we investigated whether the processing of color information or semantic categories is affected by crowding. When priming effects vary in size in relation to prime visibility, it indicates that crowding interferes with the processing of the investigated stimulus properties (color/semantic categories). However, when priming effects emerge independent from prime visibility, it suggests that stimulus properties like color or semantic categories are processed despite crowding. Second, we investigated how the strength of the crowding effect is modulated by presenting flankers with different SOAs and contrasts. Considering the influence of temporal aspects in crowding could help to understand the underlying mechanisms and its relation to other masking methods.

To anticipate our results, we found that priming effects for color and semantic categories increased with longer SOAs between crowded primes and targets. This is similar to observations with metacontrast masking (Wernicke & Mattler, 2003; Vorberg et al., 2003). Most importantly, priming effects did not differ between primes that were crowded with different flanker contrasts. This supports the hypothesis that crowding does not interfere with the processing of color information or semantic categories.

Moreover, we showed that the discrimination performance of color and semantic categories in crowding depends on an interaction of flanker delay and flanker contrast. The performance improved with longer SOAs between prime and flanker, comparable to earlier observations (Chung, 2016; Huckauf & Heller, 2004). However, this improvement was larger for strong flanker contrast in comparison to medium flanker contrast. Regarding weak flanker contrast, ceiling performance was already reached at the shortest SOA of 30ms.

2.3 Method

2.3.1 Participants

A total of 32 healthy students from the University of Göttingen were randomly and equally assigned to two groups and participated in the experiment, which was conducted over five sessions on different days. All participants gave written informed consent and received 7€ per hour of participation. The five sessions of the experiment took about 6 hours. Participants had normal or corrected-to-normal vision and showed no deficiency in red-green vision in an Ishihara's Test with 14 colored plates (Ishihara, 1972). One group of participants performed a color discrimination task (9 female, 7 male) and the other group performed a categorical discrimination task (12 female, 4 male). In both groups, participants were on average 24 years old, ranging between 20 to 32 in the color group and between 19 to 28 in the category group.

2.3.2 Stimuli

The stimulus set illustrated in Figure 1 A consisted of 8 primes and 8 targets. The primes were the numbers 3, 4, 5 and 9 and the letters A, E, F and H, while the targets were the numbers 2, 6, 7 and 8 and the letters C, G, P and U. Different prime and target stimuli were deliberately chosen to avoid identity priming. These stimuli were presented with a size of 1.5° x 1.7° visual angle and appeared in two Iso luminant colors: green and red (both 20.5 cd/m²). Moreover, primes and targets of each stimulus category were balanced for the number of pixels and openings to avoid the possibility to solve the task based on low-level features.

To establish visual crowding, primes were presented in the middle position of a virtual 3 x 3 grid. On the remaining positions, we presented eight flankers (Figure 1 B). In this crowding display, the center-to-center distance between two adjacent elements was always 3° of visual angle. Prime, target, and flanker stimuli were generated in the form of digital characters, using different line combinations that make up the number eight. Flankers consisted of two bars that did not adjoin one another. These bars could appear vertically, horizontally, or in either orientation. In this way, the flankers resembled the prime, but could not be confused with it. In each trial a new random combination of eight flankers was drawn from a set of 13 different flankers. These eight flankers were balanced according to color (four red and four green) and with respect to the amount of horizontally and vertically oriented bars. Thus, flankers could induce visual crowding for both color and category of the prime simultaneously. To vary the strength of crowding, we presented the flankers with three different contrasts (3%, 30% and 100%) to achieve three levels of Flanker Contrast (weak, medium, and strong, respectively).

2.3.3 Tasks

On each trial, each participant was prepared to do one of two tasks depending on the unpredictable stimulus that was presented at fixation. When a target stimulus appeared, participants were instructed to discriminate the relevant feature of the target in a speeded choice RT task. When instead a blue star appeared at the target position, they were to do a prime discrimination task without speed stress on the relevant feature of the prime. Participants were instructed to take their time and answer as correctly as possible. One group of participants processed the stimuli on a perceptual task level since the relevant stimulus feature was the color of the stimuli and they were instructed to respond with a left (right) hand response to green (red) color of the target or the prime stimulus. The other group processed the stimuli on a semantic categorization level since the relevant stimulus feature was its category and they were instructed to respond with a left (right) hand response to when the target or the prime was a letter (digit).

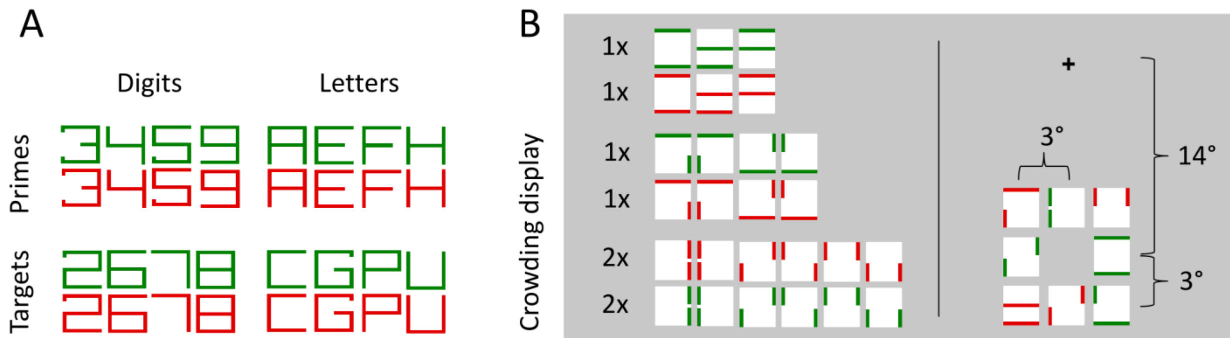

Figure 1. Study 1: stimuli.
A) The primes and targets used in the experiment included 4 numbers and 4 letters in the colors red and green.
B) Illustration of the flanker stimuli used to build the crowding display. To indicate the basic field of each stimulus, flankers are shown here on a white square. On each trial 8 new flankers were randomly drawn from a set of 13 flanker configurations with the restriction that one of each of the upper four lines of configurations was drawn and that the resulting crowding display always included 4 green and 4 red flankers with the same amount of vertically and horizontally oriented bars.
The crowding display without the prime can be seen on the right. The prime was presented in 14° eccentricity and 8 flankers were arranged around its position with a center-to-center distance of 3° visual angle. Note that all stimuli were presented on a gray background in the experiment.

2.3.4 Apparatus

Stimuli were presented on a CRT monitor (resolution 1024 x 768 pixels, 100Hz refresh rate) on a light grey background (RGB-value = 200, 200, 200) controlled by a computer using Presentation® software (Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). Participants sat in a dark room at a viewing distance of 67 cm with their head held constant in a chin rest. Responses were measured with a conventional computer keyboard. To control for the gaze position monocular eye movements were recorded with an eye tracker on a desktop mount (EyeLink 1000, SR Research, Ontario, Canada) with 1000 Hz sampling rate.

2.3.5 Procedure

Targets were presented at the fixation position in the upper half of the screen with 9° visual angle from the center, while primes were displayed at the bottom of the screen with 5° visual angle from the center. Therefore, primes occurred with a 14° eccentricity relative to the fixation point in the lower visual field. Participants were instructed to look at the fixation position at the top of the screen during the entire duration of a trial and attend to the target and to the prime. Target and prime discrimination trials occurred randomly, but with equal frequency within a block. Both trial sequences are illustrated in Figure 2. In a prime discrimination trial, a blue star shape was shown instead of a target, indicating that participants had to report the relevant feature of the prime. When a target appeared, participants were instructed to respond to the relevant feature of the target. Thus, the response relevant stimulus was unpredictable for the participants until the target, or the blue star appeared.

In the following, we describe the sequence of events on each trial in detail. A trial was only started when the eye tracker indicated that the participant looked steadily at an annulus at the fixation position which was the target position. The gaze had to remain within a spatial circle of 5° of visual angle around the fixation point for 500 ms. During the following fixation interval of 1000 ms, two dots were presented at the respective target and prime positions. As a warning stimulus the dot at the target position changed into a cross 500 ms before the prime was displayed for 20 ms at the lower position. After a variable SOA between 30 and 120 ms the target (or the blue star) was presented for 100 ms. The flanker display appeared simultaneously with the target (or the blue star) for a duration of 20 ms.

After the appearance of the target (or the blue star) participants could execute the corresponding task. Since the two tasks had different speed requirements, we provided auditory feedback to guide participants in speed adjustments. In the speeded target discrimination task, a low tone indicated RTs > 1000 ms. In the prime discrimination task without speed stress a high tone indicated that RT < 1000 ms. In this case the trial only ended when a later response was given. In addition to this speed error feedback, an error tone gave choice error feedback when the response was incorrect. In each trial only one feedback tone could occur, and, in this case, the current trial was extended by 1000 ms.

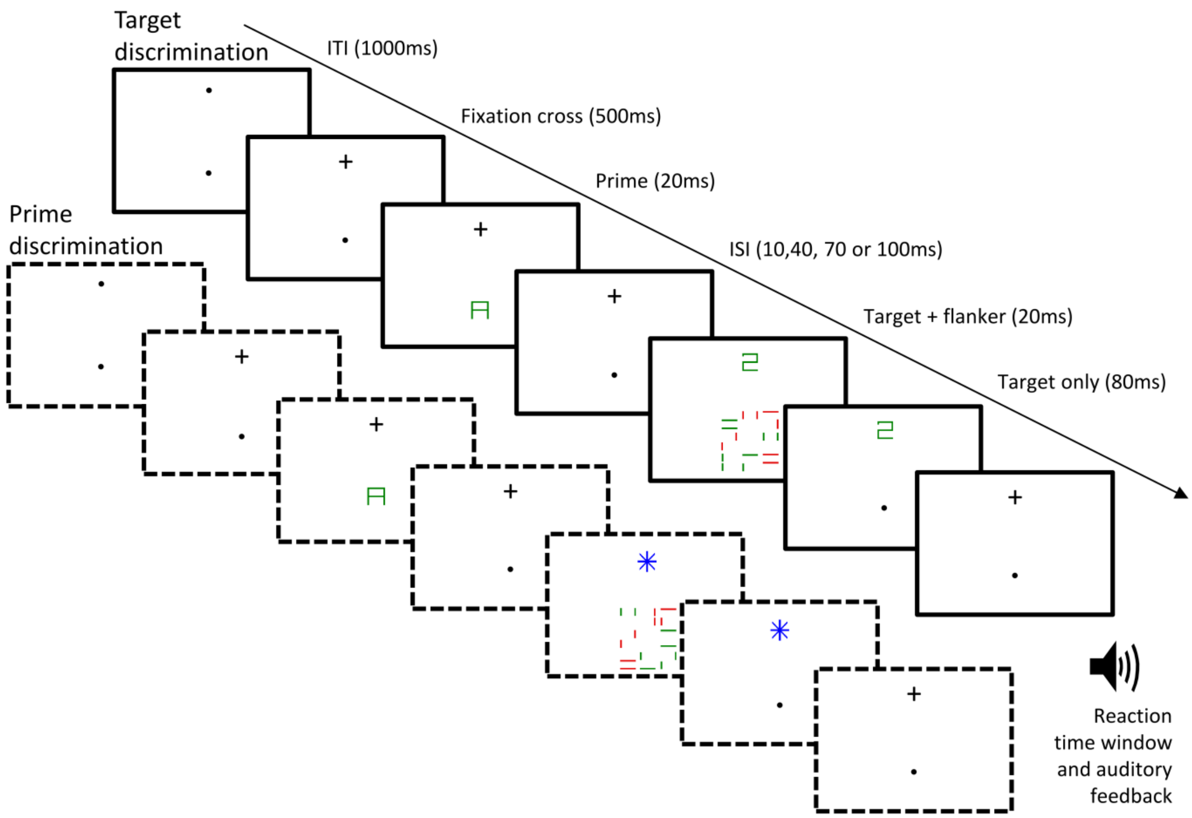

Figure 2. Study 1: sequence of events on trials with target or prime discrimination tasks. Participants were instructed to respond to the target stimulus (screens with solid borders). On 50% of the trials, however, a blue star was presented at the fixation position instead of a target. For this case, participants were instructed to respond to the peripherally presented prime (screens with dotted borders). Note that participants had to pay attention to both the prime and the target position on each trial because it was not predictable whether the prime or the target was relevant in the next trial. Speed errors or choice errors were indicated by error-tones.

2.3.6 Design

For each participant 2544 trials of experimental data were collected over five separate sessions. Each session was divided into blocks of 48 trials (9 blocks in the first session and 11 blocks in each subsequent session). For each task (target and prime discrimination), the data was collected in 24 experimental conditions which resulted from the factorial combination of the independent variables prime-target SOA (30, 60, 90, vs. 120 ms), Flanker Contrast (weak, medium or strong) and prime-target Congruency (congruent vs. incongruent). Prime-target Congruency depends on the Task Level: if stimuli are processed at a perceptual level, primes and targets can have the same color (congruent trial) or different colors (incongruent trial). If stimuli are processed at the level of semantic categorization, prime-target congruent trials result when the prime and the target are members of the same category (both digits or both letters) and incongruent trials result when the prime and the target are of different categories (digit prime and letter target or vice versa). Note that we used four different digits and letters as primes and targets. Therefore, task difficulty varies between the two Task Levels: the semantic categorization task was more difficult than the perceptual task, although both tasks used identical stimuli.

2.3.7 Statistical analysis

The first block of each session was regarded as practice and discarded from further analyses. For each participant we ran 1152 trials in the prime discrimination task and 1152 trials in the target discrimination task. Offline, after analysis of the eye tracking data, we excluded trials when the gaze departed from fixation by 2.5° of visual angle, which could result when participants moved their gaze towards the peripherally presented prime (0 - 2 trials per participant). Moreover, we excluded trials in which the initial time that a participant needed to maintain fixation to start the trial – the start-delay - was longer than two times the standard deviation of the mean of these start-delays across all trials of that participant (38 – 268 trials per participant). An overview of the number of excluded trials is given for each participant in Table 1 in the supplementary material.

Prime visibility was determined according to a signal-detection analysis (Macmillan & Creelman, 1991). For this purpose, the sensitivity d' was calculated as the difference between z-transformed hit and false alarm rates for each condition. The log-linear rule was applied to account for cases in which the hit rate equaled 1 or the false alarm rate equaled 0 (Hautus, 1995). To examine how prime visibility was affected by Task Level, Flanker Contrast and SOA a mixed analysis of variance (ANOVA) was performed on d'-values with the between subject variable Task Level (perceptual vs. semantic categorization) and the within subject variables Flanker Contrast (weak, medium, vs. strong) and prime-target SOA (30, 60, 90, vs. 120ms). Between 900 and 1128 trials remained for each participant in this analysis (Table 1, supplementary material).

Priming effects on target processing were reflected in measures of RTs and choice error rates. Priming effects were defined as higher speed and accuracy on congruent than on incongruent trials determined by the difference between RTs on prime-target incongruent minus RTs on prime-target congruent trials, and the corresponding difference in choice error rates. The experiment was designed to investigate the effects of prime stimuli with reduced visibility due to temporal crowding of different strengths. Therefore, mixed ANOVAs were conducted on RTs and arc-sin transformed choice error rates with the between subject variable Task Level (perceptual vs. semantic categorization) and the within subject variables prime-target Congruency (congruent and incongruent), prime-target SOA (30, 60, 90 and 120 ms) and Flanker Contrast (weak, medium and strong). RT analysis was conducted on all target discrimination trials with correct answers which did not follow on an error trial regardless of the task that was executed on the previous trial. Between 686 and 1029 trials remained for each participant in this analysis (Table 1, supplementary material).

All reported p-values are based on Greenhouse-Geisser corrected degrees of freedom. For the sake of readability, the stated degrees of freedom, however, are uncorrected and Greenhouse-Geisser ε is given to quantify the degree of sphericity violation. As effect sizes generalized eta squared (η^2_g) and partial eta squared are (η^2_p) given (Bakeman, 2005; Lakens, 2013).

2.4 Results

Prime visibility. Results of the ANOVA are given in Table 2 (supplementary material) and corresponding behavioral data are illustrated in Figures 3 A and 4 A. The main effect of Task Level was significant, indicating that prime visibility differed between the two tasks ($F(1,15) = 7.61$, $p = .015$, $\eta^2_g = .18$, $\eta^2_p = .34$). More specifically, overall prime discrimination performance was better in the perceptual discrimination task (d' = 2.4) than the semantic categorization task (d' = 1.6). Additionally, the main effect of SOA was significant ($F(3,45) = 79.89$, $p < .001$, $\varepsilon = .57$, $\eta^2_g = .13$, $\eta^2_p = .84$). This indicates that the overall prime visibility increased with longer SOAs (from d' = 1.6, 1.8, 2.2, to 2.4 with SOA of 30, 60, 90 and 120 ms, respectively). The significant interaction of Task Level X SOA ($F(3,45) = 5.95$, $p = .013$, $\varepsilon = .52$, $\eta^2_g = .01$, $\eta^2_p = .28$) most likely resulted from the reduced improvement in prime visibility over SOA in one task. From the shortest SOA (30 ms) to the longest SOA (120 ms) prime visibility increased from d' = 2.1 to d' = 2.7 in the perceptual discrimination task and from d' = 1.1 to d' = 2.1 in the semantic categorization task. The main effect of Flanker Contrast was significant ($F(2,30) = 116.40$, $p < .001$, $\varepsilon = .60$, $\eta^2_g = .25$, $\eta^2_p = .89$). Overall discrimination performance was best with weak flanker contrasts (d' = 2.6) and decreased with medium (d' = 2.0) and strong flanker contrasts (d' = 1.5). The interaction SOA x Flanker Contrast was significant ($F(6,90) = 26.01$, $p < .001$, $\varepsilon = .66$, $\eta^2_g = .08$, $\eta^2_p = .63$) most likely because SOA modulated temporal crowding only with medium and strong flanker contrasts. An additional analysis including only weak flanker contrasts showed that prime visibility did not differ between SOAs, $F(3,45) = 0.72$, $p = .512$, $\varepsilon = .77$, $\eta^2_g = .00$, $\eta^2_p = .05$ with d' = 2.7, 2.5, 2.7 and 2.6 for SOAs of 30, 60, 90 and 120 ms respectively. Post-hoc Bonferroni corrected paired t-tests were conducted to assess whether prime discrimination performance differed between weak, medium, and strong Flanker Contrast at each level of SOA. All three flanker contrast levels led to differences in d' with SOA of up to 90 ms (all $p < .004$). With 120 ms SOA, however, differences in prime discrimination performance diminished and did not differ between weak and medium flanker contrasts anymore ($t(31) = 0.90$, $p = .373$).

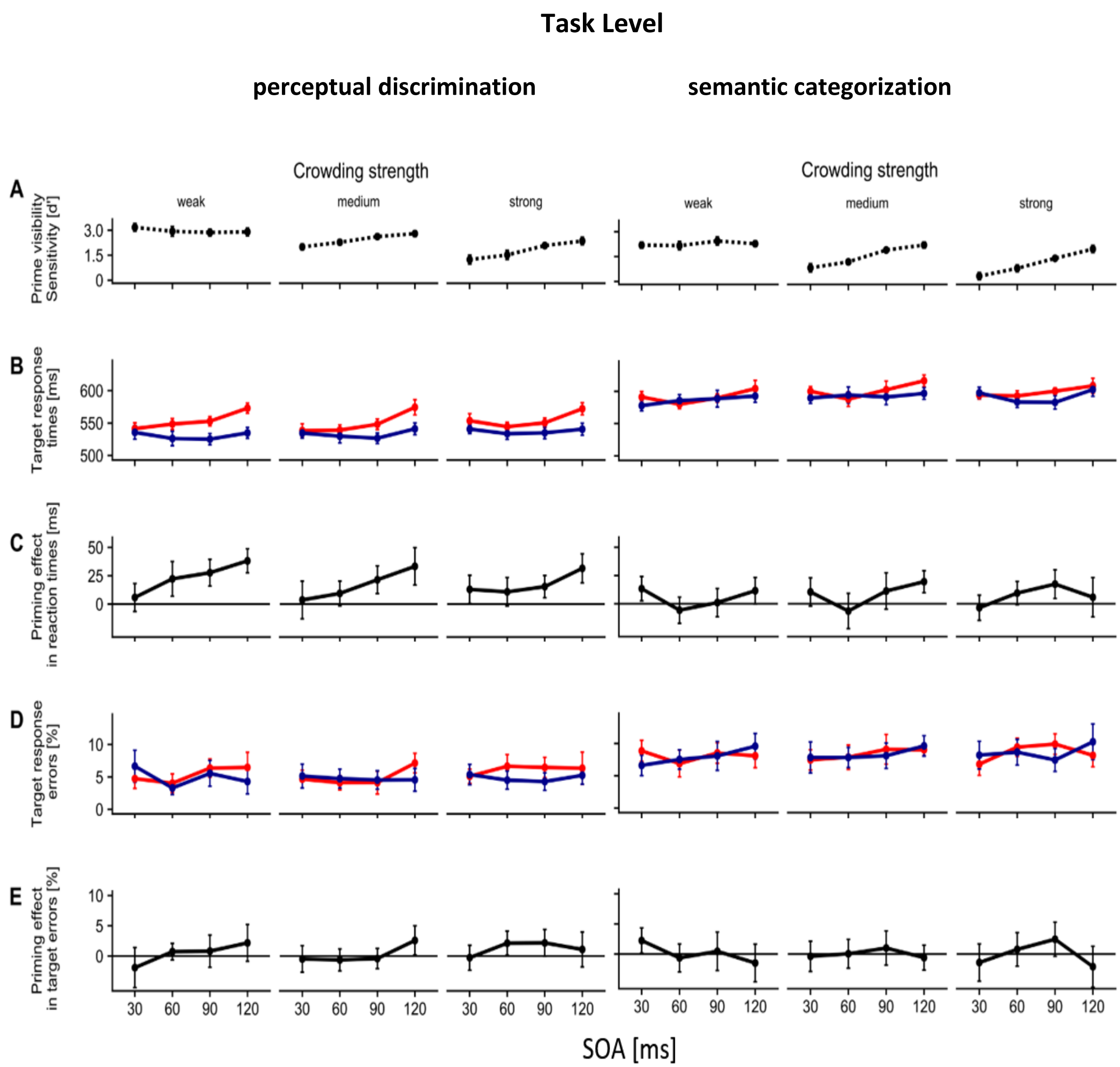

Figure 3. Study 1: performance measures as a function of Task Level, Flanker Contrast, SOA and Congruency.
A) d’ as a measure of prime visibility in the prime discrimination task.
B) RT for congruent and incongruent trials in the target discrimination task.
C) Priming effects on RT defined as the difference between RTs on incongruent minus congruent trials.
D) Choice error rates for congruent and incongruent trials in the target discrimination task.
E) Priming effects on choice error rates defined as the difference between error rates on incongruent minus congruent trials.
Performance with different flanker contrasts is given in separate columns. Error bars are Confidence Intervals corrected for within subject designs (O’Brien & Cosineau, 2014).

Summary Crowding. Prime discrimination at the perceptual level was better than at the level of semantic categorization. This effect of Task Level was modulated by SOA irrespective of Flanker Contrast. The modulation of visual crowding due to different levels of Flanker Contrast was similarly effective with both task levels, since no interaction of Flanker Contrast x Task Level was significant ($p > .25$). Additionally, this effect of Flanker Contrast was further modulated by SOA (irrespective of Task Level). We note that the flanker which induced crowding always occurred simultaneously with the target with a delay to prime onset with 30, 60, 90 or 120 ms. This SOA effect thus reflects the common finding that in temporal crowding, the crowding effect decreases when the delay between the onset of the to-be-crowded stimulus and the onset of the flanker increases (Chung, 2016; Huckauf & Heller, 2004).

RTs. Results of the ANOVA are given in Table 3 (supplementary material) and corresponding behavioral data are illustrated in Figures 3 B, C and 4 C, D. The main effect of Task Level was significant ($F(1,15) = 6.24$, $p = .025$, $\eta^2_g = .13$, $\eta^2_p = .29$) reflecting faster responses to the color of the target (543 ms) than to its semantic category (594 ms; see Figure 3 B). The main effect of Congruency was significant ($F(1,15) = 36.58$, $p < .001$, $\eta^2_g = .01$, $\eta^2_p = .71$), with longer RTs on incongruent (575 ms) than on congruent trials (562 ms). The difference between these reaction times reflects the overall priming effect of 13 ms.

Furthermore, the interaction of Task Level x Congruency was significant ($F(1,15) = 10.21$, $p = .006$, $\eta^2_g < .00$, $\eta^2_p = .40$) reflecting that the priming effect was larger in the perceptual (19 ms) than in the semantic categorization task (7 ms). The main effect of Flanker Contrast was significant ($F(2,30) = 7.68$, $p = .002$, $\varepsilon = .99$, $\eta^2_g < .00$, $\eta^2_p = .34$) with RTs of 567, 569, and 571 ms for weak, medium and strong flanker contrasts, respectively. Bonferroni corrected paired t-tests revealed that only the RT difference between weak and strong flanker contrasts was marginally significant ($t(31) = -2.94$, $p < .006$; all other $p > .006$).

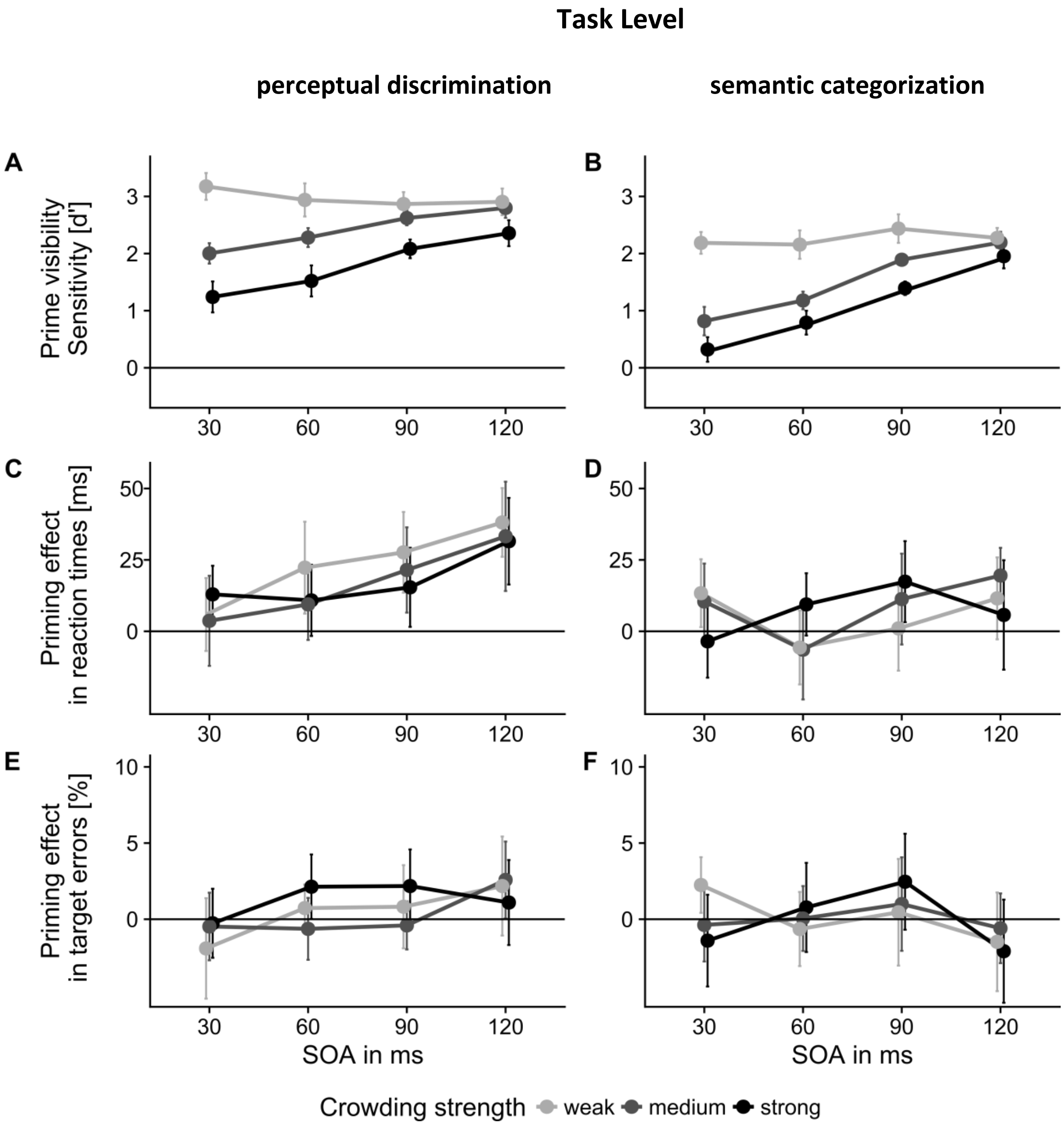

Figure 4. Study 1: prime visibility and priming effects as a function of Task Level, Flanker Contrast, and SOA.
A) Crowding effect at the perceptual and semantic categorical level in terms of d'-values.
B) Priming effect on RTs determined as the difference between RTs on incongruent trial minus RTs on congruent trials.
C) Priming effects on choice error rates. Error bars represent Confidence Intervals corrected for within subject designs (O'Brien & Cosineau, 2014).

The main effect of SOA was significant ($F(3,45) = 18.96$, $p < .001$, $\varepsilon = .75$, $\eta^2_g = .01$, $\eta^2_p = .56$), indicating that RTs were faster with shorter SOAs (566, 562, 566, and 580 ms with SOA 30, 60, 90, and 120 ms, respectively). The significant interaction SOA x Congruency ($F(3,45) = 9.29$, $p < .000$, $\varepsilon = .85$, $\eta^2_g < .00$, $\eta^2_p = .38$) reflects that the overall priming effects increased with longer SOAs from 7, 7, 16 to 23 ms. There is only marginally significant evidence for a modulation of this interaction by Task Level since the interaction Task Level x SOA x Congruency failed to be significant ($F(3,45) = 2.78$, $p = .061$, $\varepsilon = .87$, $\eta^2_g < .00$, $\eta^2_p = .16$). Most important, Congruency did not interact significantly with Flanker Contrast ($F(2,30) = 0.15$, $p = .789$, $\varepsilon = .70$, $\eta^2_g < .00$, $\eta^2_p = .01$) indicating that priming effects were not modulated by Flanker Contrast. Thus, reducing prime visibility by increasing visual crowding strength via flanker contrast manipulations did not affect the prime's influence on target processing at levels of perceptual and semantic categorization.

Choice Error Rates. ANOVA Results are given in Table 4 (supplementary material) and corresponding behavioral data are illustrated in Figures 3 D, E and 4 E, F. The main effect of Task Level was significant ($F(1,15) = 7.04$, $p = .018$, $\eta^2_g = .08$, $\eta^2_p = .32$) with 5% errors in the perceptual discrimination task and 8% errors in the semantic categorization task. The main effect of SOA was significant ($F(3,45) = 3.37$, $p < .035$, $\varepsilon = .84$, $\eta^2_g = .01$, $\eta^2_p = .18$) with 6, 6, 7, and 7% choice errors corresponding to SOA 30, 60, 90, and 120 ms, respectively. No other effect reached statistical significance.

Summary priming effects. The congruency between prime and target stimuli modulated the performance in target processing and this effect was stronger with increasing SOAs. Priming effects were larger in the perceptual discrimination task compared to the semantic categorization. However, priming effects were not modulated by the strength of crowding that was manipulated by flanker contrast. Choice error data provide no evidence for a speed-accuracy tradeoff which would complicate the interpretation of the RT data.

2.5 Discussion

The strength of the crowding effect was determined by two interacting factors: Prime-flanker SOA (30, 60, 90 and 120 ms) and flanker contrast (weak, medium strong). Thus, we achieved a gradual reduction of prime visibility with crowding regarding its color and semantical category. In general, discrimination performance improved with longer prime-flanker SOAs and with weaker flanker contrasts. However, only when flanker contrasts were strong enough to induce a crowding effect in the first place, did an additional delay in the flanker presentation further improve prime visibility. With medium and strong flanker contrast we observed monotonically increasing masking functions. This means that the ability to discriminate primes correctly improved with longer SOAs. This improvement was larger when the prime category had to be discriminated in comparison to prime color. These observations are in accordance with the findings of Huckauf and Heller (2004), who found that SOA variations in crowding led to monotonically increasing masking functions especially in conditions where crowding was strong (small target-flanker spacings and large eccentricities). In contrast to other studies, we did not observe a shift of the strongest crowding effect to positive SOAs (Chung, 2016; Huckauf & Heller, 2004). This is probably the case, because we presented the prime at 14° eccentricity with a target-flanker spacing of 3° from center-to-center (a condition that leads to a strong crowding effect), while stronger crowding effects with positive SOAs have been observed predominantly with larger target-flanker spacings at small eccentricities (a condition that leads to a weaker crowding effect).

Huckauf and Heller (2004) reported that the effect of the flankers was absent (Experiment 1) or substantially weakened (Experiment 2) at an SOA of 150ms. Likewise, we observed that flanker contrast related differences in discrimination performance attenuated with increasing SOAs. At an SOA of 120ms we found that prime visibility did not differ between weak and medium flanker contrasts anymore. In both cases, the effect of flankers was strongly reduced when they were presented 100ms after the offset of the relevant stimulus. However, when Huckauf and Heller (2004) presented isolated stimuli, the performance further improved (Experiment 3). This suggests that even flankers presented after an ISI of 100ms could affect stimulus processing. As we still observed effects between some flanker contrast levels at an SOA of 120ms, our observations support this view.

In addition to prior studies that investigated the effect of temporally delayed flanker presentation on the strength of the crowding effect (Chung, 2016; Huckauf & Heller, 2004) we further investigated the processing of these primes based on priming effects. In the analysis of target responses, we were particularly interested in the extent to which prime stimuli affect response speed and errors in discriminating the target when these primes are reduced in their visibility by crowding. This was accomplished by comparing target response speed and errors between trials in which response relevant prime and target features were different (incongruent condition) with trials in which they were similar (congruent condition). The difference between these conditions is expressed as priming effect and it indicates to what extent prime information influences target processing. It is therefore regarded as a measure of prime processing despite adverse visibility conditions. To begin with, the analysis of target response times revealed that the prime-target Congruency affected response speed. Participants took longer to discriminate between a target when prime and target were different in the response relevant feature compared to when they were similar in that feature. The overall priming effect was 13 ms, but it was larger in the color discrimination task (19 ms), compared to the categorical discrimination task (7 ms).

There are several indications that task level differed between experiments 1a and 1b. These experiments were identical except for the task relevant features of prime and target stimuli. In experiment 1a participants chose between the stimulus colors red and green and in experiment 1b different participants chose between the stimulus categories letter and digit. Thus, a stimulus discrimination based on two options was performed in both cases. However, the color discrimination task was less complex than the categorical discrimination, because the stimulus color could only be red or green, while each stimulus category consisted of eight different letters and digits. Moreover, prime and target stimuli were never the same characters to avoid repetition priming. This difference in task level was on the one hand reflected in the prime visibility. Under the same conditions, overall prime color (d' = 2.4) was easier to discriminate than prime category (d' = 1.6). Likewise, it has been found that the crowding strength was weaker for color than for other stimulus dimensions. For example, weaker crowding effects were found in color judgements (red or green hue or red saturation respectively) in comparison to the judgment of orientation and size, although the extent of crowding was similar across all stimulus dimensions (Van den Berg et al., 2007). Recently, Atilgan et al. (2020) found that the crowding induced reduction in discrimination performance was larger for form than for motion and still weaker for color relating those observations to the processing in the visual M and P pathways, which are sensitive to different stimulus features. Stimuli predominantly processed by the M pathway (motion) could be more susceptible to crowding than stimuli in the P pathways (color), probably because information is integrated over a larger area. Discrimination between forms could be affected more strongly by crowding, because it involves the integration of different stimulus components into one object.

On the other hand, task level differences in the present study can be inferred from target responses. Participants were on average 51 ms faster and made 3% less errors in responding to the target color in comparison to the target category. These findings strongly suggest that the manipulation of Task Level was effective at least insofar as the two task levels differed significantly. While the differences between the two task levels remain to be determined, our findings are consistent with the view that the two task levels required different levels of stimulus processing, a lower level in the perceptual task and a higher level in the semantic categorization task.

Further evidence for task level differences consists in the finding of increased priming effects in perceptual compared to semantic categorical processing, which is similar to findings of Wernicke and

Mattler (2019) with metacontrast masking and in accordance with the view that priming effects are reduced with higher task levels. Most importantly, however, the relation between priming effects and prime visibility did not vary significantly with task levels, although the manipulation of flanker contrast effectively modulated crowding. This finding challenges the view that conscious perception of the prime is more important for priming effects on high-level processing than on lower levels of processing.

Moreover, there was a significant interaction of prime-target Congruency with the factor SOA reflecting that response time differences in incongruent versus congruent conditions increased with longer delays between prime and target onset from 7, 7, and 16 to 23ms for SOAs of 30, 60, 90 and 120ms, respectively. A key advantage of the experimental design in this study is that prime visibility was affected by crowding which we varied in effectivity by two parameters. On the one hand, the factor SOA determined the delay at which the flankers and the target occurred. On the other hand, the strength of crowding was additionally manipulated by flanker contrasts. While longer SOAs were associated with improved prime visibility and larger priming effects, flanker contrast manipulations only affected prime visibility. This means that, although prime visibility decreased with stronger flanker contrasts (Figure 4 A, B), primes still affected target reaction times in the same manner (Figure 4 C, D). This finding suggests that priming effects profit from longer uninterrupted processing times implemented by the SOA, but an additional increase in prime visibility through weaker flanker contrast does not add to this effect. Hence, we come to the same conclusion as Vorberg et al. (2003), that the emergence of priming effects in these tasks cannot solely be based on prime visibility.

What has been shown previously with metacontrast masking is also observed in the present study with crowding. Therefore, the present findings put visual crowding on a similar level as metacontrast masking which is not interfering with perceptual or semantic categorical processing (Wernicke & Mattler, 2019). In this regard, crowding differs from other blinding methods like forward masking (Becker & Mattler, 2019), sandwich masking (Wernicke & Mattler, 2019) and CFS (Valuch &

Mattler, 2019) in which a reduction of prime visibility was accompanied with a reduction in priming effects. This view coincides with the distinction suggested by Breitmeyer (2015) that different blinding methods affect stimulus processing at different levels of visual processing. According to this view, crowding modulates conscious access of a stimulus at later levels of processing than the previously mentioned masking methods.

This study adds further evidence to the view that crowded information like color and semantic categories, although indistinguishable from its surrounding, is neuronally represented in such a way that in can affect subsequent processing (Manassi & Whitney, 2018). Perhaps this is not surprising as crowding is a constituent of our visual perception.

Although the mechanisms underlying crowding are still highly debated, our findings point to the fact that integration of target and flanker information may play an important role, not only with regard to spatial, but also temporal proximity. Similar as in visual masking, a shift from type A to type B masking functions in conditions where crowding is weaker (Chung, 2016; Huckauf & Heller, 2004) could indicate the contribution of different mechanisms in crowding, depending on spatiotemporal conditions. Bottom-up processing seems to be more severely affected at large eccentricities and with small target-flanker spacings. In this case, integration of target and flanker information seems to be especially strong when target and flankers are simultaneously presented. In contrast, the involvement of higher-level feedback becomes evident when crowding is weaker. At smaller eccentricities and larger target-flanker spacings crowding is stronger when flankers are presented with a temporal delay. However, irrespective of the mechanisms that affect recognition of crowded stimuli, crowded information does not seem to be lost as indicated by the variety of effects it can still produce. Thus, this “seeming paradox” needs to be addressed to fully understand crowding and mechanisms of object recognition more generally (Manassi & Whitney, 2018).

3 Study 2

Priming effects of visual stimuli can be similar across conditions - A direct comparison of backward pattern masking, metacontrast masking and spatiotemporal crowding

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3.1 Abstract

A variety of so-called blinding techniques are available to experimentally manipulate the visibility of a stimulus to study the processing of unconscious visual stimuli (Breitmeyer 2015). However, there is evidence that generalizations regarding the processing limit of these stimuli should be made with caution. Since different blinding techniques interfere with stimulus processing at different levels of processing to achieve invisibility, the residual processing that can be observed seems to be related to these experimental manipulations. In this study we applied a masked priming paradigm to directly compare the residual processing of simple arrow stimuli that were either visible or reduced in their visibility by backward pattern masking, metacontrast masking or spatiotemporal crowding. For this purpose, prime stimuli were presented briefly at 10° eccentricity followed by a mask associated with spatial characteristics of either of these masking conditions. A target was presented at fixation simultaneously with the mask 80 ms after the prime onset. We found that response priming effects in reaction times and error rates were not affected by any of these visibility manipulations. This suggests that the spatial layout of the mask (spatial overlap, close contours or adjacent flankers) does not affect stimulus processing under specific temporal conditions of the stimulus sequence. This has several implications for the usage of these blinding techniques. On the one hand, we presented spatiotemporal conditions in which stimulus processing seems to be dissociated from reductions in its visibility. We argue that this is the prerequisite necessary to study unconscious processing. On the other hand, these findings indicate that similar mechanisms could be involved when different blinding techniques are applied to reduce stimulus visibility. It might be of interest to study under which temporal conditions these blinding techniques affect stimulus processing differently and whether these findings extend to more complex stimuli.

3.2 Introduction

What is the processing limit of visual stimuli that are only registered unconsciously? Or, to pose the question in another way: Which processes necessarily require consciousness and which ones do not? To address issues like these a variety of blinding techniques have been developed that can be used to experimentally suppress the visibility of a stimulus up to the point where it eludes awareness. Although not consciously perceived, some residual stimulus processing still occurs (Breitmeyer, 2014). Therefore, it is possible to investigate the influence of unconscious stimuli on behavior and thereby identify processes that can function in the absence of consciousness. By identifying the limit of processes that can take place unconsciously it is then possible to approach the function of visual consciousness (Lamme, 2015). Among the variety of available blinding techniques, the suppression of stimulus visibility is achieved by interfering with different mechanisms of stimulus processing (Breitmeyer, 2015). Thus, each blinding technique has its own advantages and disadvantages in the experimental context and depending on the subject of investigation a suitable method can be chosen regarding different parameters (Kim & Blake, 2005). But are any of these techniques equally well-suited to study unconscious visual processing or does it make a difference?

Lamme (2015) proposed that the processing of unconscious visual stimuli should not be investigated with blinding techniques that depend on other functions like attention (such as inattentional blindness, change blindness or attentional blink), but rather with blinding techniques that reliably render stimuli invisible based on the interference with visual processing alone (such as visual masking, continuous flash suppression or dichoptic color fusion). Similarly, Kanai et al. (2010) make a distinction between methods used to affect stimulus awareness based on the observation of different phenomenal experiences that could indicate the contribution of distinct underlying mechanisms. They found that on the one hand, blinding techniques that interfere with perceptual processing can lead to the impression that the stimulus is absent (contrast reduction, backward masking, binocular rivalry), while on the other hand, blinding techniques that impair attentional access to a stimulus leave the impression that something was missed (dual task, attentional blink, spatial uncertainty).

A related distinction was made by Dehaene et al. (2006) suggesting that the processing of unconscious stimuli can be considered either as subliminal or preconscious (supraliminal) within the framework of the global workspace theory. According to this theory, visual stimuli are not perceived in subliminal conditions because the bottom-up processing is impaired (for example by visual masking) leading to a reduction in stimulus strength. On the contrary, visual stimuli are not perceived in preconscious conditions, because top-down processing is limited. Although the bottom-up stimulus strength is strong enough for the stimulus to become conscious, attentional resources are not sufficient for its access (which is for example the case in attentional blink or attentional blindness paradigms). Reviewing findings regarding unconscious semantic processing Kouider and Dehaene (2007) suggested that this distinction between subliminal and preconscious processing could explain why semantic priming effects are frequently observed to be small (or smaller than in conscious conditions) in masked priming experiments, while they seem to be fully preserved in experiments using attentional paradigms.

However, there are several indications that suggest exercising caution in the choice of blinding techniques beyond these considerations. There are observations that the remnant neuronal processing of stimuli that are experimentally suppressed in their visibility depends on the technique that is used (Fogelson et al., 2014). As different blinding techniques achieve suppression of stimulus visibility by targeting different levels of processing (Breitmeyer, 2015) a failure to observe stimulus processing under one blinding technique does not necessarily imply that this marks the processing limit of unconscious stimuli. Rather it reflects how visual processing is affected by a specific method of investigation. Although this problem concerns all methods that are used to study the processing of unconscious visual stimuli, it can be argued that some blinding techniques bring us closer to determine a processing limit of unconscious visual information than others.

Along these lines, Breitmeyer (2015) suggested a functional hierarchy of blinding techniques considering the processing depth of unconscious stimuli. Central to this functional hierarchy are two studies that compared how different blinding techniques interact when presented together (Breitmeyer et al., 2008; Chakravarthi & Cavanagh, 2009). This approach allows making statements about the relative functional level at which these techniques affect stimulus processing. It is based on the concept that one blinding technique A can prevent the effect of another blinding technique B when it interferes with stimulus processing on a functionally earlier level. Consequently, it can be concluded that this technique A allows a more limited depth of unconscious stimulus processing compared to technique B. According to these two studies a functional hierarchy of blinding methods would place binocular rivalry at the lowest level of preserved unconscious stimulus processing, followed by pattern backward masking, metacontrast masking and crowding. Among these blinding techniques OSM seems to allow the highest level of unconscious stimulus processing (Breitmeyer, 2015).

Taken together, these considerations point out why there is such a variety of inconclusive results in the study of unconscious visual processing that complicates determining a processing limit (Lamme, 2015; Rothkirch & Hesselmann, 2017). Furthermore, it suggests that findings of unconscious visual processing should be interpreted with caution and in relation to the mechanisms affected by a specific blinding technique. Although it is important to learn about the characteristics of individual research methods, it can further complicate comparisons between studies. But is there a way to facilitate these interpretations without getting lost in the details of the rapidly growing variety of research methods and their operationalizations? One possibility would be establishing a standardized methodological practice, which has been recently addressed by Rothkirch and Hesselmann (2017) but will be difficult to implement soon. However, there is growing interest in systematical comparisons of stimulus processing under different blinding techniques (Dubois & Faivre, 2014; Izatt et al., 2014), which could benefit this research field in many ways. First of all, direct comparisons minimize alternative explanations for diverging findings. Furthermore, the discussion of mechanisms underlying different blinding techniques could not only improve the understanding of how each technique interferes with stimulus processing but also provide a more fundamental understanding of (unconscious) visual processing by identifying common features and differences that occur under similar conditions. This could serve as no less than a basis for the development of a standard method.

Along these lines, several studies reported comparisons of the processing depth of unconscious stimuli between different blinding techniques inferring the depth of unconscious processing from priming effects (Faivre et al., 2012; Izatt et al., 2014; Peremen & Lamy, 2014). In so-called priming experiments the effect of a prime stimulus can be investigated by examining its influence on the task performance regarding a subsequently presented target stimulus. While the target stimulus is always clearly visible, the visibility of the prime can be experimentally manipulated with the help of blinding techniques. The effect of an unconscious prime on target processing is then usually compared with conditions in which a visible prime was shown.

For example, Faivre et al. (2012) showed in different experiments that prime faces expressing emotions only biased preference judgements (pleasant or unpleasant) on a subsequent neutral target stimulus when crowding was used to suppress prime visibility; no such effects were found with sandwich noise masking and CFS. Sandwich noise masking is a combination of forward and backward pattern mask, which is considered to affect stimulus processing on a relatively early level (Wernicke & Mattler, 2019; Becker & Mattler, 2019). In CFS the mechanism of binocular rivalry is used to suppress the visibility of a stimulus that is presented to one eye by simultaneously showing constantly changing salient patterns to the other eye (Tsuchiya & Koch, 2005). Following the suggestion of a functional hierarchy of blinding techniques, CFS is expected to affect stimulus processing on an earlier level than crowding. More recent studies suggest that priming effects under CFS suppression depend on the visibility of primes even when simple arrow stimuli are used (Valuch & Mattler, 2019). These results fit well with suggestions of a functional hierarchy of blinding techniques as described above. Although manipulating the task level further adds to the complexity of the study design and analysis, this approach is indispensable in the endeavor to establish a functional hierarchy of blinding techniques. The studies reported in the following took this approach.

While sandwich noise masking and CFS seemed to prevent processing of facial emotions, Faivre et al. (2012) found repetition priming effects using the same stimuli with a different task. Participants had to decide whether the target face showed happiness or anger. In these experiments, prime and target face could either be the same, or different faces showing the same emotion. When prime and target face were identical, target responses were affected by the invisible prime indicating that some perceptual processing survived sandwich noise masking and CFS. This suggests that when the task and stimulus features to be processed are sufficiently simple, there seems to be no difference in the effect of the mentioned blinding techniques. Consequently, it could be argued that differences in the detrimental effect of blinding techniques on stimulus processing are revealed only when more complex stimulus processing is required.

In another study, Peremen and Lamy (2014) compared the processing of prime arrows that were rated invisible in two experiments using CFS and metacontrast masking respectively. They found response priming effects for invisible primes only when metacontrast masking was used. In contrast to the CFS experiment of Faivre et al. (2012) their prime and target stimuli were differently shaped arrows instead of identical faces expressing the same emotion. Although the arrow stimuli are much simpler compared to faces, the processing of different forms could require a more sophisticated level of processing than the mere repetition of a stimulus. Hence, this difference in stimulus processing could be one possible explanation for the conclusion of Faivre et al. (2012) that some perceptual priming seemed to be possible during CFS, while Peremen and Lamy (2014) found that response priming was not. This concedes with the idea that different levels of complexity required for stimulus processing could reveal differences in the effect of blinding techniques.

However, when Izatt et al. (2014) investigated the processing of faces suppressed in their visibility by sandwich masking and CFS they reported inconsistent results. They found that the magnitude of priming effects depended on the visibility of the primes, whether the same face stimuli were repeated (experiment 1, repetition priming) or shown from a different angle (experiment 2, identity priming). More specifically, priming effects in a fame categorization task (famous vs unfamiliar faces) increased with prime visibility and there was no evidence for processing of unconscious faces with neither sandwich making nor CFS. These results seem to conflict with the conclusions of Faivre et al. (2012) who found face repetition priming effects with both sandwich masking and CFS. Although the experiments appear quite similar at first glance, there are large methodological differences that could account for these differences.

One major aspect is the overall approach to compare the effect of different blinding techniques. On the one hand it is possible to equate as many experimental parameters as possible between the techniques to avoid potential confounds that could account for different effects (Izatt et al., 2014). This potentially allows us to study the effects of different techniques in a within-subject design in the same experiment. On the other hand, parameters can be chosen to best fit the individual requirements of each blinding technique and thereby provide optimal conditions for effects to emerge (Faivre et al., 2012), which requires to implement different experimental procedures and therefore cannot be realized in one experiment.

Another related factor is that some blinding techniques allow for longer prime presentation durations than others. For example, primes can be shown for much longer durations with CFS than with visual masking (Kim & Blake, 2005). However, this potentially complicates comparisons because longer prime durations could lead to larger or different effects, even when presented in the absence of stimulus awareness. For example, Faivre and Kouider (2011b) observed positive priming effects with shorter prime durations (200 ms) and negative priming effects with longer prime durations (1000 ms) when prime visibility was reduced by crowding. Similarly, Faivre et al. (2012) found negative priming effects (-18 ms) when primes were shown for 2500 ms with CFS and positive priming effects (8.7 ms) when primes were shown for 33ms with sandwich noise masking (SNM). In contrast, Izatt et al. (2014) reported that with both SNM and CFS priming effects were related to prime visibility. They presented their primes for 50ms with both techniques and increased the duration of the forward mask in sandwich masking to 700 ms to equate as many parameters as possible between CFS and sandwich masking allowing them to show both techniques intermixed in one experiment. Relatively short prime presentation times of 50 ms could be a possible explanation for why Izatt et al. (2014) did not find priming effects with CFS in contrast to Faivre et al. (2012) who showed their primes for 2500 ms. However, this does not explain the contradictory results regarding sandwich masking, because although the prime duration in the SNM experiment of Izatt et al. (2014) was longer compared to Faivre et al. (2014) (50 ms vs 33 ms), they observed no repetition priming effects in the absence of awareness.

Another central aspect in these kinds of experiments is how the visibility of suppressed primes was varied and measured. Izatt et al. (2014) manipulated prime visibility with mask contrast variations and accessed prime visibility in each trial with two measures that followed the target reaction: An objective two alternative forced choice task and a subjective visibility rating. By this they were able to investigate the association between prime visibility and its effect on target processing. In contrast, Faivre et al. (2012) did not additionally vary prime visibility and measured prime visibility only in a fraction of experimental trials in which a two-alternative forced choice task was required instead of a target reaction. In these trials the discrimination performance was at chance level and primes therefore deemed invisible. However, there was no possibility to compare priming effects between invisible and visible primes.

These comparisons illustrate that the depth of unconscious stimulus processing, inferred from the magnitude of priming effects, can largely differ between studies. Unfortunately, it is often difficult to compare the results. This can have many reasons, one of them being the blinding technique that is used. As outlined above, the processing depth of unconscious stimuli seems to depend on the blinding technique used to suppress stimulus visibility. Investigating high-level processing with a blinding technique that allows only limited processing can result in misleading conclusions regarding the processing limit of unconscious stimuli. Therefore, stimulus processing should be interpreted in relation to the method that was used to render the stimulus invisible. Likewise, systematic comparisons of residual stimulus processing should not only consider different blinding techniques, but also the task level and type of stimuli to be studied. Unfortunately, even comparisons of residual stimulus processing using the same blinding technique are difficult to make. This can have multiple reasons, because only small changes in the study design (including for example stimulus duration, assessment and variation of prime visibility, as well as statistical analysis) can have a large impact on the outcome (for a discussion see Rothkirch & Hesselmann, 2017).

In the present study we aimed at systematically comparing processing of stimuli that were subject to backward pattern masking, metacontrast masking and spatiotemporal crowding within one priming experiment. As methodological differences are inherent to the usage of different blinding techniques, we briefly review the characteristics of each blinding technique before we address the parameters that were equated to realize this endeavor.

In visual masking the visibility of a target stimulus is reduced by presenting another stimulus, called mask, that incorporates spatially arranged forms and contours like the stimulus itself (Breitmeyer & Öğmen, 2006). Different types of visual masking can be distinguished based on the spatial structure of the mask and the time of its presentation relative to the target stimulus. Typically, the mask consists of a pattern that spatially overlaps with the target. This pattern can either share no structural characteristics with the stimulus (masking by noise) or resemble the stimulus in properties such as orientation and curvature (making by structure). Furthermore, the mask can either be presented prior or subsequently to the stimulus, in which case it is referred to as either forward or backward masking. Although the mask we use shares some structural characteristics with the task relevant stimuli (see Figure 5 in the following Method section) we refer to the mask as backward pattern masking for simplicity. We renounce investigating the effects of forward masking or sandwich masking in this experiment, because of its potential detrimental influence on priming effects (Becker & Mattler, 2019; Wernicke & Mattler, 2019). Moreover, we were interested in comparing the effect of different types of masks on stimulus processing under similar conditions and therefore presented the mask always after the prime.

Metacontrast masking is another form of visual backward masking, that can be regarded as special case masking by structure (Breitmeyer & Öğmen, 2006). An important characteristic of metacontrast masking is that there is no spatial overlap with the target. However, the inner contours of the mask fit closely to the outer contours of the target stimulus, thus creating structural resemblance in the form of spatial continuation between both stimuli. The stimulus sequence in visual masking usually takes only a few hundred milliseconds. It is frequent practice to vary the temporal interval between stimulus onset and mask onset referred to as stimulus-onset-asynchrony (SOA). The strength of masking depicted as a function of SOA is informative of the temporal dynamics of stimulus processing, especially with respect to the maximal suppression of different stimulus dimensions.

Crowding is another technique that can be used to experimentally reduce the visibility of a stimulus. In contrast to visual masking, crowding is a mechanism that plays a role in everyday visual perception. It is most prominent in the visual periphery where the recognition of an object is compromised by other similar objects over a relatively large range of visual space (Whitney & Levi, 2011). Crowding is intensively investigated with respect to the spatial extent over which flankers exert their detrimental effect on the recognition of a target object in relation to the retinal eccentricity where it is presented. An influential observation by Bouma (1970) was that the critical spacing (the target-flanker distance below which the effect of crowding unfolds) equals about half the eccentricity of the target. While the extent of crowding is symmetrical around the target in foveal vision, it is elliptical in the visual periphery, extending longer in the radial direction (0.5 x eccentricity) than in the tangential direction (0.1 x eccentricity) viewed from the visual center (Toet & Levi, 2002). This critical spacing holds over a wide range of different stimuli (e.g., Van den Berg et al., 2007) and in particular when target and flanker resemble each other (Kooi et al., 1994). Thus, it has become a characteristic of crowding sometimes referred to as a rule (Pelli et al., 2004), rule of thumb (Whitney & Levi, 2011) or even law (Pelli & Tillmann, 2008) which is discussed in more detail elsewhere (see Strasburger, 2020). Although temporal variations in the presentation of flankers relative to the target are less common in crowding than in visual masking, this has been investigated in some studies (Chung, 2016; Huckauf & Heller, 2004; Lev et al., 2014, as well as the first study reported under chapter 2 in this work), and growing interest in the temporal aspects modulating crowding has led to suggestions to regard it as spatiotemporal phenomenon (Herzog et al., 2016).

To compare residual stimulus processing between different blinding techniques we designed a masked priming experiment in which three different masking conditions could be presented randomly intermixed with a pseudo-mask condition. The prime was clearly visible in the pseudo-mask condition, while its visibility was equally suppressed by backward pattern masking, metacontrast masking and spatiotemporal crowding. We used the same stimulus sequence and timing for all masking conditions while maintaining the spatial arrangement characteristic for each blinding technique (see Figure 5 in the Method section of this chapter). A prime arrow was shown for 13 ms at 10° eccentricity. After an SOA of 80 ms a clearly visible target arrow was presented at the fixation position and simultaneously a backward pattern mask, a metacontrast mask or flankers that induced crowding were presented at the previous prime position. In each trial participants gave two responses. First, they gave a speeded discrimination response on the pointing direction of the target arrow (left or right). Second, after a short delay, they were asked do the same discrimination task on the previously presented prime arrow. Thus, we were able to calculate priming effects as measure of prime processing by analyzing reaction times and errors in target responses when prime and target arrows pointed in different directions (incongruent conditions) or in the same direction (congruent condition). Additionally, discrimination accuracy of the prime arrows allowed us to assess stimulus visibility under unhindered viewing conditions or when it was affected by backward pattern masking, metacontrast masking or spatiotemporal crowding.

Do different forms of backward masking affect target processing similarly, or does the spatial layout of the mask interfere with stimulus processing in different ways? We were able address this question directly with this experiment by matching parameters of stimulus presentation that usually differ between these blinding techniques. There are two conceivable outcomes.

First, different forms of masks could have a similar effect on stimulus processing when presented under similar conditions. At the tested intermediate SOA of 80 ms between prime and mask onset it is possible that the spatial layout of the mask could have no differential effect on prime processing, because the process that interferes with prime processing could be related to higher-level interactions. For example, according to the object substitution theory recurrent processing is a prerequisite for conscious perception (Enns, 2004). Over several iterations sensory input via feedforward sweep is compared with feedback from higher levels of processing to disambiguate visual information. When the processing of a target stimulus has not sufficiently advanced before another stimulus (mask) is presented, incoming information of this mask can interfere with the processing of the target information resulting in impaired target recognition. Within this framework it is conceivable that all forms of backward masking could similarly affect stimulus processing, when the mismatch between feedforward and feedback information is the central mechanism that leads to reduced stimulus visibility. In this case we would expect to observe that residual prime processing, assessed in the form of priming effects, does not differ between conditions in which the prime discrimination accuracy was unaffected or reduced by backward pattern masking, metacontrast masking and spatiotemporal crowding.

Alternatively, even when different forms of backward masking are equally effective in reducing the visibility of a stimulus, the residual processing could depend on specific interactions with the spatial layout of the mask. Especially at short intervals between the presentation of a stimulus and a mask, stimulus identification is supposed to be impaired, because information from both stimuli is temporally integrated into one object (e.g., Enns, 2004). This mechanism could be especially severe when there is spatial overlap between stimulus and mask as is the case with pattern masking. In contrast, when metacontrast masking or the presentation of temporally delayed flankers affect stimulus recognition, other mechanisms like local contour interactions could play a major role. Consequently, the effects on stimulus processing could differ between those types of backward masks. This hypothesis fits well with the idea of a functional hierarchy of blinding methods proposed by Breitmeyer (2015) and is discussed above. Residual prime processing could be more severely impaired when masking by patterns (that spatially overlap with the prime) is used in comparison to a metacontrast masking or surrounding flankers are used to induce crowding. In this case we would expect to observe smaller priming effects when backward pattern masking is used compared to the other conditions.

We found that processing of primes was similar across all masking conditions as indicated by an overall response priming effect of 34 ms in RTs and of 6 % error rates. At the same time prime visibility was significantly (and to a similar degree) reduced by backward pattern masking, metacontrast masking and spatiotemporal crowding in comparison to the pseudo-mask condition. These results indicate that the spatial layout of the mask that affects stimulus visibility does not interfere with prime processing at an SOA of 80 ms. This could be related to a process that is shared between different types of blinding techniques under certain conditions, which in turn could be related to higher-level interactions between prime and mask information. This is further addressed in the discussion.

3.3 Method

3.3.1 Sample

In this study 16 students (13 female, 3 male) from the University of Goettingen were invited to join three separate experimental sessions lasting about an hour each. They gave written informed consent and received 7€ per hour of participation. The students were on average 25 years old (ranging from 20 to 26 years). All of them reported normal or corrected-to-normal vision and were otherwise healthy.

3.3.2 Stimuli

All stimuli were displayed in black (RGB-value = 0, 0, 0) on a light grey background (RGB-value 200, 200, 200) on a CRT monitor with 1024 x 768 pixels resolution and a refresh rate of 75 hz. As prime and target stimuli we used double arrow symbols pointing left (<<) or right (>>), appearing in the size of 1.2° x 1.4° visual angle. For these stimuli we created specific masks according to the criteria of different blinding techniques. The metacontrast mask was a black rectangle (2.7° x 2.9° visual angle) with two rectangular slots (0.55° x 1.4° visual angle) in which each arrow element fitted directly. Pattern masks were assembled from partially overlapping elements displayed in a rectangle of the same size as the metacontrast mask. These elements were 16 vertical (0.3° x 1.1°) and 16 horizontal (1.1° x 0.3°) bars, each with a tip at one end pointing in an orthogonal direction. The number of elements was kept constant while their exact position within the rectangle was jittered and thus slightly different in each presentation. The flankers used to induce crowding were created from the same elements used to build the pattern masks. One flanker consisted of either two vertical or two horizontal elements. For a complete crowding display 8 flankers were randomly assigned to one of 8 positions around a central omission in a 3 by 3 grid in which the center-to-center distance between each element was 2° visual angle. The prime arrow fitted into the center of this flanker arrangement. A pseudo-mask was created as a control condition. It consisted of four small dots (2 x 2 pixel) in each corner of an imaginary rectangle that had the same size as the metacontrast mask. In contrast to different types of backward masks including masking by noise and metacontrast, masking by four dots was not effective in reducing stimulus visibility at an SOA between 0 - 100 ms (Enns, 2004).

3.3.3 Procedure

The experiment proceeded in a dark room with participants seated in front of the monitor. Their heads were positioned on a chin rest to maintain a viewing distance of 67 cm. During the whole experiment a test coordinator sat in the same room behind a screening wall to operate the eye tracker (EyeLink 1000, SR Research, Ontario, Canada). Monocular eye movements were recorded with 1000Hz sampling rate. Participants initiated each trial by looking at the fixation point in the upper part of the screen. A trial started only when the eye tracking signal was steady for 500 ms. The stimulus display was controlled by a computer using Presentation® software (Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) and is illustrated for one trial in Figure 5.

At the beginning of each trial two points were presented for 1 second. The first point in the upper part of the monitor marked the fixation position, while the second point displayed at 10° eccentricity below fixation indicated the position where primes would occur. Participants were instructed to keep looking at the fixation position during the whole trial sequence and the second dot helped them to direct their attention to the prime position when it appeared. The occurrence of the prime was predictable, because the fixation point turned into a cross for 500 ms, after which the prime was presented for one frame (13 ms). The dot indicating the primes position disappeared 100ms before the prime display to reduce additional interference in the form of forward masking effects. The target always appeared with an SOA of 80 ms between prime onset and target onset. Target stimuli were shown for 107 ms at the fixation position and therefore easy to distinguish. Together with the target a mask was shown in the lower part of the screen where the prime was previously presented.

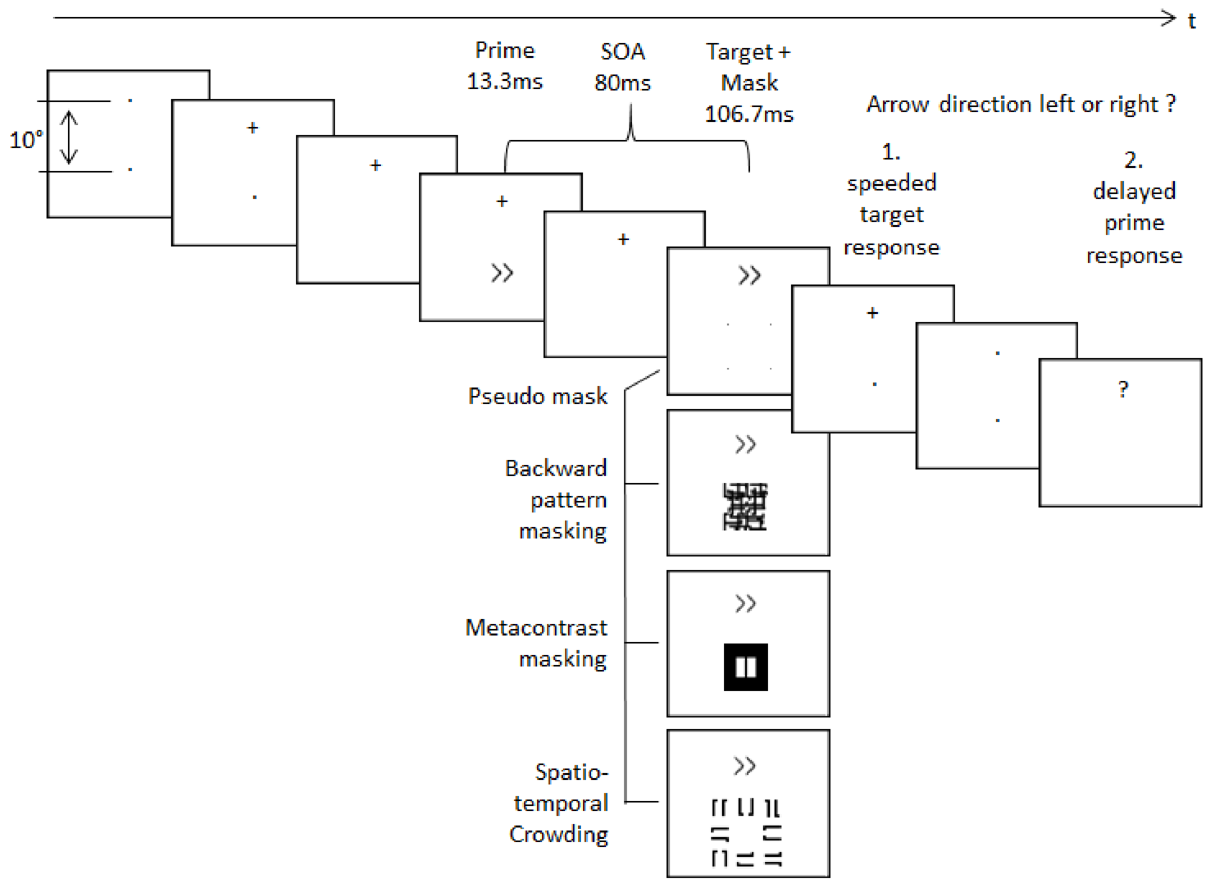

Figure 5. Study 2: stimulus sequence in the masked priming experiment.
For the entire duration of a trail participants were instructed to look at the dot in the upper part of the screen. The second dot at 10° eccentricity below fixation indicated the position where the prime would appear for 13 ms. Target and mask were displayed simultaneously after a fixed SOA of 80 ms. Four Masking Conditions were presented randomly intermixed. In each trial participants were asked to give two consecutive responses. As soon as the target appeared its pointing direction had to be chosen (left or right). After a delay of 1 s, in which two dots appear at the screen, a question mark was presented for 3 s. During this time participants had to indicate the pointing direction of the prime arrow (left or right) that was previously presented in the visual periphery. Stimuli are not true to scale but increased in size for illustration purposes.

During the next second participants were asked to respond as quickly as possible to the target arrow's pointing direction by pressing the left or right control key on a conventional computer keyboard with the respective index finger. Participants were instructed to keep their fingers above these keys during the experiment. Directly after the target response a waiting period of 1 second followed during which the two dots were shown indicating target and prime position. Then, both dots disappeared, and a question mark was displayed at the fixation position for 3 seconds. During this time participants were asked to indicate the pointing direction of the prime and false responses did not abort the trial. Auditory error feedback was given when target or prime responses were incorrect extending the current trial duration by 1 second. This feedback was given only in the first session to improve task performance.

3.3.4 Design

Over the duration of three one-hour sessions 864 trials were acquired per participant on different days. One session was divided into 9 blocks to allow for short breaks and recalibrations of the eye tracker signal in between. Each block consisted of 32 trials in which the experimental conditions were balanced and presented randomly. Experimental conditions included the Masking Condition (pseudo-mask, backward pattern mask, metacontrast mask and spatiotemporal crowding) and the Congruency of prime and target arrows, which could either point in the same direction (congruent) or in different directions (incongruent). Consequently, each prime-target combination was shown with each Masking condition twice per block (2 Prime direction x 2 target direction x 4 Masking condition). In this way, it was also ensured that the same amount of left and right responses was required per block. As dependent variables we measured target response speed and accuracy, and prime discrimination accuracy.

3.3.5 Statistical Analysis

For the statistical analysis a number of trials were excluded, summarized for each participant in table 5 (supplemental material). First of all, the complete first session and the first block of each subsequent session was discarded as practice runs. From the pilot study and similar experiments, we learned that a considerable amount of training is required to be able to fulfill the task with a stable performance. Experiments where participants are asked to discriminate stimuli based on features that they often have to guess are inherently difficult and can be frustrating. However, this experiment placed additional demands on the participants, because they were asked to give two consecutive responses in each trial which required a rapid covert shift of attention, because primes were presented in the visual periphery in a rapid trial sequence. With practice trials excluded, there were 512 trials left per participant. We analyzed the eye tracking data and excluded all trials, in which participants directly gazed at the peripherally presented prime (fixation error trials) or trials in which the beginning of the sequence was delayed for more than two standard deviations of the individual mean (start delay trials). This could occur whenever the eye tracking signal was too unstable to initiate the start of a trial.

The visibility of primes was assessed as discrimination accuracy. Each trial in which a target response error occurred was excluded for the analysis of prime responses, because we did not want to include trials that could be affected by the processing of target errors. For the remaining trials we calculated d' as a measure of sensitivity within each blinding technique, since d' is calculated as the difference between z-transformed hit and false alarm rates and we accounted for cases in which hit rates equaled 1 or false alarm rates equaled 0 by implementing the log-linear rule (Hautus, 1995). A one-way repeated measure analysis of variance (ANOVA) was calculated on d' with the factor Masking Condition to examine how prime visibility was influenced by pseudo-masks, backward pattern masks, metacontrast masks or spatiotemporal crowding.

For the analysis of target reaction times only trials with correct responses were included. Target reaction times were analyzed with a two-way repeated measures ANOVA including the factors Masking Condition (pseudo-mask, backward pattern mask, metacontrast mask and spatiotemporal crowding) and Congruency (congruent, incongruent). In this way we examined whether participants responded more slowly to targets when prime and target arrows pointed in opposite directions (incongruent trials) compared to when primes and targets pointed in the same direction (congruent trials) and, most importantly, whether this difference in reaction times was influenced by primes that were reduced in their visibility by applying different blinding techniques. Target response accuracy was analyzed analogously to reaction times and for this error rates have been transformed using the arcsine square root transformation.

The results of ANOVA for d', reaction times and error rates are given in Table 7 and Table 8 in the supplemental material section in this chapter. The p-values are Greenhouse-Geisser corrected whenever sphericity could be an issue. Degrees of freedom (df) are given in uncorrected form with the corresponding Greenhouse-Geisser estimates (ε). As effects sizes generalized eta-squared (η^2_g) and partial eta-squared are (η^2_p) specified (Bakeman, 2005; Lakens, 2013). Whenever the factor Masking Condition was significant, post-hoc pairwise comparisons were performed using paired t-tests with Bonferroni corrected alpha levels (.05/6) for further significance testing between the factor levels.

3.4 Results

Prime visibility. A repeated-measures ANOVA on d' showed that the effect of Masking Condition was significant ($F(3,45) = 25.77$, $p < .000$, $\varepsilon = .45$, $\eta^2_g = .33$, $\eta^2_p = .63$), see also Table 6 supplemental material). The d' values for each condition are illustrated in Figure 6 A. Post-hoc pairwise comparisons indicated that prime visibility did not differ between backward pattern masks (d' = 0.5), metacontrast masks (d' = 0.6) and spatiotemporal crowding (d' = 0.4) respectively (all $p > .083$). However, prime visibility was significantly higher in the pseudo-mask condition (d' = 1.9) compared to each of the other Masking Conditions (all $p < .001$). Additionally, it was assessed whether primes could be regarded as invisible, which is frequently associated with chance level performance (d' = 0) in a given task. However, values of d' significantly differed from zero with pattern masks ($t(15) = 3.1$, $p = .007$), metacontrast masks ($t(15) = 3.39$, $p = .004$), and spatiotemporal crowding ($t(15) = 2.69$, $p = .017$).

RTs. Reaction times in target responses were analyzed by a two-way repeated measures ANOVA with the factors Masking Condition and Congruency. In general, a main effect of Congruency revealed that target responses were slower when prime and target arrow pointed in different directions (M = 386 ms) compared to similar directions (M = 352 ms) ($F(1,15) = 32.79$, $p < .001$, $\eta^2_g = .08$, $\eta^2_p = .69$).

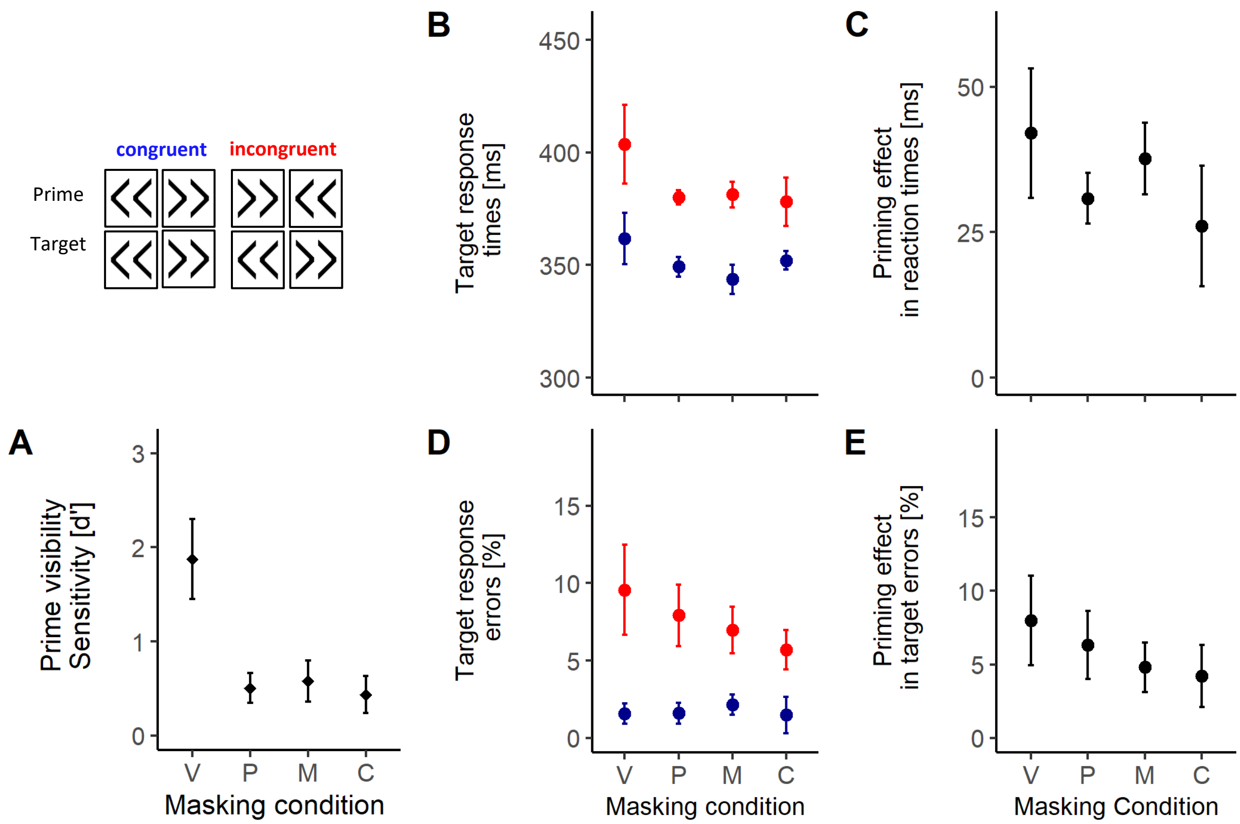

Figure 6. Study 2: performance measures for different Masking Conditions in which either a pseudo mask (V), a pattern mask (P), a metacontrast mask (M) or spatiotemporal crowding (C) was used to interfere with the processing of prime arrows.
A) Sensitivity (d') as a measure of prime visibility.
B) Target discrimination RTs when the pointing direction of prime and target arrows was incongruent (red) or congruent (blue). C) Priming effect in RTs defined as difference between RTs in incongruent and congruent conditions.
D) Target discrimination errors when the pointing direction of prime and target arrows was incongruent (red) or congruent (blue).
E) Priming effect in errors defined difference between errors in incongruent (red) and congruent (blue) conditions. Error bars are Confidence Intervals corrected for within subject designs (O'Brien & Cosineau, 2014).

This can be seen in Figure 6 B, where reaction times in incongruent conditions (red) are larger than in congruent conditions (blue) for each Masking Condition. These Congruency related reaction time differences reflect an overall priming effect of 34 ms. Additionally, a significant effect of Masking Condition ($F(3,45) = 5.19$, $p = .033$, $\eta^2_g = .02$, $\eta^2_p = .26$) indicated that reaction speed depended on the type of mask that was used to manipulate prime visibility. Pairwise post-hoc comparisons revealed that target responses were slower when a pseudo-mask was shown (M = 383 ms) compared to backward pattern masks (M = 365 ms, t(15) = 2.5, p = .024), metacontrast masks (*M* = 363 ms, *t*(15) = 2.47, *p* = .026) or spatiotemporal crowding (*M* = 365 ms, *t*(15) = 2.05, *p* = .058). However, reaction times were similar between backward pattern masks, metacontrast masks and spatiotemporal crowding, respectively (all *p* > .083). This can also be seen in Figure 6 B, as reaction times were larger with pseudo-masks compared to any other Masking Condition for both incongruent (red) and congruent (blue) conditions. It is important to note, that the interaction between both factors was not significant. This reflects that the Congruency effect was not affected by the type of mask and thus it can be concluded that processing of primes was similar across Masking conditions (priming effects in Figure 6 A).

Error Rates. Similar results showed in the analysis of target error rates with a two-way repeated measures ANOVA including the factors Congruency and Masking Condition. A main effect of Congruency reflected that more errors were made in discriminating the pointing direction of target arrows when prime and target were incongruent (M = 8 %) than congruent (M = 2%) (F(1,15) = 31.9, p < .001, η2g = .30, η2p = .68), which can be seen in Figure 6 D for red and blue dots respectively. This difference in target response errors reflects an overall priming effect of 6%. A significant main effect of Masking Condition (F(3,45) = 3.33, p = .034, ε = .88, η2g = .03, η2p = .18) indicated that the accuracy in target reactions depended on the type of mask used to affect prime visibility. Pairwise post hoc comparisons with paired t-tests showed that significantly less errors were made when spatiotemporal crowding (M = 4%) was used compared to backward pattern masks (*M* = 5%, *t*(15) = 3.11, *p* = .007), metacontrast masks (*M* = 5%, *t*(15) = 1.94, *p* = .072) or pseudo-masks (*M* = 6%, *t*(15) = 2.33, *p* = .034), while no significant differences were found between those three conditions (all *p* > .083). This can be seen in Figure 6 D, when error rates for incongruent (red) and congruent (blue) conditions are taken together. Most importantly, the interaction between Congruency and Masking Condition was not significant, indicating that the Congruency effect in error rates was similar across all Masking Conditions (priming effects in Figure 6 E).

3.5 Discussion

The aim of the present study was to systematically compare the influence of three different blinding techniques on stimulus processing in contrast to a pseudo-mask condition in which the prime stimulus was more clearly visible. While prime visibility was equally reduced by backward pattern masking, metacontrast masking and spatiotemporal crowding in contrast to the pseudo-mask condition we found that priming effects in reaction times and error rates were similar across all four conditions. These results support the hypothesis that the spatial layout of the mask characteristic for different blinding techniques does not affect stimulus processing when it is presented under similar temporal conditions. Importantly, it suggests that conditions like these are especially well suited to study the limit of unconscious visual processing, because the reduction of stimulus visibility can be achieved while the residual processing remains unaffected.

One major concern in the study of unconscious processing is that the residual processing is limited by the blinding technique that is used to manipulate visibility (Fogelson et al., 2104). This is related to the assumption that the mechanisms by which different blinding techniques prevent stimulus visibility interfere with different levels of stimulus processing. Consequently, general claims about unconscious visual processing based on findings with one specific blinding technique could be unreliable and potentially contradict findings made with other blinding techniques. Along these lines it has been proposed to classify blinding techniques according to the depth of unconscious processing they maintain (Breitmeyer, 2015). To examine these suggestions systematical comparisons of stimulus processing under different experimental manipulations of visibility are indicated. There are several studies comparing the effects of visual masking on stimulus processing to other blinding techniques (e.g., Faivre et al., 2012; Izatt et al., 2014; Peremen & Lamy, 2014). However, experimental procedures differ considerably between blinding techniques and even findings within the same blinding technique can be difficult to compare because of methodological differences.

Therefore, we developed a masked priming paradigm focusing on finding similar conditions in which backward pattern masking, metacontrast making and spatiotemporal crowding could be applied while maintaining characteristics specific to each technique. Under these conditions we minimized potential alternative explanations that could account for differences found in residual prime processing between the studied blinding techniques. Thus, it was possible to test the hypothesis whether the processing depth depends on the different blinding techniques and draw conclusions about mechanisms that are either specific to one technique or similarly involved in different ones.

We found that prime visibility was reduced to similar extents by backward pattern masking, metacontrast masking and spatiotemporal crowding, and to a larger degree compared to the pseudo-mask condition. The observed response priming effects did not differ between these conditions, with an overall priming effect of 34 ms in reaction times and 6% in error rates. This indicated that critical prime information was processed to similar degrees whether the prime was visible or strongly reduced in visibility by backward masks with different spatial layouts. Although we cannot exclude the possibility that priming effects could be diminished when prime discrimination performance was at chance level, there are observations supporting the view that priming effects would emerge to similar degrees. For example, action priming effects with arrow stimuli have been observed to be independent from prime visibility when metacontrast masking was used (Vorberg et al., 2003). Ranging from SOAs of 14 to 70 ms the arrow pointing direction could not be distinguished above chance level, while priming effect characteristically increased with SOA. In this case primes are regarded as invisible, although the detection of primes increased with SOA as well. Importantly, it is the critical feature that could not be recognized. When crowding is used as a blinding technique, stimuli can still be detected, but not distinguished from the surrounding flankers (Pelli et al., 2004). Nonetheless, response priming effects were observed with similar stimuli under these conditions (Faivre & Kouider, 2011a). Previous findings (study 1 chapter 2) indicate that priming effects were not related to visibility manipulations in spatiotemporal crowding for discriminations of color and semantic categories. In this study the flankers were presented with different SOAs and contrasts. While prime visibility increased with longer prime-flanker SOAs (resembling type A masking functions) and with weaker flanker contrasts, prime processing did not vary with flanker contrast related differences in visibility. Instead, priming effects increased with SOA as frequently observed with visual masking (Vorberg et al., 2003). Thus, this suggests that response priming effects could also be independent from prime visibility when spatiotemporal crowding is used. The dissociation of action priming effects from prime visibility has been linked to the idea of an action system and a perception system that are differently affected by metacontrast masking (Vorberg et al., 2003). These action priming effects are assumed not to be limited to arrow stimuli but could be associated with responses to different visual input.

We investigated priming effects regarding the processing of arrow stimuli with two pointing directions to further examine a functional hierarchy of blinding techniques starting with simple stimuli. Future investigations should test whether these findings can be replicated with more complex stimuli and tasks that require higher level processing. While it is inevitable to probe the unconscious processing of increasingly complex stimulus features to approximate a processing limit in the absence of awareness, the processing of higher-level information could be limited by some blinding techniques while others still allow for higher level processing.

Our findings support the hypothesis that higher-level interactions between prime and mask information could be associated with the reductions in prime visibility (Bachmann, 2005; Enns, 2004). Incoming information of the mask interfered with the processing of the previously presented prime, before a conscious prime representation could emerge. Consequently, prime identification was affected, but some residual processing survived, which was observed in the form of priming effects. With a prime-mask SOA of 80 ms we did not find differences in the effect of masks with different spatial layouts on prime visibility or processing. However, it could be that with shorter SOAs (below 50 ms) other mechanisms are involved that could for example lead to reduced priming effects, especially in the case of backward pattern masking, because prime and mask information is already integrated at lower processing levels (Bachmann, 2005).

Some trade-offs had to be made to realize this experiment, which is discussed in the following. Although the effectivity of different blinding techniques in reducing stimulus visibility is maximal under different conditions, we equated as many parameters as possible between pattern masking, metacontrast masking and crowding to show them randomly intermixed in one masked priming experiment. For this purpose, primes were presented at 10° in the lower visual field, which is characteristic for crowding, but only for a short duration of 13 ms and with a trial sequence that rather resembled procedures in metacontrast masking. The target stimulus was presented with an SOA of 80 ms and appeared simultaneously with the masks for 107 ms. These masks fulfilled characteristic features specific to pattern masking (spatial overlap), metacontrast masking (close contours) and crowding (adjacent flankers), but some compromises had to be made. Although pattern masks can be used as forward and backward masks and visibility reduction is usually strong at short SOAs (Breitmeyer & Öğmen, 2006) or when a combination of both is employed (sandwich masking), we only used backward pattern masking in this experiment. Moreover, nearby flankers that reduce the ability to discriminate a stimulus due to crowding are usually shown simultaneously (Pelli et al., 2004). To increase comparability to backward pattern masking and metacontrast masking we presented the flankers with the same SOA and thus refer to it as spatiotemporal crowding. There are indications that the strongest crowding effect does not necessarily depend on temporal coincidence of prime and flankers but can (under some conditions with larger target-flanker distances and smaller eccentricities) be shifted to positive target-flanker SOAs (Chung, 2016; Huckauf & Heller, 2004). Because we did not vary the SOA to address this question, it can only be assumed that the applied SOA of 80 ms did not produce the strongest crowding effect with small target-flanker spacing (2° from center-to-center) and relatively large eccentricity (10° from fixation). These conditions are rather associated with type A masking functions in which stimulus visibility increases with larger target-flanker SOAs (Chung, 2016; Huckauf & Heller, 2004), which was also observed in a previous study (chapter 2).

Consequently, the effectiveness of each blinding technique we used to render the prime stimulus invisible was restricted. We had to make the compromise that prime visibility was not reduced to chance performance (associated with d' = 0) in the discrimination task with neither blinding technique. This can on the one hand be attributed to the parameters of stimulus presentation that were chosen to increase comparability between different techniques instead of maximizing the efficiency of a specific one. Clearly it seems impossible to achieve both, as each blinding technique unfolds its effect optimally under different conditions. On the other hand, we assessed prime visibility in each trial over three sessions with 864 trials in total. This could have led to an overestimation of prime visibility, because participants improved their ability to discriminate primes under adverse viewing conditions due to perceptual learning or the usage of perceptual cues that allowed them to guess critical prime features above chance level without seeing the prime. Perceptual learning has for example been observed in metacontrast masking, where the prime discrimination performance improved over several sessions, without affecting the processing of these primes (Albrecht et al., 2010) and in visual crowding, where the performance to recognize a target letter flanked by another letter at each side improved over 6000 trials of practice (Chung, 2007). As the discrimination performance was above chance level with all blinding techniques compared in this study, we cannot make statements about unconscious visual processing.

The assessment of stimulus visibility in experiments using blinding techniques to render stimuli invisible is a critical subject in the investigation of unconscious processing. For this reason, it is surprising that there is no approach that is largely agreed upon, but a variety of individual solutions accompanied by different problems. Thus, it is not clear for example whether it is preferred to test prime visibility in each trial (risking to overestimate visibility) or only in a fraction of trials (potentially underestimating prime visibility). When stimuli cannot be considered invisible despite great efforts in finding the optimal conditions there is little informative value about the processing of unconscious stimuli. Perhaps this is the reason why experiments differ so much in detail even when the same blinding technique is used. Optimal conditions are very difficult to determine, because they are affected by a variety of factors interacting with each other. The problem of finding a general approach could be related, because specific solutions may only work under accordingly specific circumstances. This in turn complicates the consolidation and comparison of different findings regarding the processing limit of unconscious stimuli. How can visibility be varied, measured and analyzed, so that stimuli can be considered genuinely invisible? More agreement on questions like these would be conductive to the development in this research area (Rothkirch & Hesselmann, 2017).

However, our primary goal was a different one. We aimed at systematically investigating how residual prime processing could be differentially affected by the blinding techniques used to manipulate stimulus visibility. In the context of the search for the limit of unconscious processing the importance of finding conditions in which the processing of stimuli is not affected by the blinding technique cannot be stressed enough. Since it is conceivable that residual processing is always related to experimental manipulations, comparative studies are a step towards identifying general mechanisms that interfere with stimulus processing and by this improve hypotheses about the nature and extent of processing related to conscious perception of visual stimuli.

4 General Discussion

The general aim of this doctoral thesis was to provide further evidence on how stimulus processing could be affected by different blinding techniques. In the context of vast difficulties in finding a consensus about the NCCs or the potential limit of unconscious processing, different factors regarding the research practice in this field have been criticized (Rothkirch & Hesselmann, 2017). One confounding factor that seems to be more and more acknowledged is the dependence of residual stimulus processing on the method that is used to manipulate visibility (Breitmeyer, 2015; Fogelson et al., 2014). There seem to be different classes of blinding techniques that share some properties, which have been implemented in different theories of consciousness like the GNW theory (Naccache & Dehaene, 2001; Dehaene et al., 2006) or the RP hypothesis (Lamme, 2006; 2010). In this context blinding techniques that affect stimulus processing at an early level are not suited to investigate the processing of unconscious stimuli. This would be indicated by priming effects that vary with prime visibility, which has been observed even for simple arrow stimuli in the context of forward masking (Becker & Mattler, 2019) and CFS (Valuch & Mattler, 2019). On the other hand, other blinding techniques like attentional blink, inattentional blindness and change blindness were associated with preconscious (Dehaene et al., 2006) or recurrent (Lamme, 2010) processing. Although observed effects of unconscious stimulus processing can be large in these conditions, some argue that it should not be the preferred method to investigate visual processing, because they depend strongly on other cognitive functions like attention or working memory (Lamme, 2015).

Visual masking instead seems to be well suited to study visual processing, because a wide range of different stimuli can be rendered subliminal while at the same time residual processing seems not to be affected. Similar observations were made with visual crowding.

By systematically comparing stimulus processing between those blinding techniques, it was further explored whether residual stimulus processing differed between them. This can have implications for the choice of blinding techniques in future research and improve the understanding of the underlying mechanisms more generally that are either unique to a blinding technique or shared between them. This understanding is an essential prerequisite for generalized statements about the limit of unconscious stimulus processing and the neuronal correlates of consciousness, because our conclusion should not be misled by the effect of a method of investigation. Taken together the experiments performed within the scope of this doctoral thesis aimed at comparing the influence of different blinding techniques on the reduction of stimulus visibility and its processing. According to the functional hierarchy of blinding techniques (Breitmeyer, 2015) the suggested depth of stimulus processing could be more limited for backward pattern masking than for metacontrast masking, while crowding could allow for a larger degree than both masking techniques. This difference is especially relevant considering that all of these techniques are frequently used to figure out where the limit of unconscious stimulus processing lies. Since there is such a large variety of blinding techniques and their methodological realization, findings should be interpreted with caution and with respect to a specific blinding technique.

In chapter 2 we reported a study that investigated the effect of spatiotemporal crowding on stimulus visibility and processing with letters and digits that were either colored red or green. By applying either a categorical discrimination task or a color discrimination task to the stimuli in the priming experiment we were able to compare the performance between different task levels. We parametrically varied the visibility of peripherally presented prime stimuli by showing the flankers that induced crowding with three different contrasts. Thus, we could show that priming effects did not depend on the visibility of the primes. Moreover, priming effects increased with larger SOAs between prime and target onset. This was the case in both experiments although allover priming effects were larger for the discrimination of the color compared to the category of the stimuli. These results are comparable to metacontrast masking experiments, which indicates that similar mechanisms could play a role in crowding, when the flanker onset is delayed relative to the prime onset.

In chapter 3 the effect of three different blinding techniques on stimulus visibility and processing was investigated in one priming experiment. For this purpose, we equated as many parameters of stimulus presentation as possible while maintaining the spatial characteristics specific to each technique. The visibility of prime arrows was reduced to similar degrees by backward pattern masking, metacontrast masking and spatiotemporal crowding in contrast to a visible prime. Priming effects were equally large between all conditions, indicating that the type of the mask did not differently influence stimulus processing when presented under similar temporal conditions. On the one hand, this emphasizes the importance of the interaction of spatial and temporal characteristics that are often specific to different blinding techniques. On the other hand, equating some of these characteristics allowed us to think outside the research tradition specific to a blinding technique and thereby consider more general mechanisms that affect visibility and processing of these stimuli. Similarly, others have suggested that models of visual masking and crowding could profit from the integration of both spatial and temporal parameters (Francis & Cho, 2008), as both are usually focused on only one of those parameters.

More generally, systematic comparisons of the effects of different blinding techniques are an important step towards understanding the more general mechanisms underlying the processing of conscious versus unconscious stimuli. First of all, this minimizes the possibility of methodological aspects that could account for differences in results within and between blinding techniques. This includes for example the type, size, duration or location of the suppressed stimulus and which task has to be performed. Another important methodological aspect is the assessment of prime visibility. Specifically, whether conditions with suppressed visibility are compared to visible primes (contrastive approach) or whether prime visibility is parametrically varied, the type of visibility assessment (objective measure or subjective measure or both) and whether visibility is measured in each trial or only in a fraction of trials. Only small changes in one of these aspects can have large effects on the study outcome.

Moreover, by equating as many parameters as possible between different blinding techniques systematical comparisons allow to further narrow down which aspects of a blinding technique account for its specific effect. Is it the temporal sequence or the spatial layout of the stimuli or rather a combination of both? And how does this interact with SOAs? Along these lines the second study (chapter 3) showed that the spatial layout characteristic for a pattern mask, a metacontrast mask and crowding did not affect stimulus processing differently when all masks were presented in the visual periphery with an SOA of 80 ms. This result contradicts the prediction based on the functional hierarchy suggested by Breitmeyer (2015) at first glance. However, it is possible that differences between these blinding techniques could be revealed in shorter or longer SOAs (Bachmann, 2005) or with stimuli that require higher level processing. This is a subject for further investigation. Nevertheless, it is interesting that with this specific timing the mechanism that affects stimulus visibility could be similar between backward pattern masking, metacontrast masking and spatiotemporal crowding. A different, possibly more fruitful approach to describe these results could be to focus less on the distinction between those blinding techniques but rather to explore under which conditions different effects emerge. This could lay the foundation for a more general understanding of the mechanisms that underlie the processing of unconscious stimuli and how these are limited.

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6 Supplemental Material

Table 1. Study 1: numbers of classified trials for each participant (VP) performing either the perceptual color discrimination task (P) or the semantic category discrimination (SC) task

VP	Task level	Fixation error trials	Start delay trials	Choice errors in the speeded RT task	Target reaction post-error trials	Target reaction trials	Target reaction trials [%]	Prime visibility trials	Prime visibility trials [%]
1	P	2	96	127	174	854	74	1088	94
2	P	0	59	74	146	925	80	1113	97
3	P	0	127	56	98	976	85	1075	93
4	P	0	204	22	108	1005	87	988	86
5	P	0	106	37	153	932	81	1085	94
6	P	0	97	49	87	969	84	1116	97
7	P	0	86	138	227	798	69	1106	96
8	P	0	76	60	203	874	76	1115	97
9	P	0	90	101	152	883	77	1109	96
10	P	0	61	44	155	937	81	1120	97
11	P	1	80	54	200	886	77	1103	96
12	P	0	87	19	69	1029	89	1110	96
13	P	0	65	19	101	1007	87	1123	97
14	P	0	268	18	129	998	87	900	78
15	P	1	97	38	83	1018	88	1084	94
16	P	0	53	182	279	730	63	1120	97
17	SC	0	93	126	275	771	67	1105	96
18	SC	0	116	49	261	843	73	1050	91
19	SC	0	106	123	186	852	74	1060	92
20	SC	0	115	59	266	827	72	1064	92
21	SC	0	91	22	207	883	77	1115	97
22	SC	1	92	57	269	813	71	1106	96
23	SC	0	92	50	154	932	81	1088	94
24	SC	0	38	75	250	834	72	1128	98
25	SC	2	84	59	169	912	79	1097	95
26	SC	0	98	84	129	923	80	1104	96
27	SC	0	93	173	234	783	68	1093	95
28	SC	0	52	57	297	798	69	1123	97
29	SC	0	79	47	211	888	77	1102	96
30	SC	0	114	29	203	903	78	1073	93
31	SC	2	53	33	190	914	79	1126	98
32	SC	0	58	179	319	689	60	1116	97

Table 2. Study 1: results of the ANOVA on prime visibility (d') with the factors Task Level (perceptual and semantic categorization), SOA (30, 60, 90, and 120 ms), and Flanker Contrast (weak, medium and strong)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	F	p	η^2_g	η^2_p
(Intercept)	1	15		1560.41	85.02	275.29	.000	.86	.95
Task Level	1	15		56.37	111.14	7.61	.015	.18	.34
SOA	3	45	0.57	37.79	7.10	79.89	.000	.13	.84
Flanker Contrast	2	30	0.60	86.51	11.15	116.40	.000	.25	.89
Task Level x SOA	3	45	0.52	3.65	9.18	5.95	.013	.01	.28
Task Level x Flanker Contrast	2	30	0.70	0.93	9.65	1.45	.252	.00	.09
SOA x Flanker Contrast	6	90	0.66	21.61	12.46	26.01	.000	.08	.63
Task Level x SOA x Flanker Contrast	6	90	0.53	0.69	9.93	1.04	.385	.00	.06

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse-Geisser multiplier for degrees of freedom, p-values in the table incorporate the Greenhouse-Geisser correction. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η^2_g indicates generalized eta squared. η^2_p indicates partial eta squared.

Table 3. Study 1: results of the ANOVA on RTs with the factors Task Level (color discrimination and categorical discrimination), Prime-Target Congruency (congruent and incongruent), SOA (30, 60, 90 and 120ms), and Flanker Contrast strength (weak, medium and strong)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g	η^2_p
(Intercept)	1	15		248306573.83	1742717.53	2137.24	.000	.99	.99
Task Level	1	15		487151.44	1170496.88	6.24	.025	.13	.29
Congruency	1	15		33365.96	13683.23	36.58	.000	.01	.71
Task Level x Congruency	1	15		7341.22	10786.61	10.21	.006	.00	.40
SOA	3	45	0.75	34148.85	27013.55	18.96	.000	.01	.56
Flanker Contrast	2	30	0.99	3908.15	7637.26	7.68	.002	.00	.34
Task Level x SOA	3	45	0.82	685.64	17842.08	0.58	.601	.00	.04
Task Level x Flanker Contrast	2	30	0.98	2934.16	15774.78	2.79	.078	.00	.16
SOA x Flanker Contrast	6	90	0.64	1428.99	31031.04	0.69	.597	.00	.04
SOA x Congruency	3	45	0.85	9017.23	14555.76	9.29	.000	.00	.38
Flanker Contrast x Congruency	2	30	0.70	116.17	11996.42	0.15	.789	.00	.01
Task Level x SOA x Flanker Contrast	6	90	0.65	718.71	25837.02	0.42	.790	.00	.03
Task Level x SOA x Congruency	3	45	0.87	2839.45	15306.57	2.78	.061	.00	.16
Task Level x Flanker Contrast x Congruency	2	30	0.82	918.63	12466.43	1.11	.336	.00	.07
SOA x Flanker Contrast x Congruency	6	90	0.81	1320.38	25981.94	0.76	.576	.00	.05
Task Level x SOA x Flanker Contrast x Congruency	6	90	0.73	4044.55	34213.98	1.77	.139	.00	.11

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse-Geisser multiplier for degrees of freedom, *p*-values in the table incorporate the Greenhouse-Geisser correction. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η^2_g indicates generalized eta squared. η^2_p indicates partial eta squared.

Table 4. Study 1: results of the ANOVA on target errors with the factors Task Level (color discrimination and categorical discrimination), Prime-Target Congruency (congruent and incongruent), SOA (30, 60, 90 and 120 ms), and Flanker Contrast strength (weak, medium and strong)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	F	p	η^2_g	η^2_p
(Intercept)	1	15		39.85	5.66	105.69	.000	.75	.88
Task Level	1	15		1.13	2.40	7.04	.018	.08	.32
Congruency	1	15		0.01	0.07	2.91	.109	.00	.16
Task Level x Congruency	1	15		0.01	0.10	1.71	.210	.00	.10
SOA	3	45	0.84	0.07	0.29	3.37	.035	.01	.18
Flanker Contrast	2	30	0.80	0.03	0.27	1.57	.229	.00	.10
Task Level x SOA	3	45	0.94	0.02	0.34	0.96	.417	.00	.06
Task Level x Flanker Contrast	2	30	0.97	0.00	0.21	0.09	.914	.00	.01
SOA x Flanker Contrast	6	90	0.63	0.06	0.83	1.06	.383	.00	.07
SOA x Congruency	3	45	0.94	0.02	0.45	0.75	.519	.00	.05
Flanker Contrast x Congruency	2	30	0.90	0.00	0.17	0.38	.668	.00	.02
Task Level x SOA x Flanker Contrast	6	90	0.70	0.02	0.54	0.55	.705	.00	.04
Task Level x SOA x Congruency	3	45	0.94	0.03	0.31	1.38	.263	.00	.08
Task Level x Flanker Contrast x Congruency	2	30	0.91	0.00	0.20	0.15	.843	.00	.01
SOA x Flanker Contrast x Congruency	6	90	0.70	0.03	0.58	0.74	.578	.00	.05
Task Level x SOA x Flanker Contrast x Congruency	6	90	0.64	0.04	0.56	0.99	.420	.00	.06

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse-Geisser multiplier for degrees of freedom, p-values in the table incorporate the Greenhouse-Geisser correction. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η^2_g indicates generalized eta squared. η^2_p indicates partial eta squared.

Table 5. Study 2: numbers of classified trials for each participant (VP)

VP	Fixation error trials	Start delay trials	Target response errors	Target response trials	Target response trials [%]	No Prime response	Prime response trials	Prime response trials [%]
1	0	21	58	434	85	2	432	84
2	0	26	13	474	93	11	463	90
3	0	9	32	471	92	0	471	92
4	1	28	16	468	91	10	465	91
5	0	26	30	458	89	1	457	89
6	0	14	23	477	93	3	474	93
7	0	24	6	482	94	1	481	94
8	1	29	15	468	91	9	460	90
9	1	22	89	406	79	48	371	72
10	0	18	9	486	95	3	484	95
11	5	15	22	472	92	5	467	91
12	2	19	37	455	89	1	454	89
13	2	9	11	490	96	0	490	96
14	0	10	34	469	92	0	469	92
15	1	27	67	423	83	4	422	82
16	0	19	5	489	96	0	489	96

Table 6. Study 2: results of the repeated-measures ANOVA on prime visibility (d') with the factor Masking Condition (pseudo-mask, a backward pattern mask, metacontrast mask and spatiotemporal crowding)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g	η^2_p
(Intercept)	1	15		46.10	31.93	21.66	.000	.51	.59
Masking Condition	3	45	.45	22.60	13.15	25.77	.000	.33	.63

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse-Geisser multiplier for degrees of freedom, *p*-values incorporate this correction and degrees of freedom are given in uncorrected form. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η^2_g indicates generalized eta-squared and η^2_p partial eta-squared.

Table 7. Study 2: results of the two-way repeated-measures ANOVA on RTs with the factors Prime-Target Congruency (congruent and incongruent) and Masking Condition (pseudo-mask, backward pattern mask, metacontrast mask and spatiotemporal crowding)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g	η^2_p
(Intercept)	1	15		17404933.63	365886.80	713.5 4	.000	.98	.98
Congruency	1	15		37367.29	17092.04	32.79	.000	.08	.69
Masking Condition	3	45	0.37	8473.36	24504.14	5.19	.033	.02	.26
Congruency x Masking Condition	3	45	0.64	1211.43	6716.92	2.71	.086	.00	.15

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse-Geisser multiplier for degrees of freedom, *p*-values in the table incorporate this correction and degrees of freedom are given in uncorrected form. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η^2_g indicates generalized eta-squared and η^2_g partial eta-squared.

Table 8. Study 2: results of the two-way repeated-measures ANOVA on target errors with the factors Prime-Target Congruency (congruent and incongruent) and Masking Condition (pseudo-mask, backward pattern mask, metacontrast mask and spatiotemporal crowding)

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	F	p	η^2_g	η^2_p
(Intercept)	1	15		3.56	0.91	58.41	.000	.67	.80
Congruency	1	15		0.78	0.37	31.90	.000	.30	.68
Masking Condition	3	45	0.88	0.05	0.24	3.33	.034	.03	.18
Congruency x Masking Condition	3	45	0.95	0.01	0.27	0.61	.603	.01	.04

Note. df_{Num} indicates degrees of freedom numerator. df_{Den} indicates degrees of freedom denominator. Epsilon indicates Greenhouse-Geisser multiplier for degrees of freedom, *p*-values in the table incorporate this correction and degrees of freedom are given in uncorrected form. SS_{Num} indicates sum of squares numerator. SS_{Den} indicates sum of squares denominator. η^2_g indicates generalized eta-squared and η^2_p partial eta-squared.

7 List of Figures

8 List of Abbreviations

ANOVA	analysis of variance
CFF	continuous flicker fusion
CFS	continuous flash suppression
GNW	global neuronal workspace
fMRI	functional magnetic resonance imaging
ISI	inter-stimulus interval
ITT	information integration theory
MAE	motion after effect
NCC	neuronal correlates of consciousness
OSM	object substitution masking
RP	recurrent processing
RT	reaction times
SOA	stimulus onset asynchrony
SNM	sandwich noise masking
TEAE	threshold elevation after effect

Declaration of originality

I hereby confirm that all parts of the dissertation were written by myself and that assistance of third parties was only requested if scientifically justifiable and acceptable within the examination regulations. All utilized sources of information have been quoted and are given in the reference list.

Göttingen, 14.11.2020

Anne Sommerfeld