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Psychophysical magic: rendering the visible 'invisible'

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What are the neural correlates of conscious visual awareness? Tackling this question requires contrasting neural correlates of stimulus processing culminating in visual awareness with neural correlates of stimulus processing unaccompanied by awareness. To produce these two neural states, one must be able to erase an otherwise visible stimulus from awareness. This article describes and assesses visual phenomena involving dissociation of physical stimulation and conscious awareness: degraded stimulation, visual masking, visual crowding, bistable figures, binocular rivalry, motion-induced blindness, inattentional blindness, change blindness and attentional blink. No single approach stands above the others, but those producing changing visual awareness despite invariant physical stimulation are clearly preferable. Such phenomena can help lead us ultimately to a comprehensive account of the neural correlates of conscious awareness.

Introduction

Tantalizing observations linking perception and brain states have fueled the conviction that a principled account of the neural events underlying consciousness could be within our grasp [1–3] (but see [4]). An important first step is to identify neural events reliably and uniquely correlated with states of consciousness, and vision affords a particularly opportune modality for discovering such correlations. But how are we to tackle the daunting challenge of identifying neural correlates of conscious visual awareness?

Outlines of a possible strategy emerge from the scheme shown in Figure 1, which categorizes visual experiences, conscious and unconscious, and stimulus conditions evoking those experiences. The search for neural correlates of visual awareness (NCVA) targets the upper left cell of the matrix: neural events associated with conscious awareness of objects and events populating our everyday experiences. However, this category of events alone cannot uniquely specify NCVA – one must also discern neural events produced by effective stimulation *unaccompanied* by conscious awareness. One needs, in other words, to contrast neural correlates of stimulus processing culminating in visual awareness (upper left cell of Figure 1) from neural correlates of stimulus processing unaccompanied by awareness (lower left cell). To contrast these two neural states, we must find ways to render an otherwise visible stimulus invisible. In this article, we describe various psychophysical techniques for manipulating visual awareness and evaluate the strengths and weaknesses of those techniques. We will not discuss experiments that have used these techniques in neurophysiological or brain imaging studies to get at NCVA; many of those studies have been reviewed elsewhere [5,6]. Nor will we discuss in detail the thorny methodological issues involved in verifying whether or not a person is consciously aware of a visual stimulus (but see Box 1).

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As we look at the various techniques, we will evaluate each in terms of the following criteria:

- Does the technique work with a broad range of visual stimuli (*generality*)?
- Does the technique work equally well in central and peripheral vision (*visual field*)?
- Are there constraints on the exposure duration of the stimulus (*duration*)?
- Does the technique abolish all aspects of visual awareness (*robustness*)?
- Does physical stimulation remain invariant when visual awareness fluctuates (*invariant stimulation*)?

These criteria embody two overarching themes: (1) the extent to which a given technique allows the use of stimulus conditions mirroring those encountered during everyday visual experience, and (2) the extent to which the technique unambiguously dissociates awareness from unawareness.

Degraded visual stimulation

The simplest means for removing an otherwise effective visual stimulus from awareness is to degrade the stimulus

		Stimulus	
		Present	Absent
Perceiver awareness	Conscious	*	***
	Unconscious	**	

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Figure 1. Diagram showing combinations of two alternative states of physical stimulation (stimulus 'present' or stimulus 'absent') and two alternative states of awareness ('conscious' and 'unconscious'). The main text of this article focuses on strategies for producing the conditions corresponding to the cells marked * and **. Box 2 describes complementary strategies for examining conditions corresponding to the cell marked ***.

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Box 1. Measuring visual awareness

Research on unconscious perception is beset by controversy concerning the definition and measurement of awareness: how can one confidently know that a stimulus supporting 'unconscious perception' truly falls outside of awareness? Researchers used to rely heavily on subjective threshold measures inferred from 'yes/no' detection tasks, but signal detection theory (SDT) changed the way researchers thought about subjective reports: such judgments necessarily require establishing some criterion for deciding when a given stimulus was 'present' in awareness, a criterion that could itself introduce an arbitrary, unreliable boundary between awareness and unawareness [54]. Since the advent of SDT, much work has gone into developing models and measurement procedures for getting at unconscious perception uncontaminated by non-sensory, decisional factors. Investigators now routinely use forced-choice procedures that yield more criterion-independent measures of whether or not a stimulus is visible. The observer is 'forced' to verify stimulus detectability by specifying the interval or the location in which stimulation occurred, or is 'forced' to confirm stimulus recognition by specifying whether the stimulus comprised one quality (e.g. motion to the left) or the other (motion to the right). Ironically, people often claim they are merely guessing even when their forced-choice performance is significantly above chance. This dissociation has led some to distinguish between the 'objective' threshold and the subjective threshold (for a review, see [55]).

Concerns about methodological validity also arise when observers track fluctuations in the appearance of a visual stimulus by pressing buttons. Widely used in studies of bistable perception, tracking, too, forces an observer to adopt some criterion for distinguishing stimulus *A* from stimulus *B*, which is not problematic when the two perceptual alternatives are mutually exclusive, as with ambiguous figures (Figure 3a). With binocular rivalry, however, transitions between perceptual states may include mixtures of both alternatives, thereby complicating the tracking decision [56]. Cognizant of these problems, investigators have developed indirect 'probe' techniques for assaying the current perceptual state of a given stimulus [57], as well as techniques for promoting more clear-cut, predictable transitions from one state to another [58]. Eventually, it may be possible to rely on brain scanning signals to indicate which one of several alternative stimuli is currently represented within the visual pathways [59].

by presenting it too briefly for reliable detection [7] or by superimposing 'noise' on it [8]. For decades degradation represented the chief method for studying perception without awareness [9]. As a technique for studying awareness, however, degradation is useful only when the stimulus is rendered invisible because of limitations within central neural processes and not because of peripheral degradation (e.g. optical blur) in the input to those processes.

This technique is nicely exemplified by a recent 'incidental' learning study [8]. While performing a demanding task at the fovea, observers were exposed to a dynamic random-dot display in which coherent motion was presented below the visibility threshold. On a subsequent direction-discrimination task, these observers showed significant benefits from mere exposure to the subthreshold motion, implying perceptual learning outside of conscious awareness.

In an interesting variant of the degradation strategy [10], laser interferometry was used to image on the retina a grating whose spatial frequency was beyond the limits of visual resolution – observers could not tell whether they were viewing a grating or an uncontoured patch of the same average luminance as the grating. Observers adapted to this 'invisible' grating for a minute or so and then performed several forced-choice tasks (Box 1) using a visible 'test' grating slightly lower in spatial frequency than the invisible adaptation grating. Remarkably, the test grating's appearance was altered by prior exposure to the invisible adaptation grating.

Stimulus degradation certainly can render an object invisible, but this technique is confined to particular, uncommon stimulus conditions – ordinarily, the focus of awareness is not objects that are briefly presented, embedded in noise or specified by spatial details at the limits of resolution. Moreover, degradation is notoriously suspect as a means for manipulating awareness because of criterion effects associated with judging whether or not a degraded stimulus really falls outside conscious awareness [9,11]. Of particular concern, physical stimulation differs for undegraded and degraded conditions, which correspond to the two event categories of interest in Figure 1 (observer 'aware' and observer 'unaware' respectively). These differences make it uncertain whether comparing results from these conditions reveals anything about NCVA.

Disruption of awareness by masking and crowding

Visual backward masking

A widely used technique for dissociating awareness and stimulation is visual backward masking: a brief 'target' stimulus followed shortly thereafter by a 'mask' (see Figure 2a). With appropriate timing and spatial arrangement of target and mask, the technique works very effectively on a wide range of stimuli: an ordinarily visible

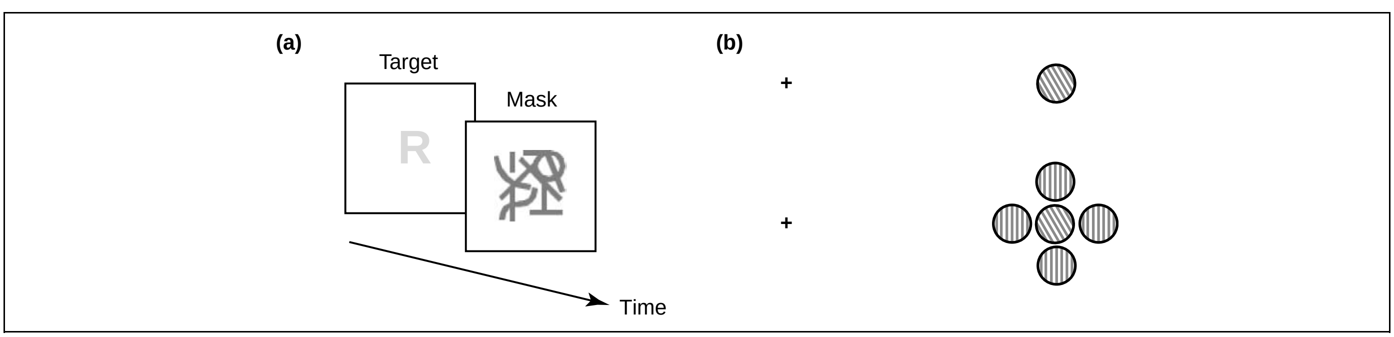

Figure 2. Two techniques where awareness of one stimulus is rendered invisible by the presence of other stimuli. **(a)** Schematic of backward masking, whereby a briefly presented 'target' stimulus is erased from awareness by subsequent presentation of a 'mask' in close spatial and temporal proximity to the target. **(b)** Example of visual crowding. When viewed in the peripheral visual field (fixation on the cross), the diagonal grating is visible on its own but is unrecognizable when surrounded by neighboring gratings.

target can be erased from visual awareness by the mask [12]. Unlike stimulus degradation, masking involves stimulus conditions that, in one respect, typify everyday vision: different objects viewed in rapid succession.

Now days it is commonly accepted that the mask 'halts' processing of the target, thereby abbreviating the target's effective duration. (When a mask precedes a target in time, which is called forward masking, target invisibility presumably results from reduction in effective target contrast at peripheral stages of processing, not from disruption of central processing [12].) A currently popular theory posits that the mask disrupts feedback signals associated with the target, thus abolishing 're-entrant signals' required for conscious perception of the target [13]. Whatever causes it, backward masking can indeed dissociate preconscious analyses of salient visual stimulation from processing underlying conscious visual awareness. Thus, for example, pictures masked to invisibility can nonetheless prime identification of subsequently viewed stimuli [14], and the color of a target masked to invisibility still exerts a color-specific influence on reaction times to the mask itself [15].

Popularity notwithstanding, backward masking has several limitations. For one, masking, like degradation, uses different conditions of physical stimulation to produce awareness (unmasked) and unawareness (masked). This limitation can be circumvented by focusing on trials yielding hits and trials yielding misses under identical stimulus masking conditions [16]. For another, masking entails brief target presentation immediately preceding a mask that, itself, must appear within close spatial proximity of the target. Although useful in mapping the microgenesis of form perception [17], this narrow range of transient conditions is not conducive to creating sustained periods of perceptual invisibility. (This limitation can be side-stepped using the repetitive flash technique that creates both forward and backward masking – see demonstrations at: http://neuralcorrelate.com/bni_steve.htm).

Finally, in some circumstances a masked target can be unidentifiable yet detectable: observers can be aware that a stimulus appeared without being aware of what it was [18], thus blurring the distinction between awareness and unawareness.

Visual crowding

A normally visible figure may be unrecognizable when flanked by other, nearby stimuli [19]. Called crowding, this phenomenon, unlike backward masking, works effectively for extended viewing periods (Figure 2b). Even when rendered unrecognizable by crowding, a figure can remain perceptually effective. Thus, for example, a crowded figure can still produce several visual aftereffects of adaptation [20,21] and can influence the overall texture appearance of a cluster of figures in which the crowded target is embedded [22].

Unfortunately, crowding is robust primarily within the peripheral visual field, where spatial resolution is relatively coarse, not within central vision where the spotlight of visual awareness is ordinarily focused; careful fixation, too, must be insured to maintain crowding. Moreover, crowding may interfere with identification of a target whose presence can still be detected [23], thus complicating interpretations of crowding's relation to visual awareness. Finally, crowding does not satisfy the criterion of invariant stimulation.

Changing awareness during bistable perception

All of the techniques discussed above use some kind of change in stimulation to render a normally visible stimulus invisible. There are also conditions, however, where an observer experiences fluctuations in perception despite *unchanging* visual stimulation, with a given perceptual interpretation moving in and out of awareness. In the scheme shown in Figure 1, the stimulus 'present' switches between two competing states of awareness, implying the existence of changing patterns of neural activity despite invariant stimulation. For this reason, bistable perception, as these phenomena are called, provides a particularly appealing means for identifying NCVA [24,25]. Bistable perception can be provoked in several different ways (see Figure 3) each of which we examine in this section.

Bistable figures

Some figures (Figures 3a) engender fluctuations in visual awareness because they portray alternative, contradictory figure/ground interpretations. Others (Figures 3b) portray ambiguous depth relations among constituent features,

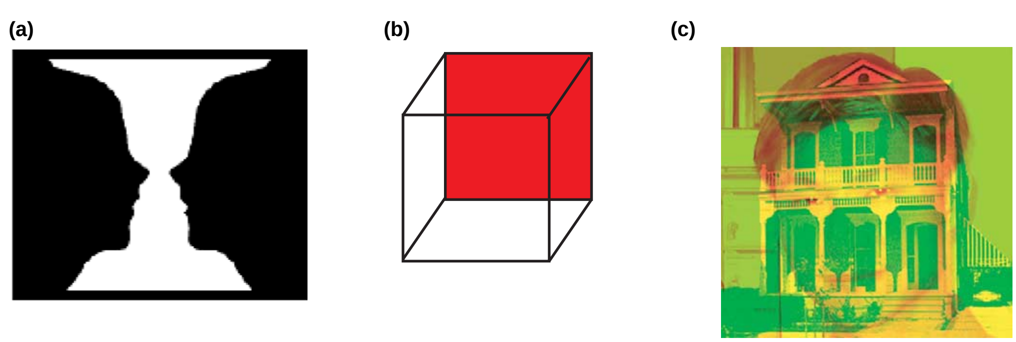

Figure 3. Visual conditions producing changes in perceptual awareness despite unchanging visual stimulation. **(a)** Rubin's vase/face figure. With extended viewing, one sometimes sees a white vase against a black background and other times two black faces against a white background. **(b)** Necker cube. The red portion of the cube sometimes appears to be the near surface and other times the far surface. **(c)** Binocular rivalry. Dissimilar stimuli presented separately to the two eyes compete for dominance (in this anaglyph rivalry between the face and the house can be experienced by viewing the figure through red/green glasses).

leading to spontaneous perspective reversals over time. In both cases, the brain resolves the perceptual contradiction by favoring first one interpretation and then the other, with switches in perception occurring haphazardly over time [26].

Ambiguous figures have several benefits as tools for manipulating awareness: (i) a given perceptual state can last for several seconds, (ii) alternative perceptual states tend to be mutually exclusive (thereby minimizing criterion problems), and (iii) the inducing figures can be large and do not require steady visual fixation [27], all conditions akin to ordinary viewing. On the downside, inability to predict exactly when perception will change makes it impossible to synchronize that change with other events (e.g. onset of a brain scan pulse sequence), except by relying on the observer's subjective report which invariably lags the change itself. Fortunately, some degree of control over the dynamics of bistability can be achieved with periodic presentations interleaved with blank periods [28]. Another disadvantage is the very small number of ambiguous figures capable of evoking bistability, a limitation that compromises the stimulus generality of the technique.

Binocular rivalry

Bistable perception can also be induced by presenting dissimilar monocular patterns to corresponding areas of the two eyes (Figure 3c). Called binocular rivalry, these stimulus conditions produce patent fluctuations in visual awareness [29]. Unlike bistable figures, rivalry does not result from ambiguity but, instead, from visual conflict: *any* two dissimilar patterns can be used to induce rivalry, not just figures producing alternative figure/ground interpretations. Thus, a wide variety of visual patterns can be strategically designed to target given brain regions. For example, Tong and colleagues [30] used a face and a house as rival targets to discover reciprocal activations in the fusiform face area and the parahippocampal place area coincident with perception of the face and the house, respectively. Logothetis and colleagues likewise have used tailor-made rival figures to study single-unit activity in awake, behaving monkeys experiencing binocular rivalry [24,31,32].

Using rivalry, psychophysical studies have examined whether visual patterns remain effective when suppressed from awareness [33]. Aspects of visual processing immune to suppression include motion priming [34], tilt adaptation [35] and orientation-selective color adaptation [36]. Aspects of visual processing blocked by suppression include object priming [37], adaptation to optic flow [38] and adaptation to faces [39].

Rivalry, like bistable figures, produces unpredictable switches in perception, but this shortcoming can be surmounted by appropriately timing the onsets of left and right eye stimulation, a procedure dubbed flash suppression [40]. Another drawback to rivalry is the tendency for relatively large rival targets to produce periods of mixed dominance comprising bits and pieces of both rival patterns: mixtures confound binary judgments of dominance. The incidence of piecemeal rivalry can be minimized by using relatively small rival targets with foveal viewing or by imaging larger targets in the periphery [41].

Motion-induced blindness

When a relatively small object is embedded within a larger optic flow field, the object can disappear from awareness for several seconds at a time, a compelling phenomenon called motion-induced blindness (MIB) [42] (for a demonstration, see the supplementary data for this article at: 10.1016/j.tics.2005.06.012). For that matter, several spatially distributed, small objects can disappear all at the same time during MIB, especially if those objects share a common stimulus property such as orientation [43]. Objects rendered invisible by MIB retain some effectiveness, including the capacity to produce orientation-selective adaptation [44] and to induce negative afterimages [45]. Moreover, people remain keenly sensitive to the physical removal of an object erased from awareness by MIB, verifying the continued neural representation of that invisible object [46].

As with other forms of bistable perception, MIB involves unpredictable fluctuation in visibility, and the rates of fluctuation vary widely among individuals [43]. The presence of a large moving pattern is required to induce MIB, and stable fixation must be maintained to experience it – eye movements can trigger the object's immediate release from MIB. In our experience, MIB – unlike rivalry or bistable figures – is not experienced when the object of regard is foveally viewed nor when the target is a relatively large, complex object such as a face. These limitations restrict MIB's range of utility for investigating NCVA.

Disrupted awareness by distracted attention

Visual awareness of an object can be disrupted by distracting an observer's attention from that object, and several effective strategies are available for abolishing awareness by attentional distraction.

Inattentional blindness and change blindness

When engaged in a demanding task, observers may utterly fail to detect a salient but unexpected visual stimulus [47]. In essence, attention focused on one object or event can render people temporarily 'blind' to other stimuli, hence the term 'inattentional blindness' (IB). During IB aspects of cognitive processing of a stimulus (e.g. semantic analysis) remain intact even though that stimulus (e.g. a word) is extinguished from awareness [47]. For that matter, people can be blind to conspicuous changes in the visual scene even when their attention is *not* explicitly directed elsewhere by a demanding task. Thus, for example, when viewing two successive pictures separated in time by a blank interval, observers might fail to notice a change in the picture (Figure 4a). For that matter, observers sometimes fail to notice even that one person has changed into another when their view of the scene is momentarily blocked by an occluding surface (for remarkable demonstrations of this phenomenon, see http://viscog.beckman.uiuc.edu/djs_lab/demos.html). Called 'change blindness' (CB) this phenomenon too might be related to attention's being diverted from the change

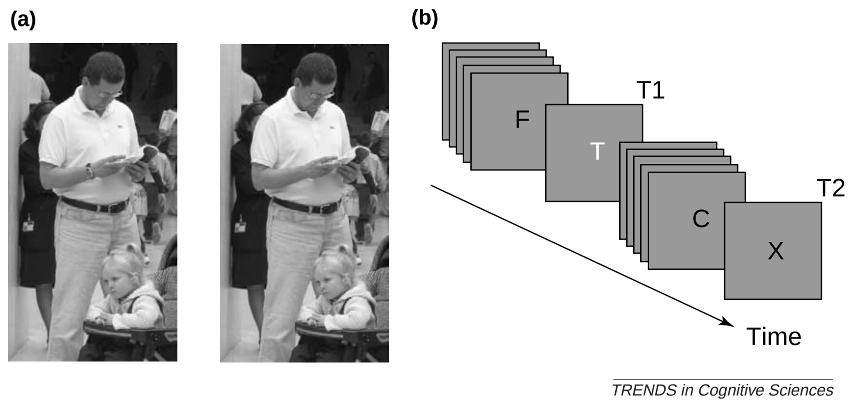

Figure 4. Lack of awareness caused by failures in attention. **(a)** Change blindness. With repetitive, sequential presentation of these two pictures with blank intervals separating the two, observers often go many seconds without noticing the change within the picture (the man's watch disappears from his arm). **(b)** Schematic of rapid serial visual presentation used to induce the attentional blink. In this example, a series of letters is shown in rapid succession. When required to look for one target, T1 (a white letter, in this example), observers often fail to see a second target, T2 (an X in this example), when T2 appears less than 500 ms after T1.

event [48], although in some circumstances changes to an attended object itself can go unnoticed [49].

As tools for studying awareness, both IB and CB effectively capture the essence of common, everyday experience: we have all failed to 'see' an otherwise conspicuous object within our field of view. Moreover, both forms of 'blindness' can be induced in a wide variety of objects, including geometric shapes, words and faces. As laboratory tools, however, IB and CB have several limitations. IB works in only a fraction of observers tested,

Table 1. Relative strengths of various psychophysical techniques for erasing a stimulus from visual awareness

Overarching themes	Stimulus generality				Effectiveness			
Strengths / Strategies	Variety of stimuli [a]	Stimulus size [b]	Visual field location [c]	Temporal aspects of stimulation [d]	Unambiguous invisibility [e]	Invariant stimulation [f]	Duration [g]	Predictability [h]
Backward masking	Green	Yellow	Green	Red	Yellow	Yellow	Red	Green
Crowding	?	?	Red	Green	Red	Red	Green	Green
Bistable figures	Red	Green	Green	Green	Green	Green	Green	Red
Binocular rivalry	Green	Red	Green	Green	Green	Green	Green	Red
Motion-induced blindness	Yellow	Yellow	Red	Green	Green	Green	Green	Red
Inattentional/ Change blindness	Green/Green	Green/Green	Yellow/Yellow	Yellow/Yellow	Yellow/Green	Yellow/Green	Yellow/Green	Yellow/Red
Attentional blink	Green	Green	Green	Red	Yellow	Green	Red	Green

Relative strength: Weak (red) – Strong (green)

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[a]Variety of stimuli – is the technique effective at rendering a wide variety of stimuli invisible? [b]Stimulus size – does the technique work over a wide range of stimulus sizes? [c]Visual field location – does the technique work equally well in central and in peripheral vision? [d]Temporal aspects of stimulation – are there constraints on the exposure duration or on the timing of the stimulus? [e]Unambiguous invisibility – does the state of unawareness involve complete, unambiguous invisibility of the stimulus? [f]Invariant stimulation – does physical stimulation remain invariant when visual awareness fluctuates? [g]Duration – do the periods of unawareness last for longer than a few hundred milliseconds? [h]Predictability – is the onset of unawareness controllable, and are the durations of unawareness predictable?

and even those participants naturally begin to look for unexpected 'probe' events once they've discerned that such events may occur. CB, by contrast, works for all observers, and foreknowledge of the existence of change does not compromise the resulting 'blindness.' However, the state of 'blindness' typifying CB is more robust when the observer is looking away from the changing target item (peripheral visual field), with 'awareness' more likely to arise when the observer is looking at the target (central visual field) [48]. Finally, IB and CB may not always represent 'pure' cases of perception without awareness but, instead, may entail failures to report ephemeral conscious experiences [50].

Attentional blink

When required to search for two (or more) visual targets within a rapidly presented sequence of items (Figure 4), observers are very likely to miss the second target when it closely follows the first [51]. The unpredictable appearance of the first target seems to commandeer attention, with the second target falling within a brief refractory period analogous to an eye-blink (thus the term attentional blink: AB). A stimulus rendered invisible by the AB can still impact visual processing [52], making the AB an attractive means for studying networks controlling visual awareness [53].

AB offers several advantages as a technique for studying NCVA: it works with a variety of stimuli, the size of which is not crucial, it occurs with central or with peripheral viewing, it involves no changes in stimulus conditions, and the timing of the 'blink' event is strictly determined. Moreover, the AB, unlike IB, occurs despite foreknowledge of the likelihood of the second target; repeated testing is feasible. On the down side, the AB is limited to very briefly presented targets that must fall within a very narrow temporal window. Also, with the AB paradigm, as with IB and CB, selective attention and states of awareness resulting from attentional selection are intertwined – their effects are difficult to untangle.

Conclusions

Our survey has focused on strategies for rendering an ordinarily visible stimulus invisible. Table 1 summarizes the relative strengths and weaknesses of those strategies in terms of their robustness and generality. No single strategy stands out as clearly superior, and the utility of a given strategy will depend on constraints imposed by the experimental protocol. Eventually, a comprehensive account of NCVA must explain why normally visible, salient stimuli disappear from awareness when subjected to any and all of these different forms of psychophysical legerdemain. The explanation, of course, might not be the same for all of these various forms of invisibility. Finally, there also exist conditions where conscious visual awareness occurs in the absence of external stimulation (the upper right cell of Figure 1), and those conditions, too, can be exploited to study the NCVA (see Box 2).

Box 2. Seeing things that aren't really there

This article focuses on conditions where presentation of a normally visible stimulus is blocked from conscious awareness, but the converse also happens: people can be visually aware of a stimulus even though nothing resembling that stimulus is actually present. These beguiling occurrences, too, can be used to probe neural concomitants of visual awareness.

Visual aftereffects following adaptation can be construed as perceptual awareness in the absence of appropriate stimulation. Consider, for example, the motion aftereffect (MAE): following prolonged viewing of motion in a given direction, a stationary object looks like it's moving in the opposite direction. Accompanying this illusory visual experience is enhanced activity within several brain areas involved in motion perception [60,61]. Likewise, a constellation of brain areas shows activity when people experience the McCollough aftereffect, perception of illusory colors when viewing achromatic, oriented contours [62,63].

People also see things that aren't really there when viewing illusory figures like the ones shown in Figure I. Here, too, we may ask where within the visual nervous system are there patterns of activation uniquely associated with awareness of these illusory objects [64].

Within the context of SDT, investigators can exploit the existence of 'false alarm' ('yes' responses when *no* stimulus was present) to infer the nature of signals ordinarily associated with 'hits' ('yes' responses when a stimulus *was* present). This strategy is akin to studying events within the upper right-hand cell of Figure 1 (main text), where awareness occurs in the absence of stimulation. On false alarm trials, 'noise' signals arising by chance presumably mimic the appearance of the stimulus and, thereby, fool the observer into saying 'yes'. By averaging the noise stimuli present on false alarm trials, structured signal patterns can emerge [65].

Finally, there are phenomena characterized by vivid sensory experiences in the absence of appropriate sensory stimulation. One such condition is hallucination, illusory awareness of something or somebody that is not really there. Visual hallucinations accompanying late onset eye disease or blindness (Charles Bonnet syndrome) are accompanied by activation of cortical areas specialized for the visual content of the hallucinations [66]. A non-pathological but rare condition involving awareness without appropriate stimulation is synesthesia [67]. Some synesthetes, for example, see vivid colors when viewing achromatic letters and numbers, with the colors located on the characters themselves–these illusory colors behave much like real colors do for non-synesthetic observers, and brain areas selectively responsive to real colored objects are also active when people with color-synesthesia experience illusory colors [68,69].

Figure I. An example of illusory contours (see text).

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Supplementary data

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