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THE BREAKING CONTINUOUS FLASH SUPPRESSION PARADIGM

Review, evaluation, and outlook

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Understanding the function and neural basis of conscious awareness is one of the major challenges of cognitive psychology and neuroscience. One promising approach to is to map out those perceptual and cognitive functions that can take place outside of conscious awareness, i.e. unconsciously (Kouider & Faivre, 2017). Ultimately, this research program could yield a set of functions that cannot occur unconsciously and are tightly linked to conscious awareness, which would provide important insights into the functional role of conscious awareness (Baars, 1988). Alternatively, it may turn out that virtually all perceptual and cognitive processes can transpire unconsciously, rendering conscious awareness an epiphenomenon.

However, a consensus on the scope and potential limits of unconscious processing seems currently out of reach. The reason for this is not simply a lack of studies testing whether certain perceptual or cognitive functions depend on conscious awareness. Rather, based on the same published data some researchers conclude that unconscious processing can carry out basically any high-level function (Hassin, 2013), whereas others are more skeptical, proposing that unconscious processing is quite limited (Hesselmann & Moors, 2015). This disagreement stems partly from different definitions of the term "unconscious" in social psychology (where it is often used interchangeably with "implicit", i.e. without conscious knowledge of an experimental manipulation) and cognitive psychology (where it is mostly used to refer to a "non-reportable" stimulus feature during its presentation).

But even within experimental psychology and cognitive neuroscience some authors conclude that there is no evidence even for very basic unconscious visual perception (Peters & Lau, 2015), while others propose that even complex semantic integration can occur unconsciously (Sklar, Deouell, & Hassin, 2018). Much of this controversy is due to the use of a range of widely differing experimental approaches to unconscious processing. Different researchers adopt different experimental paradigms, different psychophysical techniques for presenting stimuli outside of conscious awareness, and different measures to demonstrate the absence of conscious perception. Some of these approaches, such as the classical dissociation paradigm, are grounded in a long history of experimentation, have high face validity, and a large literature discussing their theoretical underpinnings (e.g. Erdelyi, 1986; Greenwald & Draine, 1998; Merikle, Smilek, & Eastwood, 2001; Schmidt & Vorberg, 2006; Snodgrass, Bernat, & Shevrin, 2004). Other, more recently developed approaches, such as the "breaking CFS" paradigm discussed in this chapter, are currently widely applied although their underlying rationale has not yet been fully developed. Not all researchers consider findings obtained with these novel approaches convincing evidence for unconscious processing.

1 Continuous flash suppression (CFS)

In the domain of vision, the development of a novel psychophysical technique, named continuous flash suppression (CFS; Tsuchiya & Koch, 2005) has sparked a tidal wave of interest in unconscious processing (see Figure 1.1). CFS is a strong

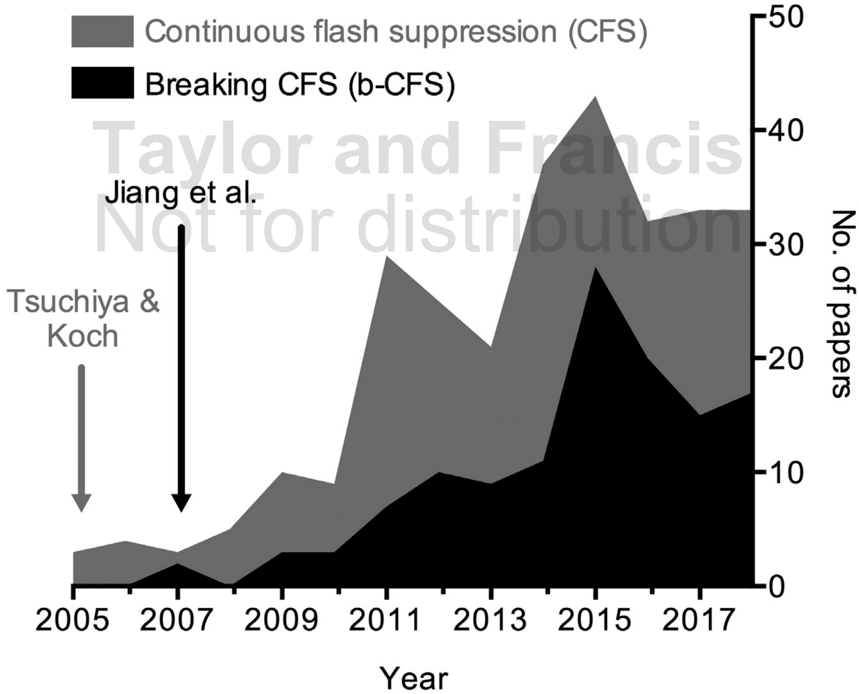

FIGURE 1.1 Number of CFS publications per year, from the publication by Tsuchiya and Koch (2005) who developed the technique of CFS to August 2018. Also plotted is the subset of papers that adopted some variant of the "breaking CFS" paradigm first introduced by Jiang, Costello, and He (2007). Publications are based on data from the website of Pieter Moors (www.gestaltrevision.be/s/cfs, retrieved August 10, 2018).

interocular suppression technique, in which the presentation of flashing, high-contrast dynamic masks to one eye can render an image (the target) presented to the other eye invisible for up to several seconds. Because CFS is straightforward to implement and allows for long periods of subjective invisibility of complex visual stimuli, this technique has been widely adopted to study unconscious processing. While many studies have combined CFS with traditional dissociation paradigms for studying unconscious processing, the technique also inspired the development of a novel paradigm, the so-called "breaking CFS" (b-CFS; Jiang, Costello, & He, 2007; Stein, Hebart, & Sterzer, 2011a) paradigm.

Although nearly half of all studies using the psychophysical technique of CFS adopted some variant of the b-CFS paradigm (see Figure 1.1), it is currently debated whether this paradigm is indeed measuring unconscious processing (Gayet, Van der Stigchel, & Paffen, 2014; Stein et al., 2011a; Stein & Sterzer, 2014; Yang, Brascamp, Kang, & Blake, 2014). In this chapter, I will first compare the rationale of the b-CFS paradigm to classic dissociation paradigms (sections 2 and 3). I will then review how the paradigm has been applied to study unconscious processing, including an overview of the most common b-CFS tasks and measures. This review will include a critical evaluation of what can be concluded from findings obtained with b-CFS, and how control conditions and additional paradigms might or might not be helpful in interpreting b-CFS results (section 4). In the final part, I will propose possible future avenues for embedding the b-CFS paradigm in the classical dissociation framework (section 5).

2 The classic dissociation paradigm

To better illustrate why the b-CFS paradigm represents a novel, uncommon way of measuring unconscious visual processing, it is necessary to briefly describe the most common approach to unconscious visual processing, the classic dissociation paradigm (Erdelyi, 1986). This approach is very intuitive: a stimulus is rendered invisible and two measures are collected, one measure of stimulus awareness and one measure of stimulus processing. According to the simple dissociation logic (Schmidt & Vorberg, 2006), unconscious processing is demonstrated when the awareness measure shows null sensitivity while the processing measure shows some sensitivity. For the present purpose, it is helpful to distinguish between two variants of the classic dissociation paradigm, which I term the "direct-indirect" dissociation paradigm, often used in "priming-like" studies and the "direct-direct" dissociation paradigm, often used in "blindsight-like" studies.

2.1 The direct-indirect dissociation paradigm in "priming-like" studies

This approach contrasts a direct task assessing stimulus awareness (with the instructions explicitly referring to the invisible stimulus) with an indirect task assessing incidental stimulus processing (Figure 1.2a). There are many different measures of stimulus processing, the most popular being priming, where the invisible stimulus exerts an influence on the response to a subsequent visible stimulus. Other common measures of stimulus processing include attentional cueing, adaptation aftereffects, and recordings of neural activity. There are also many different ways of assessing stimulus awareness, each with their own advantages and disadvantages. Some researchers use subjective awareness measures in which participants simply indicate whether they did or did not see a stimulus, rate stimulus visibility, or their confidence. Other researchers prefer objective awareness measures to show that participants are unable to either detect the invisible stimulus or to discriminate certain stimulus features. The pros and cons of subjective and objective measures have been discussed elsewhere (e.g. Cheesman & Merikle, 1986; Kunimoto, Miller, & Pashler, 2001; Schmidt, 2015; Snodgrass et al., 2004). Suffice it to say that subjective measures may be too liberal, as they tend to underestimate stimulus awareness and thus may overestimate the extent of unconscious processing, while objective measures may be too conservative and thus may underestimate the extent of unconscious processing.

2.2 The direct-direct dissociation paradigm in "blindsight-like" studies

In this less commonly used variant of the dissociation paradigm, two direct tasks are contrasted, one assessing stimulus awareness and the other stimulus processing (Figure 1.2b). Here, both tasks explicitly refer to the invisible stimulus. Although this approach has a long tradition and was adopted long before the discovery of "blindsight" (e.g. Sidis, 1898) it seems intuitive to label it "blindsight-like" because the basic idea is reminiscent of the behavior of certain patients with visual cortex lesions. These blindsight patients report no awareness of a visual stimulus that they can nevertheless detect and discriminate with high accuracy (Weiskrantz, 1986). Similarly, with healthy subjects a subjective measure of stimulus awareness, such as a seen/unseen judgment or a visibility rating, can be contrasted with an objective measure of stimulus processing, such as discrimination of a stimulus feature (e.g. Soto, Mäntylä, & Silvanto, 2011). One important concern with this approach is that subjective measures require subjects to set an arbitrary criterion for reporting stimulus awareness. This criterion may be too conservative, such that weakly conscious stimuli are categorized as unconscious. Performance without subjective awareness could thus reflect weakly conscious rather than truly unconscious processing (e.g. Eriksen, 1960; Peters & Lau, 2005; Stein, Kaiser, & Hesselmann, 2016).

Aside from these methodological concerns, it is interesting to note that even within the classic dissociation paradigm the same task can be used to index either conscious or unconscious processing. In the direct-indirect variant of the dissociation paradigm a direct, objective task, such as stimulus detection, often serves to measure awareness, whereas in the direct-direct variant of the dissociation paradigm the same direct, objective task could serve to measure stimulus processing. This inconsistent usage of tasks and measures contributes to the difficulty of aggregating data from different paradigms into a general theory of unconscious processing.

2.3 CFS studies adopting the classic dissociation paradigm

Before the development of CFS, most studies adopting the direct-indirect variant of the dissociation paradigm used some form of backward masking, where the visibility of very brief, binocularly presented stimuli is degraded by the presentation of a succeeding visual pattern (Breitmeyer & Ögmen, 2006). This approach has yielded evidence for high-level semantic unconscious processing under backward masking (Kouider & Dehaene, 2007; Van den Bussche, Van den Noortgate, & Reynvoet, 2009). Initial priming and adaptation aftereffect studies using CFS, by contrast, showed that unconscious processing is comparably limited (e.g. Almeida, Mahon, Nakayama, & Caramazza, 2008; Moradi, Koch, & Shimojo, 2005). By now, the CFS literature using the classic direct-indirect dissociation paradigm has become increasingly complex. Although a review is beyond the scope of this chapter, it is useful to highlight the discrepancy between findings obtained with the direct-indirect dissociation paradigm and the b-CFS paradigm with one select example: A number of behavioral studies adopting the direct-indirect dissociation paradigm have found little evidence for unconscious processing of facial attributes (other than emotional expression) under CFS (Amihai, Deouell, & Bentin, 2011; Shin, Stolte, & Chong, 2009; Stein, Peelen, & Sterzer, 2012a; Stein & Sterzer, 2011; Xu, Zhang, & Geng, 2018; but see Hung, Nieh, & Hsieh, 2016; Xu, Zhang, & Geng, 2011). In contrast, as reviewed below, b-CFS studies have provided evidence for unconscious processing of various facial attributes (section 4.1.2). This can be seen as evidence that the b-CFS paradigm is more sensitive to unconscious processing than the direct-indirect dissociation paradigm.

Comparably far less CFS studies have adopted the direct-direct dissociation paradigm. Only a handful of behavioral studies compared a subjective awareness measure to an objective performance measure (for an fMRI study, see Hesselmann, Hebart, & Malach, 2011). These studies found, even for subjectively unconscious stimuli, above-chance localization (Oliver, Mao, & Mitchell, 2015; Vieira, Wen, Oliver, & Mitchell, 2017; Bergström & Eriksson, 2015, 2018) and discrimination (Bergström & Eriksson, 2015, 2018; Song & Hao, 2016). However, all three studies suffer from the criterion problem mentioned above: participants may have categorized weakly conscious stimuli as unconscious. Recent work using criterion-free measures of subjective awareness and backward masking found no evidence for unconscious processing when this criterion issue was ruled out (Peters & Lau, 2015). Thus, the direct-direct dissociation paradigm seems comparably insensitive to unconscious processing, even with backward masking. Nevertheless, I believe that there are elegant ways for including modified versions of the direct-direct dissociation logic in improved future versions of the b-CFS paradigm, and will propose a way of incorporating this method in b-CFS at the end of this chapter (section 5.2).

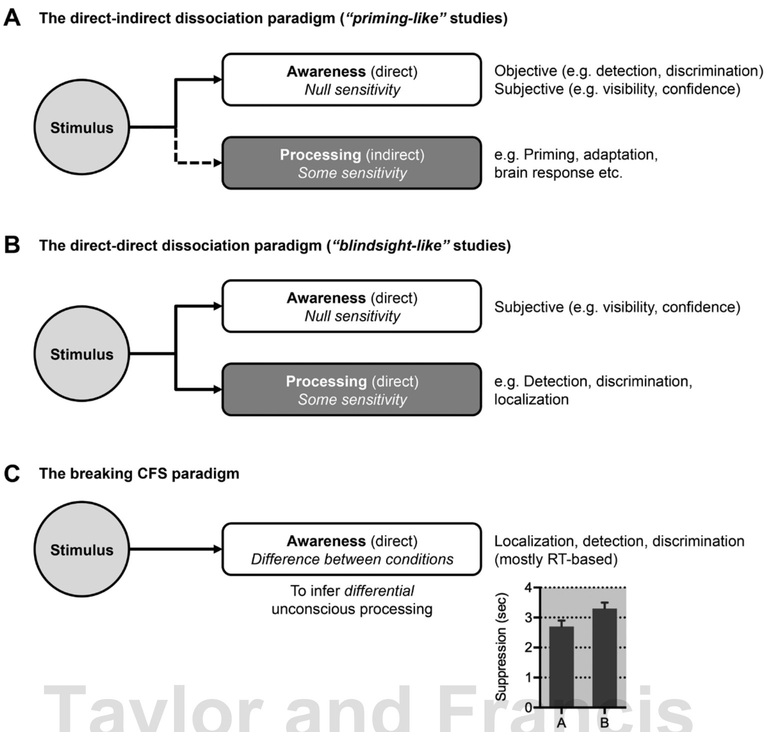

FIGURE 1.2 The three most popular paradigms for measuring unconscious visual processing. (a) In the direct-indirect dissociation paradigm a direct measure of awareness is contrasted with an indirect measure of stimulus processing and unconscious processing is inferred when the former shows null sensitivity while the latter shows some sensitivity. (b) In the direct-direct dissociation paradigm a direct measure of subjective awareness is contrasted with a direct measure of stimulus processing (which can be the same as the direct measure of awareness in the direct-indirect dissociation paradigm) and unconscious processing is inferred when the former shows null sensitivity while the latter shows some sensitivity. (c) In the b-CFS paradigm, only one direct measure of awareness is collected. Differences between stimulus conditions in this measure are thought to reflect differential unconscious processing.

3 The breaking CFS (b-CFS) paradigm

The b-CFS paradigm differs fundamentally from the variants of the dissociation paradigm. In its basic form, the b-CFS paradigm consists of only one direct task rather than two tasks or measures, and no attempt is being made to contrast and dissociate different measures. This single direct task capitalizes on the fact that CFS can render a stimulus (the "target") invisible for up to several seconds, but eventually the stimulus will perceptually "break" through the CFS masks and enter awareness. The b-CFS paradigm aims to track the time different target stimuli need to overcome CFS and break into awareness, most commonly through speeded localization or detection responses (see section 4.2). Localization or detection latencies are taken as estimates of the duration of perceptual suppression. Differences in suppression time between different target conditions are thought to reflect differences in unconscious processing the stimuli receive while still being suppressed (Figure 1.2c). Shorter suppression times are believed to indicate enhanced, faster, or more fluent unconscious processing.

The b-CFS paradigm is used to infer *differential unconscious processing* of one condition relative to another condition. This is different from the classic dissociation paradigm which could, in principle, be used to study unconscious processing with one suppressed stimulus only, e.g. by testing priming from one particular stimulus exemplar (e.g. one face identity). The b-CFS paradigm requires the comparison of at least two different, initially suppressed targets. In the first published b-CFS study, Jiang and colleagues (2007) compared suppression times of upright to inverted faces (i.e. rotated by 180 degrees) and found that upright faces break into awareness more quickly. According to the b-CFS logic this shows that upright and inverted faces receive differential unconscious processing while still being fully suppressed. This indicates that information about face orientation can be represented unconsciously. Clearly, for this reasoning to be valid the two target conditions should not differ along any other dimension. For example, higher luminance contrast in one condition would trivially account for shorter suppression times. Indeed, as discussed below (section 4.1.1), differences in such low-level stimulus properties represent a major difficulty in interpreting b-CFS findings, especially for studies comparing target stimuli that have inherent, uncontrollable physical differences, such as faces with different emotional expressions (see section 4.1.2).

The more general conceptual issue with the b-CFS paradigm is that its basic logic seems at odds with previous and more common ways of measuring unconscious processing, such as the classic dissociation paradigm. The one measure collected in b-CFS studies is a direct measure of stimulus awareness. In most studies, this measure is a speeded response, i.e. a subjective measure (participants need to decide when they have enough sensory evidence to press a button; see section 4.2). In both the direct-indirect and the direct-direct version of the classic dissociation paradigm this direct task would represent a measure of stimulus awareness, not a measure of unconscious stimulus processing. Why, then, are differences in this direct measure in b-CFS paradigms used to measure differential unconscious processing? Two different underlying rationales are adopted in the b-CFS literature. As these are rarely made fully explicit (but see Stein & Sterzer, 2014), it is useful to flesh them out in some detail.

3.1 Differences in detectability reflect differential unconscious processing

One rationale is that differences in the time target stimuli need to break into awareness simply reflect differences in preceding unconscious processing. This view is based on the idea of a temporal sequence from unconscious processing to conscious awareness. It also assumes that there is a more or less discrete transition from unconscious processing to conscious awareness that can be tracked with high precision, for example, by using simple (speeded) localization or detection responses. Because of the assumed sequential stream from unconscious processing to conscious awareness, differences between stimuli in transition times must imply differences in unconscious processing.

It is interesting that this logic is commonly adopted in b-CFS studies but only very rarely when other psychophysical techniques are used. In fact, the same logic could in principle be applied to any experiment measuring differences in stimulus detectability, irrespective of whether CFS or backward masking, or any other psychophysical technique (e.g. crowding, visual search, rapid serial visual presentation, simultaneous noise masking, etc.) is used (Dijksterhuis & Aarts, 2003; Gaillard, Del Cul, Naccache, Vinckier, Cohen, & Dehaene, 2006). With CFS, this logic may be more readily adopted because stimuli remain invisible for up to several seconds before they enter awareness, and this may be suggestive of an extended period of unconscious processing. With other techniques, such as backward masking, this time can be in the order of several milliseconds only. This comparably short period, however, does not exclude differential responses to different stimuli, for example, in a rapid feedforward sweep of visual processing (Van Rullen, 2007). Although stimulus detection most likely involves different neural processes for different psychophysical techniques, this is not directly relevant for the basic logic assuming (a) an unconscious-conscious sequence and (b) a precise measure of the transition point. As such, this logic could be similarly applied to other techniques.

Independent of the psychophysical technique, researchers adopting this logic need to address several challenges. One of the most obvious problems is that it is debated whether a discrete transition point from unconscious processing to conscious awareness exists, with a whole literature investigating the question whether consciousness is gradual or dichotomous (e.g. Asplund, Fougnie, Zughni, Martin, & Marois, 2014; Nieuwenhuis & de Kleijn, 2011; Overgaard, Rote, Mouridsen, & Ramsøy, 2006; Sergent & Dehaene, 2004). Furthermore, even if such a transition point existed, it is questionable whether any particular behavioral response could be used to track this point with sufficient precision. A particularly pressing issue with the tasks commonly used in b-CFS studies is that responses may be influenced by perceptual processes that occur after the transition into awareness (e.g. categorization, exemplar-level identification, etc.) or even by later non-perceptual processes (e.g. naming, decision, response selection, etc.). Below I will review which tasks and responses are currently used in b-CFS studies (section 4.2), how researchers attempt to control post-perceptual processes by non-CFS control conditions (section 4.3), and give some recommendations for future research (section 5).

3.2 CFS-specific unconscious processing differences

An alternative rationale in the b-CFS literature is to base any conclusion about unconscious processing on a comparison with a non-CFS control condition. As we described previously (Stein & Sterzer, 2014), on this account unconscious processing is inferred from b-CFS only *because* CFS is used to render a stimulus invisible. That is, differences in target detectability are attributed to differential processing that took place specifically under CFS, i.e. to *CFS-specific* differences. For this reasoning to be valid, *non CFS-specific* differences in stimulus detectability need to be excluded as a cause for differences in suppression times.

To isolate CFS-specific processing, suppression times are compared to a binocular or monocular control condition, in which the same task as in b-CFS is implemented, but stimuli are presented in a way that does not induce interocular suppression. The target is most commonly gradually blended in on top of the flashing CFS masks. Targets and masks are presented either to both eyes or to one eye only, with the other eye receiving no visual stimulation. The control condition is intended to perceptually resemble b-CFS and to capture all non-CFS specific differences in stimulus detectability that might have contributed to differences in suppression times. Following this logic, CFS-specific unconscious processing differences are inferred when the difference in suppression times is larger than the effect obtained in the control condition.

We have argued that this conclusion is unwarranted (Stein et al., 2011a; Stein & Sterzer, 2014) because it seems impossible to develop a control condition that captures all aspects of non CFS-specific processing that might contribute to differences in suppression times. For example, in b-CFS perceptual uncertainty about target appearance tends to be much greater than in control conditions (see section 4.3), and participants can easily tell b-CFS and control conditions apart, demonstrating that they are not perceptually matched (Stein et al., 2011a). Thus, at least in its present form, the logic of comparing b-CFS to control conditions cannot provide unequivocal evidence for CFS-specific unconscious processing.

There may be one exception, namely when significant differences between stimulus conditions are obtained both in b-CFS and in the control condition, but with the effect going in opposite directions in the two conditions (see Stein & Sterzer, 2014). Such opposite effects would render CFS-specific unconscious processing differences as a cause for differences in suppression times more likely. To date there has only been one such finding in the literature: Prioli and Kahan (2015) found that in b-CFS neutral words were identified faster than negative words, whereas in the control condition negative words were identified faster than neutral words. However, this study used an RT-based identification task that can strongly be affected by post-perceptual biases (see section 4.2.1), and their influence may differ between b-CFS and the control condition. Also, this study adopted a between-subject design with different participants in b-CFS and in the control condition, and the critical interaction effect just crossed the threshold for statistical significance, thus calling for independent replication.

4 Review of b-CFS studies

From the above summary of the two different rationales that are commonly used to infer unconscious processing from b-CFS it is clear that the exact implementation of the paradigm is of critical importance. In the following, I will review the most common experimental manipulations used in published b-CFS studies, summarize the key findings (section 4.1), critically evaluate the tasks and measures that have been employed (section 4.2), and review whether and how control conditions have been implemented, and to what extent b-CFS results have been compared to other psychophysical techniques (section 4.3).

For Figure 1.1, I identified 125 publications that used some version of the b-CFS paradigm in a broad sense. This also included studies that did not explicitly compare suppression times for different stimulus conditions but used b-CFS paradigms to measure eye dominance (Ding, Naber, Gayet, Van der Stigchel, & Paffen, 2018; Yang, Blake, & MacDonald, 2010) or to probe into the influence of visual properties of the CFS mask, such as its orientation, spatial frequency, color, flash frequency, pattern, and similarity with visual properties of the target (Drewes, Zhu, & Melcher, 2018; Han & Alais, 2018; Han, Blake, & Alais, 2018; Han, Lunghi, & Alais, 2016; Hong & Blake, 2009; Kaunitz, Fracasso, Skujevskis, & Melcher, 2014; Moors, Wagemans, & de-Wit, 2014; Zhan, Engelen, & de Gelder, 2018). While these studies are of foundational importance for our understanding of the CFS technique itself, in the following review I only included those 115 b-CFS publications that compared suppression times for different target stimuli.

4.1 Topics and experimental manipulations

4.1.1 Visual features

Although the debate on the extent of unconscious processing revolves around the processing of "higher-level" (i.e. semantic or conceptual) stimulus dimensions, b-CFS has also widely been used to measure visual processing of "lower-level" visual stimulus properties. These studies found that suppression times are shorter for targets that have higher contrast (e.g. Akechi, Stein, Senju, Kikuchi, Tojo, Osanai, & Hasegawa, 2014; Akechi, Stein, Yikuchi, Tojo, Osanai, & Hasegawa, 2015; Kaunitz et al., 2014; Song & Yao, 2016), larger retinal size (Heyman & Moors, 2014), higher spatial frequency (Yang & Blake, 2012), radial rather than tangential orientation or motion (Hong, 2015), higher moving speed (Ananyev, Penney, & Hsieh, 2017), higher motion and form coherence (Chung & Khuu, 2014; Kaunitz, Fracasso, Lingnau, & Melcher, 2013), collinear rather than orthogonal contours (Li & Li, 2015), and for targets that contain a hole (Meng, Cui, Zhou, Chen, & Ma, 2012; Zhu, Drewes, & Melcher, 2016). Taken together, these findings indicate that most manipulations that increase a target's visual salience are associated with shorter suppression times.

Another important factor is target-mask similarity: the more similar the visual features of the target and the CFS mask the longer the suppression time (Han & Alais, 2018; Yang & Blake 2012; but not for moving speed, see Ananyev et al., 2017). Interestingly, this influence of target-mask similarity is not limited to visual features alone. When CFS masks consist of images from object categories that have similar representations in higher-level visual cortex as the target object (e.g. buildings and cars) suppression times are longer than when representations are comparably dissimilar (e.g. building and bodies; Cohen, Nakayama, Konkle, Stantić, & Alvarez, 2015). While these effects related to target-mask similarity and to lower-level physical visual features are not directly relevant for answering whether higher-level stimulus properties affect suppression times, it is important to consider these influences when comparing physically different stimuli.

To illustrate, one b-CFS study found that "pacmen" stimuli oriented in a way that created a Kanisza surface broke suppression faster than rotated control stimuli (Wang, Weng, & He, 2012). Originally, this was interpreted as showing that certain aspects of perceptual grouping could occur unconsciously, thereby representing one example of a b-CFS finding that was at odds with results from CFS experiments adopting the classic dissociation paradigm, which showed no evidence for unconscious perceptual grouping (Harris, Schwarzkopf, Song, Bahrami, & Rees, 2012). However, subsequent experiments revealed that the advantage of Kanisza targets was unrelated to the perception of a Kanisza surface but instead reflected lower-level confounding factors such as collinear edges and the presence of certain orientations (Moors, Wagemans, van Ee, & de-Wit, 2016c). This demonstrates the importance of matching b-CFS target conditions on all potentially relevant lower-level properties before inferring high-level unconscious processing differences.

Although this particular study suggests that there is little influence of inferred visual properties (the Kanisza surface) on b-CFS, other work has recently shown that stimuli which are consciously perceived as causal events (a moving disc launching the movement of another disc) are associated with shorter suppression times than nearly identical stimuli that elicit less of a causal percept (Moors, Wagemans, & de-Wit, 2017). To conclusively determine whether such inferred stimulus properties can influence suppression time, more b-CFS studies using ambiguous stimuli or visual "illusions" are required.

4.1.2 Faces, objects, and emotional stimuli

Since the first b-CFS publication that reported a strong effect of face inversion (Jiang et al., 2007) many studies replicated this finding (e.g. Akechi et al., 2015; Gayet & Stein, 2017; Kobylka, Persike, & Meinhardt, 2017; Moors, Wagemans, & de-Wit, 2016b; Stein et al., 2011a). Subsequent studies used the inversion manipulation both to study unconscious object processing as well as to control for low-level physical differences among stimuli. Image inversion is an elegant manipulation as it keeps physical properties (pixel values) intact, while it disrupts the stimuli's meaningfulness, configuration, or structure. Inversion effects in b-CFS have been found to be larger for faces and human bodies than for houses (Zhou, Zhang, Liu, Yang, & Qu, 2010a) or for other animate and inanimate objects (Stein, Sterzer, & Peelen, 2012b). This indicates some face- and body-specific unconscious processing, and most likely reflects an effect of visual experience or expertise, as inversion effects are also larger for faces seen under natural lighting conditions (Stein, Peelen, & Sterzer, 2011b), for faces from one's own race and age group (Stein, End, & Sterzer, 2014), and for objects of expertise (Stein, Reeder, & Peelen, 2016).

One topic that has attracted a lot of research interest is whether emotional or socially relevant stimuli receive privileged unconscious processing, perhaps mediated by a specialized subcortical pathway to the amygdala (e.g. Pessoa & Adolphs, 2010; Tamietto & de Gelder, 2010; also see Madipakkam & Rothkirch, Chapter 4 in this volume). Already the second published b-CFS study showed an advantage of fearful over neutral and happy faces, but this fear advantage was similarly present for inverted faces (Yang, Zald, & Blake, 2007). If this effect was related to differences in emotional meaning one would expect a smaller effect for inverted faces, as it is more difficult to extract emotional meaning from inverted faces. A full-strength effect for inverted faces indicates that low-level physical differences between faces – which are fully preserved in inverted faces – caused the effect. Many subsequent b-CFS studies manipulated facial expressions, consistently finding an advantage of fearful expressions (e.g. Capitão, Underdown, Vile, Yang, Harmer, & Murphy, 2014; Oliver, Mao, & Mitchell, 2015; Zhan, Hortensius, & de Gelder, 2015). Other studies showed that this effect does not rely on a specialized subcortical pathway to the amygdala (Stein, Seymour, Hebart, & Sterzer, 2014; Tsuchiya, Moradi, Felsen, Yamazaki, & Adolphs, 2009) but reflects specific physical differences between stimuli that are unrelated to emotion per se (Gray, Adams, Hedger, Newton, & Garner, 2013; Hedger, Adams, & Garner, 2015; also see Stein & Sterzer, 2012).

Many other properties of faces have been studied using b-CFS (also see Axelrod, Bar, & Rees, 2015). These studies found shorter suppression times for faces making eye contact (Chen & Yeh, 2012; Madipakkam, Rothkirch, Guggenmos, Heinz, & Sterzer, 2015; Stein, Senju, Peelen, & Sterzer, 2011c; Yokoyama, Noguchi, & Kita, 2013), for faces turned towards the viewer (Gobbini, Gors, Halchenko, Hughes, Cipolli, 2013a), for trustworthy and non-dominant faces (Abir, Sklar, Dotsch, Todorov, & Hassin, 2018; Getov, Kanai, Bahrami, & Rees, 2015; Stein, Awad, Gayet, & Peelen, 2018; Stewart, Ajina, Getov, Bahrami, Todorov, & Rees, 2012), for attractive faces (Hung et al., 2016; Nakamura & Kawabata, 2018), male adult and female baby faces compared to male baby and female adult faces (Zheng, Luo, Hu, & Peng, 2018), for faces of friends compared to strangers (Gobbini, Gors, Halchenko, Rogers, Guntupalli, Highes, & Cipolli, 2013b), and for one's own face compared to famous faces (Geng, Zhang, Li, Tao, & Xu, 2012). However, these studies either did not use an inversion control (Geng et al., 2012; Getov et al., 2015; Gobbini et al., 2013a, 2013b; Hung et al., 2016; Madipakkam et al., 2015; Stewart et al., 2012; Yokoyama et al., 2013; Zheng et al., 2018) or found similar effects for inverted faces (Abir et al., 2018; Chen & Yeh, 2012; Nakamura & Kawabata, 2018; Stein et al., 2011c, 2018), such that differences in suppression times could have reflected physical differences rather than differential processing of the facial property per se. Similarly, differences in suppression times between different emotional body postures (Zhan et al., 2015) or between snakes and birds (Gomes, Silva, Silva, & Soares, 2017; Gomes, Soares, Silva, & Silva, 2018) could reflect confounding physical differences between stimuli (for recent evidence supporting this view, see Stein et al., 2018, and Gayet, Stein, & Peelen, in press).

Thus, even when accepting the b-CFS rationale that suppression time differences reflect unconscious processing differences, it is not yet clear whether these facial attributes or affective stimulus properties are indeed registered under suppression. Alternatively, some uncontrolled physical difference among stimuli could have caused these effects. Some studies addressed this issue by showing that b-CFS effects correlated with questionnaire-based personality traits (Capitão et al., 2014; Oliver et al., 2015; Schmack, Burk, Haynes, & Sterzer, 2016; Stewart et al., 2012). Here, the idea is that the individual significance of a stimulus determines the extent of unconscious processing. For example, the advantage of spiders over flowers in b-CFS was correlated with self-reported spider phobia symptoms (Schmack et al., 2016), and the b-CFS disadvantage of dominant faces with less self-reported propensity to trust (Stewart et al., 2012). Although these correlations are typically weak and sometimes not replicable (Stein et al., 2018, failed to replicate Stewart et al., 2012), this may represent a promising approach to unconscious processing of behaviorally relevant stimuli.

In summary, b-CFS experiments with faces and objects show that suppression times are influenced by familiarity, meaningfulness, or visual expertise, with more familiar stimuli having privileged access to awareness. Future studies implementing more stringent low-level controls are required to answer whether other properties related to a face's or object's emotional or social significance can indeed influence suppression times.

4.1.3 Words and phrases

Similar to faces, also suppression times for words are influenced by familiarity. A participant's familiarity with a writing system (Chinese, English, Hebrew) results in shorter suppression times (Jiang et al., 2007; Rabagliati, Robertson, & Carmel, 2018), and a b-CFS inversion effect exists for words as well (Kerr, Hesselmann, Räling, Wartenburger, & Sterzer, 2017; Yang, Tien, Yang, & Yeh, 2017; Yang & Yeh, 2011, 2014; but see Heyman & Moors, 2014). Surprisingly, no consistent effect of word frequency on suppression times has been found (Heyman & Moors, 2014; Prioli & Kahan, 2015), and one study even failed to find differences between real words and pseudo-words (Heyman & Moors, 2014). This may indicate that the influence of familiarity (as evidenced by the inversion effect) is limited to the processing of single upright vs. inverted letters, while integration into whole words might be disrupted by CFS.

Above and beyond familiarity, the use of words or phrases as stimuli offers unique possibilities to test for influences of self-relevance, emotional content, and semantics on suppression times while minimizing differences in low-level physical factors. Unfortunately, the b-CFS literature is far from consistent regarding the existence of such higher-level effects. While there are no differences between words denoting attributed that were judged to be self-related or not (Noel, Blanke, Serino, & Salomon, 2017), two studies found an effect of a word's emotional meaning, with negative Chinese and English single words taking longer than neutral words to break suppression (Prioli & Kahan, 2015; Yang & Yeh, 2011), an effect akin to "perceptual defense" (Postman, Bronson, & Gropper, 1953). Yang and Yeh (2011) also included an inversion control, such that physical differences between negative and neutral words were an unlikely cause for the effect.

While these studies investigated the processing of single words, another study received much attention for being the first to provide evidence that suppression times could be influenced by the semantic relationship among multiple words, i.e. phrases (Sklar, Levy, Goldstein, Mandel, Maril, & Hassin, 2012). This study found *shorter* suppression times for negative phrases (e.g. electric chair) than for neutral phrases (e.g. dining table), a finding that is difficult to reconcile with evidence for perceptual defense for single negative words. Furthermore, this study also found *shorter* suppression times for semantically incoherent phrases (e.g. I ironed the coffee) than for coherent phrases (e.g. I drank coffee), a result that is at odds with the more commonly reported b-CFS advantage of familiar stimuli. While these results were considered the first evidence for multi-word integration under CFS ("reading"), a recent large-scale replication failed to replicate these findings (Rabagliati et al., 2018; for another conceptual replication failure see Yang et al., 2017).

Thus, also for words there is good evidence that visual familiarity influences suppression times, although this effect may be related to single-letter processing. Semantic effects, by contrast, seem limited, although the study by Yang and Yeh (2011) provides some initial evidence for an effect of valence that is specific to upright words. In the light of recent failures to replicate high-profile b-CFS findings (Rabagliati et al., 2018; Moors, Boelens, van Overwalle, & Wagemans, 2016a; also see below), these interesting findings require independent replication.

4.1.4 Perceptual and affective learning

One elegant way of ruling out confounding low-level physical stimulus differences is to record suppression times for stimuli that differ only with regard to their learning history. However, there is not much evidence for an effect of perceptual learning on b-CFS. In one study, several blocks of detecting gratings with a particular orientation did not result in shorter suppression times for this specific orientation (Mastropasqua, Tse, & Turatto, 2015). Similarly, perceptual learning of a particular motion direction was not associated with faster breakthrough (Paffen, Gayet, Heilbron, & Van der Stigchel, 2018). Rather, observer's overall suppression times got shorter over time, and this effect was specific to the eye of target presentation (Mastropasqua et al., 2015), but not specific to the trained feature.

In order to elicit feature-specific effects through learning, these features need to be associated with threat. One study measured suppression times for gratings that had been paired with electric shocks in a classical fear conditioning procedure (Gayet, Paffen, Belopolsky, Theeuwes, & Van der Stigchel, 2016). Fear-conditioned orientations broke suppression faster, indicating enhanced unconscious processing for stimuli that signal threat. Similar results have been obtained with fear-conditioned faces (Vieira, Wen, Oliver, & Mitchell, 2017).

This effect of affective learning seems limited to classical conditioning involving threatening unconditioned stimuli. Two studies that used an affective learning procedure in which participants learned to associate faces with negative, neutral, or positive autobiographical stories failed to obtain effects on b-CFS (Rabovsky, Stein, & Rahman, 2016; Stein, Grubb, Bertrand, Suh, & Verosky, 2017). Similarly, associating stimuli with self-relevant information (which is known to affect performance in more complex discrimination tasks) did not influence b-CFS with a standard simple localization task (Stein, Siebold, & van Zoest, 2016). Another b-CFS study found an effect of self-relevancy with an identification task (Macrae, Visokomogilski, Golubickis, Cunningham, & Sahraie, 2017), which taps into later perceptual processes and is more prone to the influence of post-perceptual factors, such that this effect may not reflect a genuine difference in transition times (see section 4.2).

4.1.5 Priming, working memory, and attention

Suppression times for identical stimuli do not only differ as a function of affective learning history, but also depending on the context in which they are presented (for an in-depth review of contextual influences, see Gayet et al., 2014). Several studies investigated how priming affects suppression times. Note that this priming procedure is different from the classical dissociation paradigm. These priming b-CFS studies measured the effect of a conscious prime on the suppression time of a subsequent target stimulus. Suppression times are shorter when prime words or images predict a target's object identity, object category, or color (Forder, Taylor, Mankin, Scott, & Franklin, 2016; Lupyan & Ward, 2013; Ostarek & Huettig, 2017; Pinto, van Gaal, de Lange, Lamme, & Seth, 2015; Stein & Peelen, 2015; Stein, Thoma, & Sterzer, 2015; Sun, Cai, & Lu, 2015). Priming can occur even on a purely semantic level. For example, a word prime (e.g. "sock") leads to shorter suppression times for semantically related targets (e.g. "shoe") than for unrelated targets (e.g. "tape"; Costello, Jiang, Baartman, McGlennen, & He, 2009; also see Kerr et al., 2017). Similar priming effects have been obtained for target words that syntactically matched a preceding prime word sequence, independent of semantics (Hung & Hsieh, 2015). Such findings indicate that unconscious processing can be influenced by conscious visual, semantic, and abstract information.

Some of these priming effects may be rather short-lived and seem to disappear when the temporal interval between prime and target is increased to more than one second (Ostarek & Huettig, 2017; but see Stein et al., 2015). Longer-lasting effects from conscious information on suppression times have been obtained in studies manipulating working memory content. Keeping a specific color, shape, face identity, or emotional facial expression in mind over the course of a b-CFS trial is associated with shorter suppression times for targets matching the content of working memory (Gayet, Paffen, & Van der Stigchel, 2013; Gayet, van Maanen, Heilbron, Paffen, & van der Stigchel, 2016; Liu, Wang, Wang, & Jiang, 2016; Pan, Lin, Zhao, & Soto, 2014). Similarly, inducing or adopting a particular attentional set or adding attentional load can influence suppression times (De Loof, Poppe, Cleeremans, Gevers, & Van Opstal 2015; Sun, Cant, & Ferber, 2016), and these attentional influences can even be eye-specific (Zhang, Jiang, & He, 2012). Thus, top-down influences seem to be capable of reaching the earliest, monocular levels of visual processing during b-CFS.

4.1.6 Multimodal integration

Another way of testing contextual influences on b-CFS is to present matching or mismatching information through other modalities. For example, smelling an odorant (the smell of the rose) during a b-CFS trial shortens suppression times for a matching target (an image of a rose) relative to a mismatching target (an image of a pen marker; Zhou, Jiang, He, & Chen, 2010b). Such findings could be taken to suggest that nonvisual sensory information can be integrated with unconscious visual information.

Several studies adopting a similar approach for the auditory modality arrived at partly inconsistent conclusions. One study found no effect from concurrent auditory stimulation (Moors, Huygelier, Wagemans, de-Wit, & van Ee, 2015), another found that a sound shortened suppression times, but that congruence between the pitch of a tone and the target's visual field location did not lead to additional benefits (Mustonen, Nuutinen, Vainio, & Häkkinen, 2018). Other studies found shorter suppression times when sounds were spatially congruent with b-CFS targets (Aller, Giani, Conrad, Watanabe, & Noppeney, 2015; Yang & Yeh, 2014), and modulations of suppression times when a sound was in or out of synch with the contrast modulation of a target grating (Hong & Shim, 2016). Evidence for such audiovisual integration has been obtained with more complex stimuli as well: Suppression times are shorter for congruent shape-sound pairings (Hung, Styles, & Hsieh, 2017), for talking faces with matched auditory sentences (Alsius & Munhall, 2013), and for images and video clips of scenes with matching scenery soundtracks (Cox & Hong, 2015; Tan & Yeh, 2015). Importantly, some of these findings are unlikely to be explained by semantic priming alone, because effects disappeared when the auditory stimulus was presented before rather than concurrently with the b-CFS target (Cox & Hong, 2015; Tan & Yeh, 2015).

Similar evidence for multimodal integration in b-CFS has been obtained for other modalities beyond audition and olfaction. One study found shorter suppression times for dots moving out of synch with a touch to participant's back (Salomon, Galli, Lukowska, Faivre, Ruiz, & Blanke, 2016a) Another study found that touching a haptic grating shortens suppression times for gratings with congruent orientations (Lunghi, Lo Verde, & Alais, 2017). Such benefits have also been found when matching vestibular signals (participant's rotation direction on a rotating chair) with the direction of optic flow targets (Salomon, Kaliuzhna, Herbelin, & Blanke, 2015). For proprioception, there is currently evidence for and against integration with visual information in b-CFS. One study found that b-CFS targets presented against an irrelevant hand background broke suppression faster when the observer's hand was in a congruent position (Salomon, Lim, Herbelin, Hesselmann, & Blanke, 2013). Another study did not find an effect of matching observer's voluntary or spontaneous facial expressions with face targets displaying emotional expression (Korb, Osimo, Suran, Goldstein, & Ruminati, 2017).

While some of these findings could reflect semantic priming or participants figuring out the purpose of the study (demand characteristics), this is unlikely to be the case for a final, particularly intriguing finding, showing that even interoceptive signals can be integrated with visual information in b-CFS: flashing targets presented in synch with participant's heartbeat were found to be associated with longer suppression times than targets presented out of synch (Salomon et al., 2016b, 2018). Importantly, this happened despite participants being unable to tell whether flashing targets (presented without CFS) were in or out of synch with their heartbeat.

4.1.7 Clinical studies

The b-CFS paradigm has also been used to study altered unconscious processing in clinical populations. All of these studies used faces or emotional stimuli as b-CFS targets, thus testing whether certain mental disorders were associated with biases in unconscious processing of socially relevant stimuli (also see Madipakkam & Rothkirch, Chapter 4 of this volume). Indeed, one study found evidence for so-called mood-congruent biases, with suppression times for sad faces being reduced in patients with major depressive disorder (Sterzer, Hilgenfeldt, Freudenberg, Bermpohl, & Adli, 2011), but a later study did not replicate this finding (Münkler, Rothkirch, Dalati, Schmack, & Sterzer, 2015). Two studies found evidence that psychopathic traits were related to longer suppression times for fearful faces (Jusyte, Mayer, Künzel, Hautzinger, & Schönenberg, 2015; Sylvers, Brennan, & Lilienfeld, 2011), which is in line with the "fearlessness" hypothesis of psychopathy (Lykken, 1957), locating its origin in impaired unconscious visual processing. Three studies tested individuals with autism spectrum disorder. While face inversion effects were found to be normal (Akechi et al., 2015), in contrast to healthy participants there was no evidence for shorter suppression times for faces making eye contact (Akechi et al., 2014) or for rewarding social scenes (Gray, Haffey, Mihaylova, & Chakrabarti, 2018). Individuals with schizophrenia, however, showed a normal b-CFS advantage for faces making eye contact (Seymour, Rhodes, Stein, & Langdon, 2016).

4.1.8 Visual integration and replication issues

The recent failure to replicate two high-profile b-CFS studies caused a debate on the possibility of unconscious visual integration under CFS (Moors, Hesselmann, Wagemans, & van Ee, 2017; Sklar et al., 2018). As reviewed above, one study found suppression time modulations from multi-word phrases (Sklar et al., 2012), indicating unconscious integration of spatially separate words ("reading"). The other study showed that scenes with incongruent objects (e.g. a chessboard in the oven) broke CFS more quickly than scenes with congruent objects (Mudrik, Breska, Lamy, & Deouell, 2011). Both original findings (advantage of incoherent phrases and of incongruent scenes) were inconsistent with the general b-CFS advantage of more familiar, typical, or meaningful stimuli and both findings failed to replicate in recent large-scale replication attempts (Moors et al., 2016a; Rabagliati et al., 2018). One other study provided evidence that pairs of objects placed in normal (congruent) spatial configurations (e.g. lamp above a table) break suppression *faster* than objects placed in uncommon configurations (e.g. lamp below a table; Stein, Kaiser, & Peelen, 2015). This effect, however, may not require explicit integration, because such typical configurations of object pairs may be processed as one perceptual unit by the visual system (Kaiser, Stein, & Peelen, 2014). Future work is required to answer whether suppression times can be influenced by target conditions where two or more distinct visual stimuli need to be integrated into a whole.

The more general issue raised by these failures to replicate highly influential b-CFS findings is to clarify whether and why b-CFS studies are prone to produce false positives. Two recent papers have highlighted how "researcher degrees of freedom" (Simmons, Nelson, & Simonsohn, 2011) may be of particular concern with the b-CFS paradigm (Kerr et al., 2017; Rabagliati et al., 2018). In brief, most b-CFS studies use RT measures (see below) and b-CFS RT distributions have positive skew and kurtosis, with an extremely long tail. Deriving an appropriate measure of central tendency is therefore not trivial, and different researchers use a wide range of different transformation and data exclusion methods (Kerr et al., 2017; also see Gayet & Stein, 2017). Future b-CFS work would greatly benefit from preregistered, openly available, or even standardized analysis pipelines (Rothkirch & Hesselmann, 2017).

4.2 Tasks and measures

Before discussing different tasks and measures used in b-CFS studies it is important to recall that suppression times should ideally provide an accurate estimate of the transition from unconscious processing to conscious awareness. Perceptual or post-perceptual processes that occur after this transition into awareness should not influence an ideal measure of suppression times.

4.2.1 Speeded RT-based measures

As can be seen in Figure 1.3, the vast majority of b-CFS studies followed the seminal study by Jiang and colleagues (2007) and adopted RT-based localization tasks, in which participants indicate as quickly and accurately as possible in which of two or four possible spatial locations a target appears. The second most common way of quantifying suppression times in b-CFS studies are RT-based detection tasks, where participants indicate as quickly and accurately as possible the appearance of a target. This detection task is sometimes followed by an additional localization task. Intuitively, stimulus detection or localization captures the transition into awareness well, while being relatively immune to later (post-)perceptual influences. As soon as one is aware of a stimulus, one should be able to report its presence or location. At the same time, neither detection nor localization requires later recognition or identification.

However, the RT-based, speeded nature of these tasks requires subjects to set some arbitrary criterion for providing their localization or detection response through a button press. The required sensory evidence will inevitably vary within and between participants (e.g. depending on motivation, exact instruction, speed-accuracy tradeoff etc.) and, more importantly, between experimental conditions. For example, it is conceivable that less sensory evidence is required to make a localization/detection response for familiar stimuli (e.g. upright faces) than for less familiar stimuli (e.g. inverted faces). In this scenario, actual transition times could be similar but recorded suppression times would differ as a function of different decision criteria. More broadly speaking, RT-based measures are susceptible to post-perceptual influences that are beyond the control of the experimenter, and can therefore not be taken as valid measures of the transition into awareness. In addition to post-perceptual decisional influences, it is also possible that later perceptual processes influence recorded suppression times. There is simply no way to tell if subjects fail to comply with instructions and, for example, decide to withhold their detection or localization response until they can partly or fully recognize and identify an initially suppressed stimulus. It is not even known whether human observers are capable of providing a speeded response to precisely indicate target localization or detection before having identified a stimulus or stimulus parts. Again, such later perceptual processes may vary between conditions (e.g. upright faces are easier to identify than inverted faces) and could influence recorded suppression times. Thus, due to the very nature of speeded RT-based tasks, differences in suppression times obtained with RT-based localization or detection tasks cannot be taken as evidence for differential unconscious processing. Any measured difference in suppression times could stem from later perceptual and even post-perceptual processes.

Some of these issues are exacerbated when RT-based discrimination or identification tasks are used (see Figure 1.3), especially when the required discrimination is not fully orthogonal to the experimental manipulation. When the required discrimination is very basic (e.g. judging the orientation of a grating) and the experimental manipulation is fully orthogonal (e.g. influence of the color of the annulus surrounding the grating on b-CFS, see Gayet et al., 2016), discrimination-based RTs are similar to localization-/detection-based RTs. However, when the required discrimination (e.g. judging the orientation of a grating) is directly related to the experimental manipulation (e.g. touching a haptic grating with congruent or incongruent orientation, see Lunghi et al., 2017), any recorded effect could be entirely related to later perceptual processes of stimulus identification (which may be speeded e.g. in the congruent cases) rather than breakthrough into awareness. Furthermore, with non-orthogonal discrimination tasks the confounding influence of post-perceptual decisional and strategic factors could be larger as well. Thus, none of these RT-based measures can be considered a valid index of a target's transition into awareness.

4.2.2 Non-speeded accuracy-based measures

A solution to some of these issues lies in adopting non-speeded accuracy-based localization or detection tasks. Such tasks can be used to derive criterion-free measures of perceptual sensitivity, for example using signal detection theory. Dependent measures in these studies include performance scores (e.g. proportion correct or *d'*) and estimates of detection or localization thresholds from adaptive staircase procedures. Only a handful of b-CFS studies used such accuracy-based detection or localization tasks instead or in addition to RT-based tasks (see Figure 1.3). The key difference in comparison with RT-based b-CFS tasks lies in fixing the duration of a trial. In RT-based tasks a trial is terminated when the subject responds, whereas in accuracy-based tasks stimuli are presented for a fixed duration and subjects respond without speed pressure. Different response criteria for different conditions should thus not affect response accuracy, such that post-perceptual influences are ruled out.

Given this advantage, why are accuracy-based tasks not more widely adopted in b-CFS studies? First, while RT-based tasks are straightforward to implement, it can be challenging and time-consuming to set up and run accuracy-based b-CFS tasks. As suppression times are highly variable within and between individuals (e.g. Stein et al., 2011a; Gayet & Stein, 2017), it can be difficult to avoid floor or ceiling effects with fixed presentation times. Staircase procedures offer a part solution by adaptively adjusting presentation times or stimulus energy based on performance (see Hung et al., 2016; Moors et al., 2015; Stein et al., 2011a). Second, RT-based measures may have more intuitive appeal. After subtracting a few hundred milliseconds for motor preparation, RTs seem to provide a direct estimate of the time it took different stimuli to enter awareness. In comparison, it may be more difficult to make sense of some estimated threshold value from a staircase procedure that converges to, say, 75 percent correct. Clearly, this should not preclude the use of accuracy-based tasks in b-CFS experiments given that such threshold estimates and estimates of associated psychometric functions are the most common dependent measures in visual psychophysics.

Finally, some researchers seem concerned that forced-choice localization performance or criterion-free measures of detection sensitivity may not capture transition into awareness, but may instead tap into blindsight-like unconscious perception (Gayet et al., 2014). Here, the issue is not that the measure may be influenced by (post-)perceptual processes that occur after the transition point but that the measure could reflect unconscious processes that occur beforehand, while not being related to stimulus awareness or reportability. Indeed, if this were the case one assumption of this approach to unconscious processing, namely a precise measure of the transition point, would not be met. However, in my view, this possibility represents an advantage rather than a problem for accuracy-based tasks. If a difference between experimental conditions in such accuracy-based tasks indeed reflected differences in preceding unconscious processing, this version of the b-CFS paradigm would actually measure what it had been developed to measure in the first place, namely differential unconscious processing. One could then also relax the assumption that a precise measure of the transition point is required to infer unconscious processing. If a measure is only tapping into processes that occur *before* rather than after the hypothetical transition point, any influence on this measure must, by definition, be unconscious.

Thus, accuracy-based tasks represent a solution to many of the issues related to RT-based measures of suppression times discussed above. Nevertheless, the actual implementation is important. Some studies fixed presentation times but combined an accuracy-based with an RT-based task, taking RTs, hit rates, and detection sensitivity (*d'*) as dependent measures (e.g. Forder et al., 2016; Lupyan & Ward, 2013; Ostarek & Huettig, 2017; Sun et al., 2015). Here, additional speeded response requirements could have interfered with perceptual sensitivity, such that differences in response criteria between conditions could inadvertently have had an effect on detection sensitivity. It would be preferable to entirely remove any speeded response requirements and take detection sensitivity or localization accuracy as the only dependent measure.

Furthermore, even when post-perceptual influences are ruled out by using non-speeded tasks, later perceptual processes may play an undesired role. Although largely unexplored, it seems possible in principle that accuracy-based, criterion-free localization or detection measures could ("recursively") be influenced by later conscious stimulus recognition or identification (e.g. Hochstein & Ahissar, 2002). This could represent a problem for the b-CFS notion of a sequential (hierarchical) stream from unconscious processing to conscious perception. In particular, when localization or detection sensitivity is relatively high (i.e. *d'* well above 0), it is very likely that in many trials stimuli were not only successfully localized or detected but also consciously identified. If successful identification could recursively influence localization or detection performance (e.g. by increasing confidence), and if identification performance differed between conditions (e.g. upright vs. inverted faces, or validly vs. invalidly primed objects), this would have a confounding influence on suppression time estimates from accuracy-based detection or localization tasks. At the end of this chapter (sections 5.1 and 5.2) I will propose two ways of avoiding this potential issue in future, improved accuracy-based b-CFS studies.

In summary, RT-based measures of suppression times are straightforward to implement but cannot provide a valid estimate of the transition into awareness. Future b-CFS studies should instead implement non-speeded detection or localization tasks to derive criterion-free measures of detection sensitivity or localization accuracy.

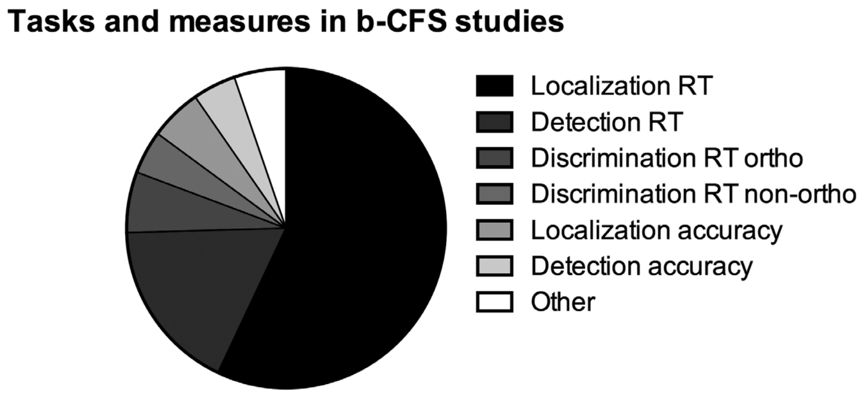

FIGURE 1.3 Tasks and measures used in b-CFS studies. The 115 b-CFS publications included in the present review were categorized according to the tasks and measures they adopted. When several tasks or measures were used in a single paper, we included the one task or measure on which the most important conclusions of the study were based. "Localization" refers to tasks requiring participants to indicate a target's location. "Detection" refers to tasks requiring participants to indicate target appearance (and sometimes, to indicate target absence). "Discrimination" refers to tasks requiring participants to categorize the target e.g. based on its features. "Ortho" means that discrimination tasks were orthogonal to the experimental manipulation (e.g. Gayet et al., 2016; response to grating orientation but study measured the influence of the color of a surrounding annulus). "Non-ortho" means that the discrimination tasks were not fully orthogonal to the experimental manipulation (e.g. Lunghi et al., 2017; response to grating orientation and study measured the influence of congruence between haptic and visual orientation). "RT" means that the primary outcome measure was response time. "Accuracy" means that some non-RT-based measure was at least one of the primary outcome measures, such as detection *d'* (e.g. Kaunitz et al., 2013), proportion correct in localization (e.g. Oliver et al., 2015), staircase thresholds for localizability (e.g. Moors et al., 2015), or staircase threshold for detectability (e.g. Hung et al., 2016). "Other" refers to measures that do not naturally fall into any of these categories, e.g. accuracy-based discrimination tasks, or subjective confidence ratings.

4.3 Control conditions and other psychophysical techniques

Forty-six out of the 115 b-CFS studies reviewed here included a non-CFS binocular or monocular control condition. With one exception (Sun et al., 2015), all of these b-CFS studies used purely RT-based tasks in both the b-CFS and in the control condition. As can be seen in Figure 1.4, nearly all of these studies obtained a significant effect in the b-CFS condition. In the control condition, by contrast, effects were either absent or strongly reduced. This may indicate that most studies were successful in controlling for the factor the control condition was intended to control for. However, I believe that this demonstrates that control conditions simply have rather poor sensitivity for measuring differences between conditions, and that this represents a serious concern for b-CFS studies that base their conclusions on a comparison with the results from such control conditions.

Control conditions have been employed in two ways. Many RT-based b-CFS studies attempted to control for the effect of post-perceptual factors on suppression times. Other b-CFS studies used control conditions to isolate CFS-specific unconscious processing differences as a cause for differences in suppression times. However, because control conditions differ from b-CFS conditions in many ways, including subjective perceptual experience, target appearance, perceptual uncertainty, and target predictability, both approaches lack validity.

4.3.1 Control for post-perceptual factors

As described above (section 4.2.1), post-perceptual factors such as differences in response criteria or motor preparation can influence RT-based measures of suppression times. Although it might be possible in principle to design a control condition that captures all post-perceptual factors that might have played a role in b-CFS, it is unlikely that control conditions that have been employed in the literature were successful in doing so. In fact, control conditions fail to mimic the rather unique perceptual experience under CFS (see Stein et al., 2011a). Subjectively, the impression of an abrupt, all-or-none transition of the target stimulus into awareness is rare in b-CFS, and partial suppression and piecemeal breakthrough are common. Because of the stochastic fluctuations of interocular suppression (Blake & Logothetis, 2002) target appearance in b-CFS is unpredictable and associated with a high degree of perceptual uncertainty. In control conditions, by contrast, targets are usually slowly blended into the CFS masks, such that subjective target appearance differs from b-CFS and is highly predictable. Indeed, b-CFS RT distributions have much more spread and much longer tails than control RT distributions.

Therefore, b-CFS may be associated with a higher degree of perceptual uncertainty than control conditions. With high perceptual uncertainty the influence of different response criteria for different conditions on recorded RT differences may be particularly strong, and may thus contribute to the sometimes surprisingly large effects obtained with b-CFS. For example, large effects have been obtained when comparing familiar (or cued, primed, predicted) stimuli, which may be associated with a lower response criterion, to unfamiliar (or non-cued, non-primed, non-predicted) stimuli (e.g. RT differences between upright and inverted faces in a simple localization task of >800 ms, see Stein et al., 2011a). In the control condition, where target appearance is highly predictable, participants may adopt a different response strategy, such that RTs may be less influenced by differential response criteria, and this may contribute to reduced or absent effects. Independent of these speculations, the mere fact that b-CFS and control conditions differ along many dimensions other than just the presence or absence of interocular suppression renders their comparison invalid. To conclusively rule out the influence of post-perceptual factors in b-CFS researchers should replace RT measures of suppression times with non-speeded, accuracy-based detection or localization tasks.

4.3.2 Isolating CFS-specific processing

The other approach of using control conditions goes beyond controlling just for post-perceptual factors. Here, an attempt is being made to show that any difference in target detectability resulted from CFS-specific differences in unconscious processing, rather than from general differences in stimulus detectability (see section 3.2). Thus, the control condition needs to measure all non-CFS specific differences in stimulus detectability that might have contributed to the b-CFS effect. As discussed above, this reasoning is unwarranted because it is unlikely that the control condition captures all of the relevant factors. In fact, standard b-CFS control conditions seem to represent a rather poor way of measuring non-CFS specific differences in stimulus detectability. For example, the detection advantage for upright over inverted faces has been obtained with several psychophysical techniques other than b-CFS (e.g. Garrido, Duchaine, & Nakayama, 2008; Purcell & Stewart, 1988), but b-CFS control conditions have repeatedly failed to yield a significant inversion effect. Again, the mere fact that control conditions are

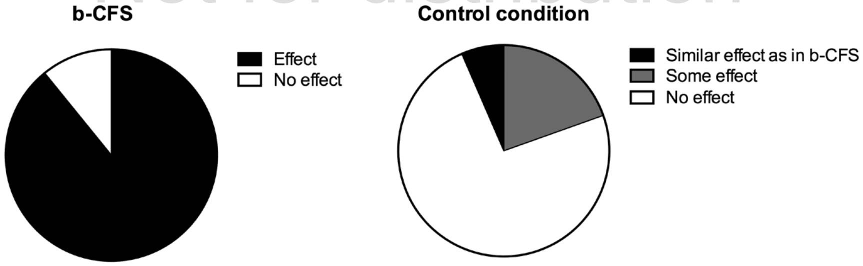

FIGURE 1.4 Effects and null effects in b-CFS studies with control conditions. Left panel: The 46 b-CFS studies that included a control condition were categorized according to whether a significant effect was obtained in the b-CFS condition or not. Studies that failed to obtain a significant effect in their main analysis but found some other effect were categorized as "no effect" (e.g. Korb et al., 2017, focused on integration with interoception but found effect from facial expressions). Right panel: Results from control conditions were categorized as "no effect" when there was no significant difference, as "some effect" when the effect was significantly smaller than in the b-CFS condition or when only some effect that was not of primary interest to the study was significant, or as "similar effect as in the b-CFS condition".

not fully comparable to b-CFS renders their comparison invalid, and conclusions about CFS-specific unconscious processing differences based on their comparison are unwarranted.

4.3.3 Comparisons with other psychophysical techniques

Only twelve b-CFS studies took the opposite approach and sought to generalize their b-CFS findings to other psychophysical techniques. These studies tested whether similar differences in stimulus detectability or early stimulus processing could be obtained with standard binocular rivalry (Stein et al., 2017; Zhou et al., 2010b), backward or sandwich masking (Hedger et al., 2015; Hung et al., 2017; Stein et al., 2014, 2015) visual search (Tsuchiya et al., 2009), inattentional blindness (Li et al., 2015), rapid serial visual presentation (Cohen et al., 2015; Gobbini et al., 2013), crowding (Salomon et al., 2016b), or attentional capture (Zheng et al., 2018). Interestingly, all eleven out of these twelve studies that obtained an effect in the b-CFS experiment also obtained some (often quite similar) effect with these other psychophysical techniques.

This illustrates two points. First, it seems that at least some of the effects obtained with b-CFS are not related to CFS-specific unconscious processing. Second, the fact that standard b-CFS control conditions usually produce null results while these other non-CFS detection measures yield significant effects suggests that control conditions indeed have rather poor sensitivity for measuring differences between conditions. Together, this adds to the concerns regarding any conclusions about CFS-specific unconscious processing (section 3.2). A more promising avenue for future studies consists in comparing effects obtained with – preferably accuracy-based, non-speeded – b-CFS detection or localization tasks to other psychophysical techniques measuring stimulus detection or localization. If differences in stimulus detectability are taken to reflect differences in preceding unconscious processing (section 3.1) the same logic should be applied to findings obtained with other psychophysical techniques.

5 Recommendations and future avenues

The b-CFS paradigm represents a novel approach to unconscious processing, fundamentally different from previous, established approaches adopting the dissociation paradigm. It remains to be seen if its underlying logic will find broad acceptance in the field. This chapter represents an attempt to flesh out and clarify the paradigm's underlying logic. Perhaps most importantly, any user of the b-CFS paradigm necessarily adopts certain assumptions, some of which might or might not be valid. Inferring CFS-specific unconscious processing from a comparison with a control condition rests on the assumption that the control condition is comparable to b-CFS. This assumption is invalid (see sections 3.2 and 4.3.2; Stein et al., 2011a; Stein & Sterzer, 2014). Inferences about CFS-specific unconscious processing are therefore unwarranted.

But even inferring unconscious processing differences from detection differences – with no claim about CFS-specificity – rests on a set of assumptions that are rarely spelled out in the literature. To reiterate (section 3.1), these are (a) a temporal sequence from unconscious processing to conscious perception and (b) a precise measure of the transition point from unconscious processing to conscious perception, or a measure that is influenced only by processes preceding the hypothetical transition point. As reviewed in the previous sections, for this reasoning to be valid suppression times need not be influenced by later perceptual processes or by post-perceptual factors.

Ruling out influences from post-perceptual factors can be achieved through non-speeded, accuracy-based detection or localization tasks (see sections 4.2 and 4.3.1). Ruling out influences from perceptual processes that only take place after the transition into awareness but may nevertheless influence suppression times is more challenging. In the final sections, I will propose two ways that may be useful for ruling out such undesirable later perceptual influences in future studies. These recommendations are not specific to b-CFS but similarly apply when other psychophysical techniques are used to measure differences in stimulus detectability.

5.1 Proposal I: Detection at threshold

One concern, even with non-speeded, accuracy-based detection or localization measures is that later perceptual processes that take place only after the transition into awareness (e.g. conscious stimulus discrimination or identification) could affect performance. As touched upon previously (section 4.2.2), it is possible in principle that a difference between conditions related to these later processes contributes to differences in detectability. Especially when overall detection or localization performance is relatively high (i.e. d' well above 0) it is likely that conscious stimulus identification occurs at least in a subset of trials. Conversely, when overall detection or localization performance is around chance level (i.e. $d' \approx 0$) conscious stimulus identification is very unlikely or impossible, assuming that discrimination and identification can occur only after initial detection.

Accordingly, one way to avoid the potentially confounding influence of later perceptual processes is to present stimuli at the (absolute) threshold for detection, such that performance is around chance level for condition A (e.g. inverted faces). This allows testing whether some manipulation hypothesized to influence the initial detection stage is associated with a lower (absolute) threshold, i.e. whether performance for condition B (e.g. upright faces) is just above chance level. A convincing demonstration of detection differences uncontaminated by later perceptual processing would establish (a) chance level performance (i.e. $d' \approx 0$) for condition A, (b) above-chance level performance (i.e. $d' > 0$) for condition B, and (c) significantly better performance for condition B than for condition A (see Figure 1.5a). Here, any difference between conditions must reflect an initial detection advantage.

This would represent a scenario where an experimental manipulation "boosts" one target stimulus into awareness (condition B, $d' > 0$), while the other remains unconscious (condition A, $d' \approx 0$). This idea of "boosting" a stimulus into awareness was coined previously in the title of the seminal paper by Lupyan and Ward (2013) who concluded that primes boosted congruent targets into awareness. However, in this study overall detection performance was very high ($d' > 1.5$), meaning that incongruent targets were consciously perceived in most trials as well. The priming effect could thus have been related to later perceptual processes. The same is true for most other b-CFS studies using accuracy-based tasks. It is thus quite possible that some of the effects reported in the literature disappear when stimuli are presented at threshold. For example, the b-CFS detection advantage for coherent radial motion relative to random walk motion, which was obtained at high levels of overall performance ($d' \approx 2$), disappeared at lower levels of overall performance ($d' \approx 0.5$; Kaunitz et al., 2013).

As the strength of CFS strongly varies between and within participants, it may be difficult in practice to present target stimuli at the threshold for detection. Although chance performance may be achieved by presenting targets for rather short presentation times and with low energy, this also risks floor effects, such that differences between conditions would be missed. Adjusting presentation parameters for each observer individually may be one solution, but trial-to-trial fluctuations in suppression strength and overall weakening of suppression strength over time (e.g. Ludwig, Sterzer, Kathmann, Franz, & Hesselmann, 2013; Mastropasqua et al., 2015; Paffen et al., 2018) represent procedural challenges. It may therefore be sensible to replace CFS with other psychophysical techniques, such as backward masking. As I have argued above, the logic of inferring unconscious processing differences from differences in detectability is not tied to the technique of CFS but can similarly be applied to other psychophysical techniques. With backward masking, for example, stimulation parameters can be more easily calibrated to present targets with maximum strength around the detection threshold.

5.2 Proposal II: Detection-discrimination dissociation

Another way to rule out any confounding influence from later perceptual processes is to demonstrate that participants cannot discriminate the relevant stimulus dimension. If the critical experimental manipulation could not be accessed but nevertheless affected detectability, this would provide convincing evidence for an initial detection difference uncontaminated by later perceptual processing. In addition, it would show that the relevant stimulus dimension was indeed truly unconscious, while still affecting detectability; thereby providing direct evidence that unconscious processing differences yielded the effect. To illustrate, if upright faces were detected better than inverted faces while participants could not discriminate between upright and inverted faces ($d' \approx 0$) this would demonstrate truly unconscious processing of the critical manipulated stimulus dimension, i.e. of face orientation. This logic could be applied to any b-CFS experiment, including studies on contextual influences, for example, by demonstrating that congruently primed targets were detected better than incongruently primed targets but participants could not discriminate between congruent and incongruent trials (*d'* ≈ 0).

This approach would effectively turn the b-CFS paradigm into a direct-direct dissociation paradigm (see Figure 1.5b). One direct measure of stimulus awareness (accuracy-based, non-speeded detection or localization) would be contrasted with a direct measure of "manipulation awareness" (accuracy-based, non-speeded discrimination of the critical experimental manipulation). Thus, on every trial, two measures would be collected, one measure of detection or localization and one measure of stimulus discriminability. There is already some b-CFS evidence that localization performance can be better than discrimination performance. Kobylka and colleagues (2017) found localization performance for faces and houses to be superior to face-house discrimination performance, and their study also revealed

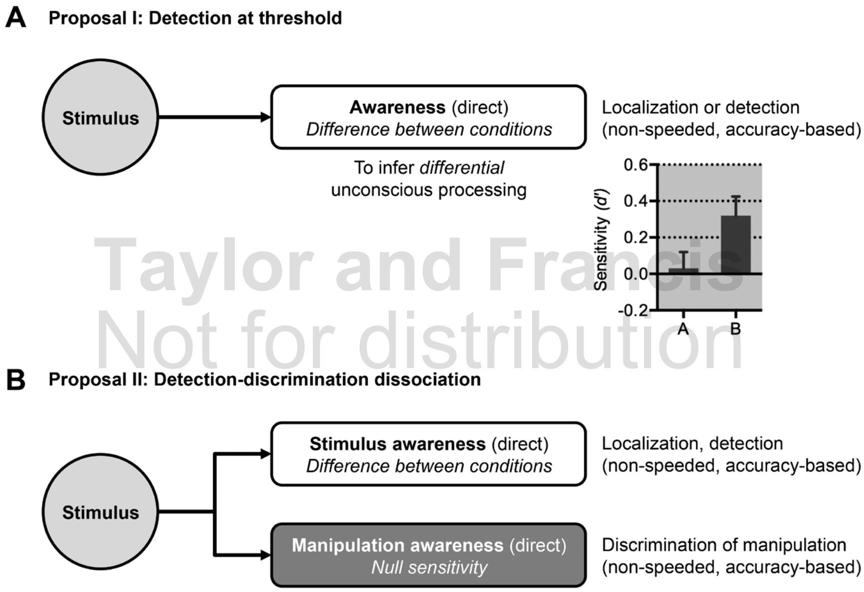

FIGURE 1.5 Two proposals for improved future detection paradigms that could provide evidence for unconscious processing differences. These proposals are not tied to the psychophysical technique of CFS but could be similarly used with other psychophysical techniques, such as backward masking. (a) In the detection-at-threshold paradigm one experimental condition (A) cannot be detected above chance (*d'* ≈ 0), while the other condition (B) is detected above chance (*d'* > 0). This would virtually rule out the potentially confounding influence of later perceptual processes on detection measures. (b) In the detection-discrimination dissociation paradigm, experimental conditions differ in detectability but participants cannot discriminate between conditions. This would show that the experimental manipulation was truly unconscious but nevertheless caused a difference in target detectability.

a face inversion effect even when discrimination ability was rather low ($d' \approx 0.5$). Note that this study did not fit the criteria of the detection-discrimination paradigm proposed here, because the discrimination task did not measure the critical stimulus manipulation (upright vs. inverted faces) and discrimination performance was significantly greater than chance.

As with the detection-at-threshold proposal, the procedural challenge lies in finding appropriate stimulus presentation parameters, in particular when using CFS. The target needs to be displayed at a level that (a) yields null sensitivity in the discrimination task but (b) some sensitivity in the detection or localization task and (c) a difference between conditions in the detection or localization task. Backward masking might be preferable over CFS to test whether such a novel dissociation can be achieved in practice.

5.3 Conclusion

Although the b-CFS paradigm has been widely adopted to study unconscious processing, its underlying assumptions have rarely been spelled out. Because b-CFS is fundamentally different from conventional dissociation approaches to unconscious processing, it is important to consider the validity of its logic. Here, I have shown that b-CFS cannot be used to infer CFS-specific unconscious processing. But even when using b-CFS to infer unconscious processing differences – independent of their CFS-specificity – confounding influences from later perceptual or post-perceptual processes need to be ruled out. Results from published b-CFS studies could have been contaminated by such factors. I have proposed two novel approaches that future studies could adopt to avoid these problems. Both the detection-at-threshold paradigm and the detection-discrimination dissociation paradigm can be used to demonstrate that a difference in stimulus detectability was caused by unconscious processing differences. Perhaps ironically, psychophysical techniques other than CFS, such as backward masking, could similarly be used to implement these novel paradigms in future studies on unconscious visual processing.

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