



Why visual attention and awareness are different

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Now that the study of consciousness is warmly embraced by cognitive scientists, much confusion seems to arise between the concepts of visual attention and visual awareness. Often, visual awareness is equated to what is in the focus of attention. There are, however, two sets of arguments to separate attention from awareness: a psychological/theoretical one and a neurobiological one. By combining these arguments I present definitions of visual attention and awareness that clearly distinguish between the two, yet explain why attention and awareness are so intricately related. In fact, there seems more overlap between mechanisms of memory and awareness than between those of attention and awareness.

Fundamental to the study of conscious experiences is the assumption that they are selective; we are not aware of everything we lay our eyes on. From the neuroscience perspective this implies that there is neural activity that produces conscious experience and neural activity that does not. Hence the, relatively new, search for the 'neural correlate of consciousness' (NCC) [1]. Another type of selection, already studied for decades, is attention; some sensory inputs are processed faster or deeper than others, and thus become more readily available for action, memory or thought [2,3]. It seems only natural that the two forms of selection share properties, and some have even argued that they are identical: we are aware of what is in the focus of attention [3,4]. This would strongly invalidate the search for the NCC. However, a strong argument can be made to clearly distinguish between the two. I will start with the psychological/theoretical part of this argument, to later add the neuroscience component. When taken together, these arguments then converge on fully separate definitions of (visual) attention and awareness, yet explain why the two seem so related.

Awareness and attentive selection

The limited nature of conscious experience is obvious from introspection but even more dramatically demonstrated in so-called change blindness (CB) [5–8] and inattentional blindness (IB) [9,10] experiments. CB occurs when subjects are viewing a scene in which one of the items changes position, color, identity, or simply disappears. Provided the image transients of such a change are masked, for example by interposing a brief blank interval between the two

versions of the scene, subjects very often do not notice the change, even when it is dramatic [5–8]. Although most prominently demonstrated in natural scenes, CB can also occur in relatively simple and abstract scenes, like the one shown in Fig. 1a, or even when there is only one stimulus in the display [6–8]. IB occurs when the subjects' attention is focused on a particular task and stimuli are presented unexpectedly. When asked afterwards about these stimuli, subjects often cannot report about them [9,10].

Some have taken the CB and IB findings to imply that, even though we think we see everything that is in front of us, we actually have a very limited conscious representation of the outside world [4]. At the least, both CB and IB hint to a selective process in which some items in a scene reach a privileged status. Unless that state is reached, stimuli are not noticed.

Attention seems to play a crucial role here. For example, cueing the relevant item before the potential change protects from CB (Fig. 1b). Also, items that grab attention by themselves survive CB [6] (but see [8]), and the same holds for IB [10]. It is crucial, however, that attention is allocated to the object near the moment of change [6,11]. Also, a similar number of items survive CB as can be stored in working memory [12,13] (about four) and storage into working memory depends on attention. It seems that attention guards the gate towards a representation that can be consciously reported or remembered (as in IB), or that can be compared with previous or succeeding stimuli (as in CB). We can summarize this view as shown in Fig. 2a. Many sensory inputs reach the brain and, via the process of attentive selection, some of these reach a conscious state, which allows us to report about them.

Other forms of selection

Obviously, there are also properties of stimuli that might never reach consciousness, not even when attended. Many invisible stimuli or attributes activate neurons. Examples are high temporal and spatial frequencies [14], anti-correlated disparity [15], physical wavelength (instead of color) [16], crowded [17] or masked stimuli [18], or the non-dominant patterns during perceptual rivalry [19]. Also, fully attended stimuli are occasionally not perceived, suggesting that sensory processing does not necessarily always complete to a perceptual stage [20].

These are all non-attentional selection mechanisms. What is perceived during rivalry, for example, is hardly under voluntary control. These mechanisms likewise filter

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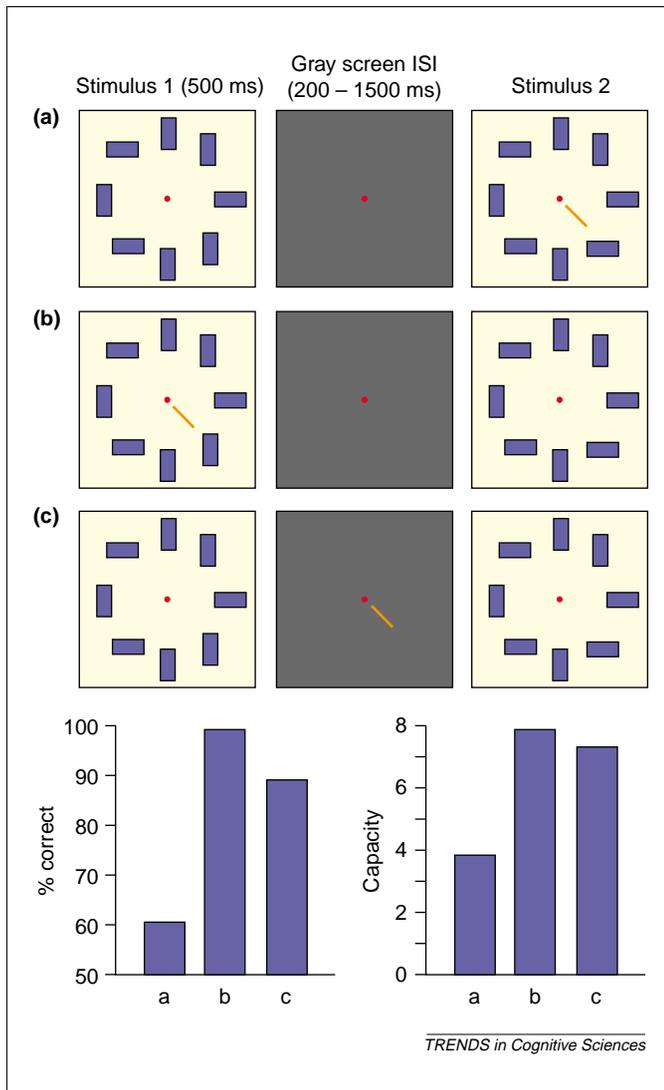


Fig. 1. Change blindness in an abstract scene, and the role of attention. In these change blindness trials (a–c), a scene containing multiple items is presented (Stimulus 1), followed by a gray screen inter-stimulus interval (ISI), after which the same scene (Stimulus 2) is shown again. The subject is then asked whether the cued item (indicated by the orange line) has changed or not. In (a) it has changed orientation. Subjects perform poorly at this task, (60% correct, lower left histogram). Performance can be converted in a ‘capacity’ measure (lower right histogram) indicating how many items the subject had available (in working memory) for change detection, in this case, approximately four items. When the to be changed item is cued in advance (b), subjects perform almost 100% correct (resulting in a virtual capacity of all eight objects). However, when subjects are cued after the disappearance of Stimulus 1 but before the onset of Stimulus 2 (c), they perform almost as well and seem to have stored almost all objects.

information before it reaches awareness. We could add these to the scheme of Fig. 2a, so that we have three classes or levels of processing that a visual input can reach: unconscious, unattended or attended. Only the last class reaches awareness (Fig. 2b).

But there is something awkward about this classification. There is no difference between attended and conscious stimuli and, as the neural basis of attention is fairly well studied [21], we would do better to eliminate one of the two terms (Fig. 2c). Some have, indeed, argued for this, stating that in fact there is no awareness beyond attention [4]. In that case, however, we would still need the term ‘unconscious’ for inputs that do not reach awareness even when attended.

Separating awareness from attention

A theoretically more logical solution is given in Fig. 2d. This model makes an early distinction between conscious and unconscious inputs, and the attentive selection process operates at an independent stage; attention does not determine whether stimuli reach a conscious state but determines whether a (conscious) report about stimuli is possible. Likewise, attention determines whether items are stored in a sufficiently stable manner (working memory) to allow a report at a later time or to allow a comparison with a subsequent scene. According to this model, CB and IB are not necessarily failures of consciousness, but of conscious memory (see [22] for a similar argument).

In other words, we are ‘conscious’ of many inputs but, without attention, this conscious experience cannot be reported and is quickly erased and forgotten. Figure 1 describes a psychophysical experiment in support of this view. We have seen that cueing the item that might change

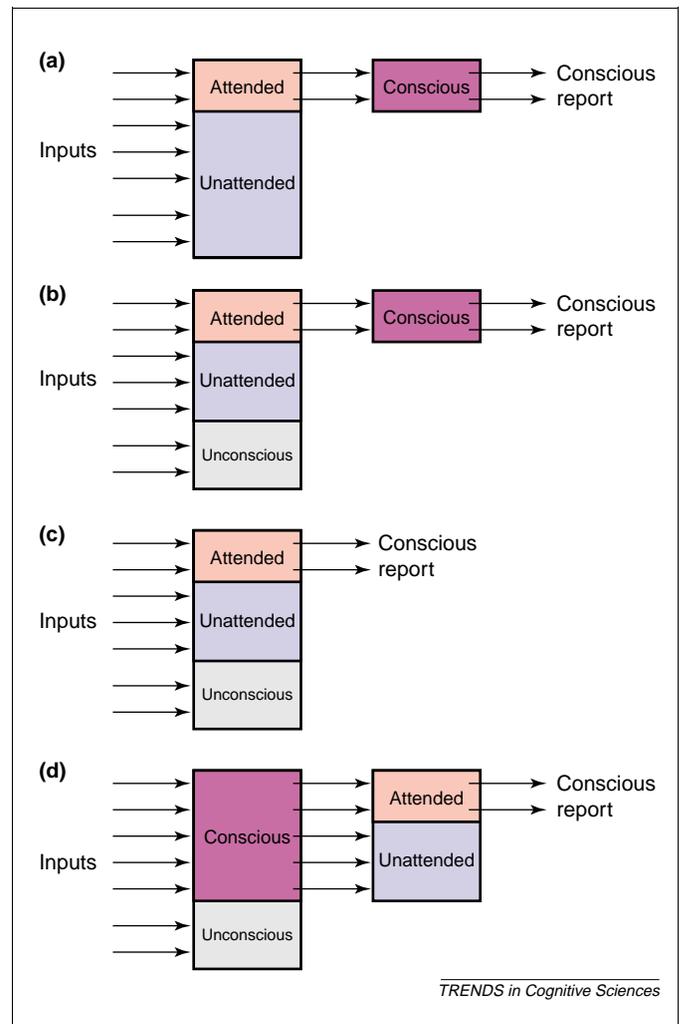


Fig. 2. Four models of visual awareness and its relation to attention. Visual awareness is limited, in the sense that we can report about only a small number of the inputs that reach us, typically those we attend to. It could be that attention determines what becomes conscious and what does not, and hence determines what we can report about (a). However, there are also non-attentional selection mechanisms for awareness (b). In these two views (a,b), there is no distinction between attention and consciousness, so that the latter term may be eliminated (c). Alternatively, the distinction between conscious and unconscious processing could be entirely separate from the attentional selection mechanism (d). In this view, many more inputs reach a conscious state, but to report about these we need attention.

in a display of many objects protects from CB (Fig. 1b). Surprisingly, however, cueing the relevant item long after the first stimulus has disappeared, but before onset of the second stimulus, also protects from CB (Fig. 1c) [23,24]. Apparently, after the first display has disappeared, a neural representation of almost the whole scene is still present and attention can select from this representation to store the relevant item in working memory. After the onset of stimulus 2, this representation has vanished, as cueing at that time does not help (Fig. 1a).

The model thus argues for the existence of a short-lived, vulnerable and not easily reportable form of visual experience, which contrasts with a more stable, reportable form of awareness. A very similar distinction has been made by Block, who distinguishes between ‘phenomenal’ and ‘access’ awareness [25]. In the domain of sensory memory, a comparable distinction is made between a retinotopic, fleeting form (iconic memory) [26] and a more durable non-retinotopic form (working memory) [27]. According to this view, attentional selection is inherently independent of either awareness or memory, but determines whether we go from phenomenal to access awareness or from iconic to working memory. Also, a conscious report is taken exactly for what it is, a motor output, and a selection (or decision, see [20,28]) process sits between the sensory experience and the motor output.

The neuroscience perspective

With the above psychological/theoretical arguments in mind, I will now turn to what neuroscience can tell us about attention and awareness. Over the last decades, neuroscience has revealed how intricate networks of nuclei, areas, pathways, modules, and so on, translate sensory input into a motor output [29]. Sophisticated computational tricks, such as recurrent processes [30], synchrony [31] or modulatory influences [32] add immense flexibility and power. Also, preceding events influence this transfer, either temporarily, because some activity reverberates in the network [27], or more lastingly by inducing chemical or anatomical changes in synaptic transmission [33].

This is, more or less, our core understanding of how the brain mediates sensory guided action and how memory of past events is incorporated in the underlying transformations. Guided by this framework we can now study the many details of these processes and try to understand how more complex cognitive functions can be built from these principles. Below, I will propose similar ‘core definitions’ of attention and awareness that fit the psychological/theoretical arguments given above and that might likewise guide our future research.

Visual attention: a convolution of processing and memory

Combining the core concepts of sensory processing and memory might be sufficient to explain visual attention [21]. Attention is a selection process where some inputs are processed faster, better or deeper than others, so that they have a better chance of producing or influencing a behavioral response or of being memorized [2,21,34]. Attention induces increased [21] and synchronous [35]

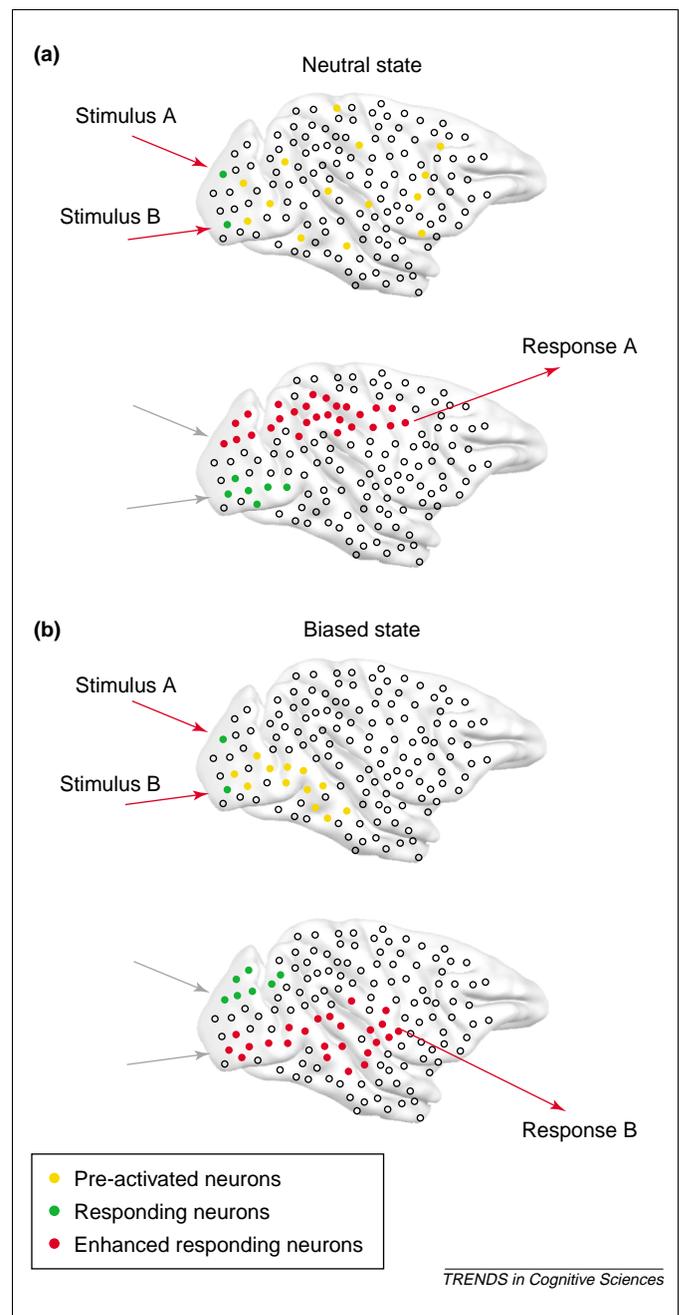


Fig. 3. Attentional selection is a convolution of memory and processing. Selection is necessary when two stimuli (labelled A, B) reach the brain but only one response is possible. Competition, typically at the level of the extrastriate areas, prevents all inputs from reaching output areas of the brain [21]. Depending on the state of the brain when stimuli arrive, either of the two outputs may be selected. (a) shows a neutral state, where Stimulus A is processed more efficiently, that is, better matches stored synaptic weights: Stimulus A is more salient and the associated neural activity in response is stronger or more synchronous (red dots). (b) shows a biased state, where the processing of a previous stimulus has left a short-term trace of activity (yellow dots). Now, processing of Stimulus B leading to a response is favored. Thus, attentional selection results from the convolution of the processing of current inputs with long- and short-term memory.

neuronal activity of those neurons processing the attended stimuli, and increased activity in parietal and frontal regions of the brain [36]. This explains why the associated stimuli are processed faster, better and deeper. But what brings the enhanced activity about?

Attention might be grabbed externally [2]. Some stimuli are simply processed more efficiently than others. These

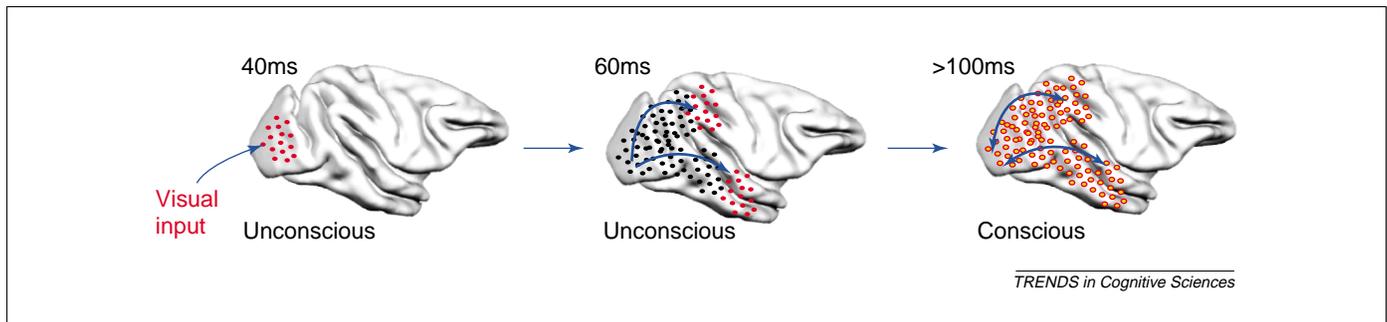


Fig. 4. Conscious visual experience requires recurrent processing. Visual input reaches the early visual areas (V1) at ~ 40 ms after stimulus onset. Visual information is then rapidly fed forward to the extrastriate areas and parietal and temporal cortex (~ 60 ms). This feedforward sweep of information processing is unconscious. At around 100 ms, early visual areas and higher areas engage in recurrent interactions, which are necessary for conscious visual experience.

stimuli we call salient. A bright stimulus will win over a dark one, a moving over a stationary, a foveal over a peripheral, and so on. This is mainly due to the properties of the adult processing network, shaped by genetics and visual experience. In other words, saliency reflects how long-term memory has shaped and modified sensory processing.

But preceding stimuli might subtly change these properties. The processing of a stimulus will leave a trace of activated and inhibited neurons that can last for a variable amount of time. The processing of subsequent stimuli might benefit from this trace if the two stimuli share properties (such as retinal position), resulting in attentional priming [37] (Fig. 3). The trace might also change in time, for example when excitation rebounds into inhibition, thus hampering subsequent processing, as in inhibition of return [2].

With endogenous attention [2], the situation becomes more complex but not fundamentally different. Now, an external event, such as an abstract cue, has to be translated in something akin to the ‘paving of the way’ described above. Parts of the brain that extract the meaning of the cue, and that are able to relate this to current needs and goals (polysensory and prefrontal areas for example), must preactivate or otherwise facilitate the appropriate sensory pathways, mostly via corticocortical feedback or subcortical routes.

In summary, the combination of sensory processing (including internal milieu variables) with short- and long-term memory explains why a particular brain at a particular moment in time is inclined to favor one stimulus over another [38]. We can even imagine this to occur in brains (or machines for that matter) without any phenomenal experience. Therefore, attention is not *a priori* associated with visual awareness.

Visual awareness requires recurrent processing

What remains to be found, then, is a similar core understanding of phenomenal experience. We know that neural (including cortical) activation does not necessarily lead to awareness. Hence the search for the NCC: the investigation of what kind of neural activity is, and is not, capable of producing awareness [1]. With respect to this question, I have made a point of abandoning the localizationist approach [39] and instead distinguish between the so-called feedforward sweep (FFS) and recurrent processing (RP) [30,40].

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The FFS is defined as the earliest activation of cells in successive areas of the cortical hierarchy. Typically, V1 starts to respond 40 ms after stimulus onset. Higher, extrastriate areas respond at slightly (yet successively) increasing latencies. By ~ 80 ms most visual areas are activated and at 120 ms visual activation can be found in all cortical areas, including motor cortex [30]. Surprisingly, these early responses already fully express the receptive field (RF) tuning properties of cells, even complex ones like face selectivity in area IT [41]. Feedforward connections are apparently capable of generating sophisticated RF tuning properties and thus extracting high-level information, which could lead to categorization [42] and selective behavioral responses.

As soon as the FFS has reached an area, recurrent interactions between neurons within that area and neurons that have been activated earlier at lower levels can start. These interactions are mediated by horizontal connections and feedback–feedforward circuits between and within areas [43]. They are expressed as modulatory influences from beyond the classical, feedforward, RF [20,30,40,43].

Some important observations can be made about the relation between FFS, RP and visual awareness:

- (1) Backward masking renders a visual stimulus invisible by presenting a second stimulus shortly (~ 40 ms) after the first [18]. The masked stimulus, although invisible, still evokes selective feedforward activation in visual and non-visual areas as widespread as V1, IT, FEF and motor cortex. Neurophysiological manifestations of recurrent interactions are, however, suppressed by backward masking [30,40,44].
- (2) With transcranial magnetic stimulation (TMS), the ongoing activity in a particular brain region can be disrupted. Applying TMS to early visual areas at a latency far beyond the FFS still renders stimuli invisible [45]. Also, TMS over the motion selective area MT induces motion sensations, unless V1 activity is disrupted at a later moment in time [46]. Because MT is higher in the visual hierarchy than V1, this implies that feedback from MT to V1 is necessary for motion awareness.
- (3) Feedforward activation of neurons can still be recorded in anesthetized animals with RF tuning properties that hardly differ from those in the awake animal. Manifestations of recurrent processing, in particular those contextual modulations that express

aspects of perceptual organization, are, however, reduced or fully suppressed under anesthesia [47].

- (4) Feedforward activation of neurons in V1 is not affected when stimuli are reported to be seen by animals engaged in a figure–ground detection task. A neural correlate of figure–ground segregation, probably mediated by recurrent interactions between V1 and extrastriate areas, and present when stimuli are seen, is, however, fully suppressed when stimuli are not seen [20].

This has led me, and others [40], to conclude that visual processing mediated by the FFS, however sophisticated, is not accompanied by awareness. Recurrent interactions are necessary for visual awareness to arise (Fig. 4).

Phenomenal versus access awareness

The distinction between phenomenal and access awareness can be understood as an interaction between the neural correlates of awareness and attentional selection (Fig. 5). If multiple stimuli are presented, these are all represented at the early stages of the FFS. However, at successively higher extrastriate areas, RFs become larger and larger so that competition between multiple stimuli starts to arise [21]. Not all stimuli can be processed in full by these receptive fields. This results in crowding phenomena, where individual awareness of closely spaced items is impaired [17]. Attentional selection (in one way or another, see above) might resolve this competition [21]. In the end, only a few stimuli reach the highest levels, up to and including areas in executive space.

Meanwhile, the early visual areas have started to engage in recurrent interactions. Visual features are related to each other, binding and segregation can occur, and perceptual organization evolves. This is what produces phenomenal awareness. Because at low levels there is relatively little competition between stimuli (unless they are close to each other), groups of recurrent interactions representing multiple stimuli are possible. We can thus have phenomenal awareness of many items in a scene.

When these recurrent interactions grow more and more widespread, and eventually include areas in executive or mnemonic space (frontal, prefrontal, temporal cortex), the visual information is put into the context of the systems' current needs, goals and full history. This is what, according to the model, produces access awareness. There is considerable competition, however, for interaction with these higher levels. Attentional selection during the feedforward sweep might already have predisposed some interactions over others. Alternatively, this selection might operate at the recurrent interactions themselves. Whatever the case, only a limited number of recurrent groups can span the range from visual to more frontal (parietal, temporal) areas. Therefore, access awareness is limited to a few items in the scene.

Conclusion: visual awareness versus attention and memory

The combined psychological and neural perspectives allow a clear distinction to be made between attention and awareness. Attentional selection is how sensorimotor

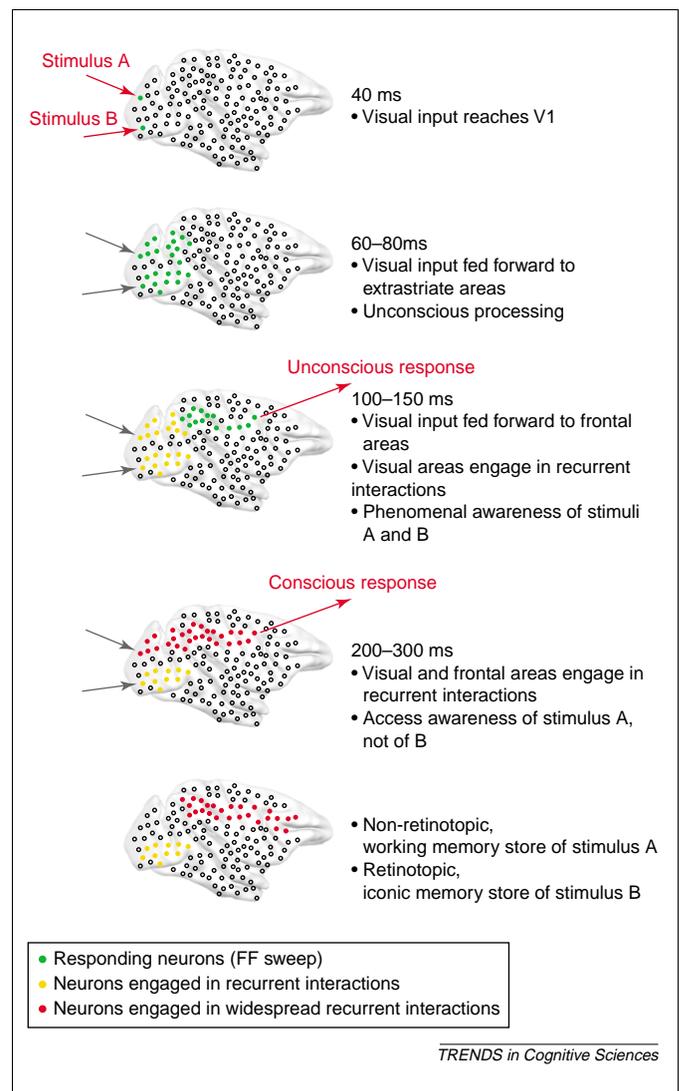


Fig. 5. Phenomenal versus access awareness. The interaction between recurrent processing (Fig. 4) and mechanisms of attentional selection (Fig. 3) is shown. As in Fig. 3, competition between the neural representations of multiple stimuli (A, B) can prevent the feedforward transfer from V1 to the executive areas of all but a few stimuli (in this case A). At lower levels, however, simultaneous representations (of both A and B) might exist. Either way, feedforward activation (green dots), both of selected (i.e. attended) and non-selected inputs, is unconscious, even though it might trigger or modify behavior. Meanwhile, neurons in activated regions start to engage in recurrent interactions, which are accompanied by increased activity or synchronous firing (yellow dots). This produces phenomenal awareness of the visual inputs (and iconic memory after removal of the stimulus). Some of these recurrent interactions become more widespread than others, and can even incorporate high-level, executive or planning regions (red dots), depending on attentional selection, in part already established during the feedforward sweep. Stimuli associated with these widespread interactions reach access awareness and can be stored in non-retinotopic working memory after removal of the stimulus.

processing is modified by the current state of the neural network, shaped by genetic factors, experience and recent events (memory). Phenomenal experience has a different origin – the recurrent interaction between groups of neurons [30,39,40]. Depending on the extent to which recurrent interactions between visual areas incorporate interactions with action or memory-related areas, awareness evolves from phenomenal to access awareness. Whether this occurs depends on attentional selection mechanisms, via influences on both the feedforward sweep and recurrent interactions. Other mechanisms, however, determine whether neurons will engage in recurrent

Box 1. Questions for future research

- Why does recurrent neural activity generate phenomenal experience whereas neural activity *per se* seems insufficient? What is so fundamentally different between these types of activity?
- Once a relation between recurrent processing and awareness is established, how is this going to explain phenomenal experience? Will neuroscientific explanations be sufficient?
- Crowding can be considered to be the spatial analogue of masking: both temporal and spatial closeness can hamper recurrent interactions at early stages, resulting in a loss of phenomenal experience. Is the effect of crowding on feedforward versus recurrent processing comparable to that of masking?
- This theory predicts a gradual transition from phenomenal (widespread, fragile, shallow) to access (capacity limited, stable, deep) awareness. Findings suggest a rather sharp transition, from unlimited to a limit of four items. Where is this coming from?
- What happens in patients with neglect or extinction? A lesion at the parieto-occipital junctions should not prevent recurrent interactions between purely visual areas. Does that imply that these patients have phenomenal but no access awareness?

interactions at all, and thus whether processing will go from an unconscious to a conscious state (Fig. 1d).

Conscious stimuli have reached a level of processing beyond initial feature detection, where at least an initial coherent perceptual interpretation of the scene is achieved. Whether at this stage the binding problem [48], in all its diversity, has been solved is not clear yet. The binding of some features of an object, such as its color and shape, might require attention, whereas other feature combinations are detected preattentively ([48] but see [38]). So it might be that the conscious level, before attention has been allocated, consists of tentatively bound features and surfaces, akin to 'mid-level vision' or the '2.5-D sketch' [49]. There is a clear distinction, however, with unconscious stages, where individual features, even features that are never perceived, are represented.

Phenomenal awareness seems to share neural mechanisms with iconic (sensory) memory and access awareness with working memory. It is probably best to reserve the term 'memory' for processes that change the state of the network. These changes can be lasting or short-lived. Also, purely unconscious (feedforward) activation is capable of inducing changes in synaptic transfer, as evidenced by priming experiments [50] and experiments showing adaptation to stimuli rendered invisible via crowding [17]. Memory and awareness are therefore different phenomena that can, however, share neural mechanisms (see Fig. 4). Some exciting avenues for future research into the relation between memory and awareness lie ahead (see Box 1).

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