Attentional resolution

Sheng He, Patrick Cavanagh and James Intriligator

Attention can enhance selectively the visual information processing of particular locations or objects. Recent studies have shown that this enhancement has limited spatial resolution, the smallest regions that can be isolated by attention are much coarser than the smallest details that can be resolved by vision. Multiple similar objects spaced more finely than the limit of attentional resolution cannot be individuated for further processing and can only be perceived as a grouped texture. As a result, at any given time, only part of the spatial and temporal information registered by the early sensory systems is available to conscious perception. It is likely that attentional resolution is limited at a stage beyond V1 and that it has a finer grain in the lower visual field than in the upper field. The spatial aperture of attention is elongated along the radial axis relative to fixation. The briefest temporal window of attention is also much broader than visual temporal resolution. Many perceptual phenomena related to rapid serial visual presentation may reflect the limited temporal resolution of attention.

We have all experienced paying attention to, or concentrating on a piece of music, a book or a thought and losing awareness of other surrounding events. Attention is such a common term in everyday life that often we do not realize the variety of attentional phenomena underlying our personal experiences. Despite William James's famous claim that: 'everybody knows what attention is', we have only a preliminary notion of what mechanisms mediate the effects of attention. Many studies in the attention literature are concerned with what it is, some are concerned with how it works and some are concerned with what happens to information that is not being attended[1–3]. In this short review, we will look at a specific question: how sharply can we focus our attention?

Many authors have used a 'spotlight' metaphor[4–6] to convey the idea that attention can be restricted to a small area (illuminating only a small part of our visual field), and that this beam of attention can move around. In the more extended 'zoom lens' metaphor[7–9], the beam not only moves but also scales up or down in size. Measurements of the distribution of attention within the beam suggest a gradient of attention, and even a tear-drop shape, oriented along radial lines from fixation[10–14].

The spatial specificity and the unitary nature of the attentional focus have been challenged recently. A number of experiments have shown that attention can be directed to non-contiguous locations[15,16] and even used to track as many as four or five randomly moving items simultaneously[17]. At the same time, other studies have demonstrated that attention is attached to objects, not locations[18,19]. When two objects are superimposed but attention is directed to only one of them, attentional facilitation is found to be specific to the object and not its location.

The grain of attention

How finely can attention be focused? Imagine there are two dots presented above a fixation point. An observer can attend to one or the other easily when the two dots are far apart (no eye movements allowed). As the two dots get closer and closer, however, it becomes increasingly difficult to focus attention on a single dot to the exclusion of the other (that is, to individuate it). As we shall see, the price of being too close is to lose access to the features of an individual item – which seem to get mixed up with those of its neighbors (Box 1). Surprisingly, this phenomenon appears to happen well before the two dots start to fuse visually and appear as a single dot.

Eriksen and his colleagues[4] proposed that the attention spotlight has a size of 1 degree, which means that if two items are spaced less than this distance apart they can no longer be accessed individually by attention. Although this number (1 degree) is valid only for the specific paradigm and stimulus placements that they used, it does suggest that attentional selection has a coarser grain than visual resolution. The limited resolution of attention was also evident in a study by Usai, Umilta and Nicoletti[20]. They showed that attention to a pac-man figure provided facilitation that was limited to targets within the pac-man except if the gap (the open mouth of the pac-man) was small. In that case, facilitation was also seen for targets in the gap as if the area through which attention had spread was a blurred version of the pac-man, blurred to the extent that the narrower gaps were filled in.

Since we will compare attentional resolution to visual resolution, let us begin with a simple description of visual resolution – the finest spacing at which visual detail can still be seen. Visual resolution is conventionally measured as the

S. He, P. Cavanagh and J. Intriligator are in the Vision Sciences Laboratory, Psychology Department, Havard University, 33 Kirkland Street, Cambridge, MA 02138, USA.

tel: +1 617 495 3884
fax: +1 617 495 3764
e-mail: sheng@wjh.harvard.edu

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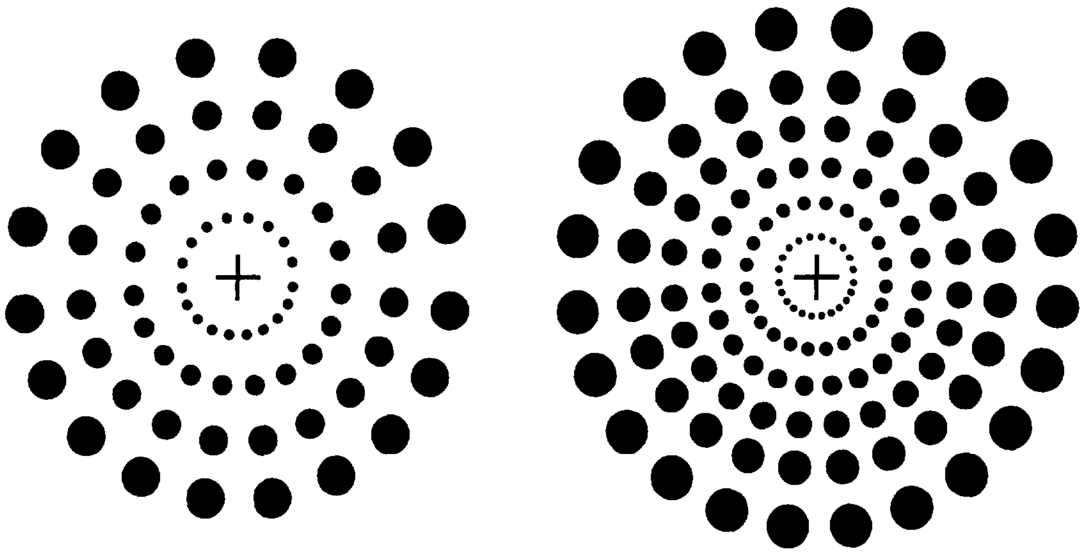
Box 1. How fine is the resolution of attention?



While fixating the cross in the center of the left-hand diagram (shown above) notice that it is fairly easy to voluntarily attend any item in the four concentric arrays. This is possible because each item is spaced at just less than the critical local density for individuation. The diagram on the right has a density that exceeds the resolution limit of our attention. Consequently, while fixating the right-hand cross, it is difficult to move your attention from one item to another. (Adapted from Intriligator and Cavanagh, ARVO, 1997.)

finest sinusoidal grating that can be seen when presented at maximum contrast[21]. Under bright illumination, an observer can normally resolve up to 55 cycles per degree (imagine 110 black and white stripes painted on your index fingernail, held out at arm's length). In this context, resolve means either that the observer can tell the grating patch apart from a uniform field (detection task) or can tell its orientation (discrimination task). This resolution limit drops dramatically as the test is moved away from the center of gaze.

We can define attentional resolution in a similar manner: the finest spacing of the bars of a high-contrast grating that allows the observer to isolate or index each bar with attention. A simple test of this ability is to count the bars without eye movements. Figure 1 demonstrates the difference between conventional visual resolution and the attentional resolution. We can see the gratings clearly and report that there are several fine bars vertically oriented. However, while fixating the central dot, it is much more difficult to individuate and count the bars in the grating to the left. We resolve the grating as textures but we cannot access the individual elements. Individuating the bars only becomes possible when the grating is much coarser, as seen on the right.

Studies on lateral inhibition or crowding

In the grating above, the cost of not being able to individuate the bars is relatively small – we do not know how many bars there are but we know that they are all vertical and thin. If each bar were subtly different, however, the cost might include the inability to report the special features of individual bars. This effect has been addressed in the extensive literature on crowding, tested typically with multiple letters presented in a row, either as a word or a non-word letter string[22,23]. These studies found that the letters in the middle of the row are more difficult to report than letters close to the fixation point, and surprisingly they are also more difficult to report than letters at the outermost position, even with prolonged viewing time[24]. Clearly, eccentricity is not a sufficient explanation for this result. Some researchers have tried to explain these findings by appealing to a sensory level lateral inhibition process, ruling out attentional factors[25] or spatial uncertainty[26]. Conversely, some authors have suggested that attention is a key factor[27,28].

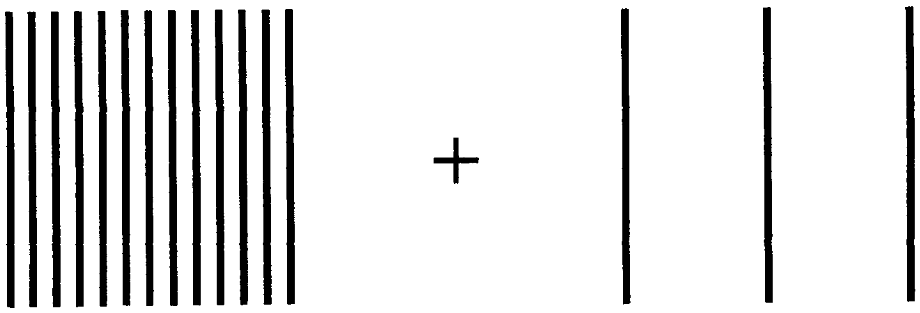


Fig. 1 An illustration of the difference between visual resolution and attentional resolution. Looking at the center cross, the grating on the left is easily resolved. One can tell the contrast, orientation and spacing of the stripes. But it is much harder, or even impossible, to attend to individual bars or count through them without moving your eyes from the fixation cross. The grating on the right side, however, is much more sparse, and it is possible to individuate the bars. Consequently, we say that the grating on the left is beyond attentional resolution, and that the one on the right is resolvable by attention.

The lateral interference effect measured in these experiments is not limited to letter stimuli. Studies on orientation discrimination and vernier acuity with line segments also have shown interference effects in the presence of properly positioned surrounding lines[29,30]. In general, when a target is embedded in multiple distractors, it is very difficult to perceive the target. It is our claim, outlined below, that this difficulty reflects to a large degree the limited spatial resolution of our attentional mechanism.

Interestingly, the crowding effect depends strongly on the similarity between the distractors and the target to be detected, and their relative depth[29,31]. Also, grouping between the distractors and the target changes the crowding effect significantly[32]. These results indicate that these effects emerge at a fairly high level.

Crowding as a measure of attentional resolution

In severe cases of crowding, a target embedded in an array of distractors cannot be selected by attention, and cannot be consciously analyzed independently of the distractors. The suggestion that the crowding effect is due largely to insufficient spatial attentional resolution is addressd by the following experiment on orientation selective adaptation[33].

Adaptation to a grating in a particular orientation will raise the threshold for subsequently detecting a grating in that same orientation much more than a grating in the orthogonal orientation. This orientation selective adaptation has been linked to neurons at the primary visual cortex and beyond[34]. In a recent study[33], we adapted our observers either to a single grating or a crowded grating array. In the latter (crowded) case, the adapting grating at the target position was essentially unavailable to conscious perception (see Fig. 2): the identification of its orientation was at chance level. However, in both the single and crowded adapting conditions, we found the same magnitude of orientation selective adaptation effect. Figure 2 shows the stimulus and the results. A grating that is unavailable to our conscious perception (due to crowding) is, nevertheless, as powerful as a single, perfectly visible grating in producing orientation specific adaptation effects. This suggests that crowding happens at a stage beyond the site of adaptation, which itself must be no earlier than V1 (no orientation analysis occurs at earlier levels). This result, like the earlier ones showing that an unresolvable high frequency grating can produce an orientation selective adaptation effect[35], is consistent with the proposal that activation of V1 neurons alone is not sufficient for visual awareness[36,37].

In the context of early versus late attentional selection, these results strongly support late selection. The lateral interference or crowding, which prevents the selection of the target grating, is certainly not at an early 'sensory' level as the information has been registered and processed to at least the level of area V1, if not higher. Is this high-level lateral interference a property of attention itself or the result of additional cortical filtering beyond area V1 but preceding attentional selection? Our example in Fig. 1 demonstrates the phenomenon of crowding occurring clearly at the level of selection. The fine vertical bars are seen clearly, and the observer can report any number of details about the lines: width, orientation, length and so on. And yet, as is revealed when attempting to count the lines without eye movements, the individual lines cannot be accessed. Classical crowding displays with adjacent letters, or the crowded grating patches used in our experiment[33], are not so simple as the set of lines shown in Fig. 1. It is possible that these more complex stimuli suffer from some high-level lateral interference that precedes selection. They must, nevertheless, all share the same selection difficulty so clearly seen in Fig. 1. It is this selection bottleneck that we are labeling the resolution limit of attention.

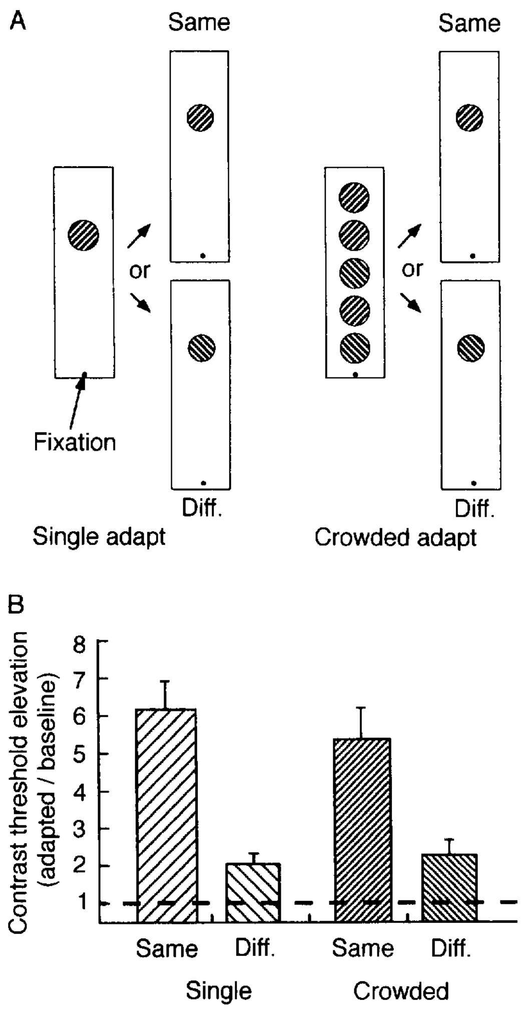


Fig. 2 Orientation selective adaptation. Orientation selective adaptation in displays where observers could and could not perceive the orientation of the adapting grating (fourth grating away from fixation). **(A)** Contrast thresholds were measured under three different conditions: adapt to a single grating, adapt to the fourth grating in a linear array of five gratings and no adaptation (baseline). **(B)** Threshold contrast elevation after adaptation relative to baseline contrast threshold before adaptation. The difference between same adapt-test orientation and different adapt-test orientation represents the strength of orientation selective adaptation. The data show that a flanked grating (orientation not perceivable) and a single grating (orientation readily perceivable) were almost equally effective in orientation specific adaptation. (From Ref. 33.)

Upper/lower field and radial/tangential inhomogeneities

The grain of visual resolution is not uniform in the visual field. It drops off precipitously with increasing distance from the center of gaze. However, the resolution of attention

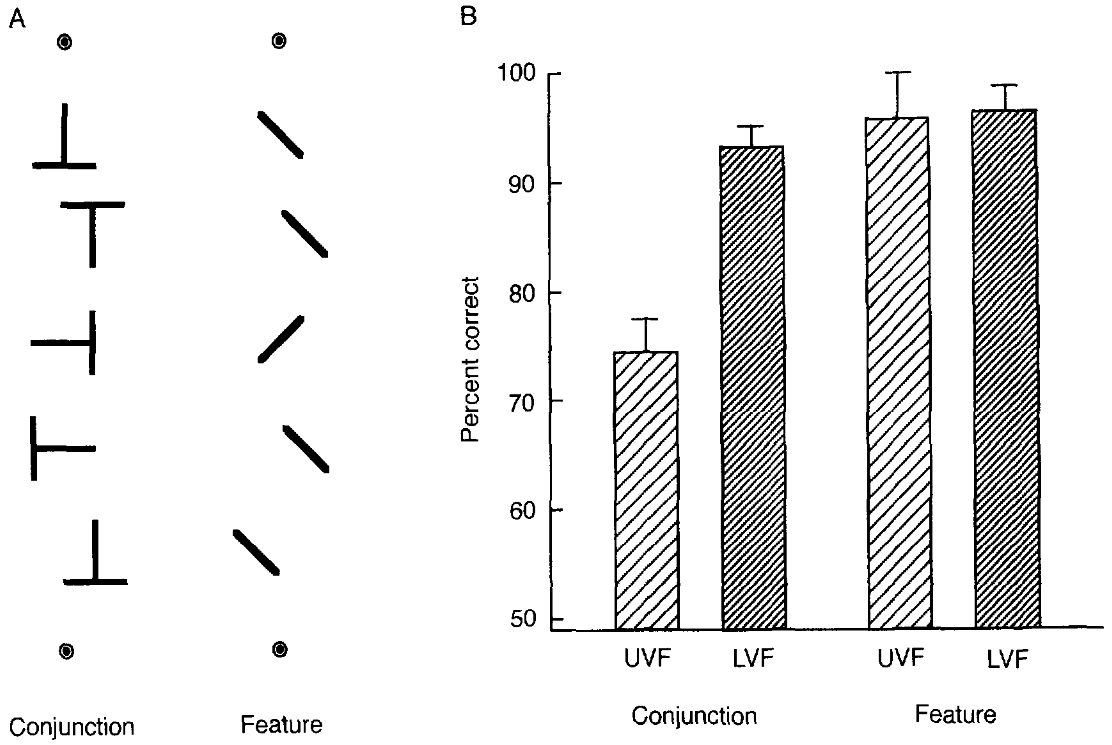


Fig. 3 Schematic examples of stimuli (A). One stimulus is used in the feature detection condition and one in the conjunction detection condition. Observers attend and respond to the presence/absence of the prespecified target (in this example, / is the target in the feature case, T tilted 90 degrees clockwise is the conjunction target). **(B)** Accuracy data collected under four different conditions. Conjunction detection suffers a large asymmetry between upper (UVF) and lower visual field (LVF), while the feature detection is equally good in both upper and lower visual field. (From Ref. 33.)

appears to have two additional inhomogeneities that are not characteristic of visual resolution. Firstly, a lower visual field advantage is found in many different tasks that require focused attention[33]. For example, in our experiment where subjects had to determine whether an item in a prespecified position (flanked with distractors) is a target or not, no marked difference between the upper and lower field was seen for targets defined by simple features (line segments with large orientation differences), but a pronounced lower field advantage was observed for targets defined by feature conjunctions (Fig. 3, from Ref. 33). The lower field advantage is also evident in an attentional tracking task (similar to that developed by Pylyshyn and his colleagues, Ref. 17), where observers were asked to track two discs among nine randomly moving discs (Fig. 4, from Ref. 33). Since the tracked discs are physically identical to the non-tracked

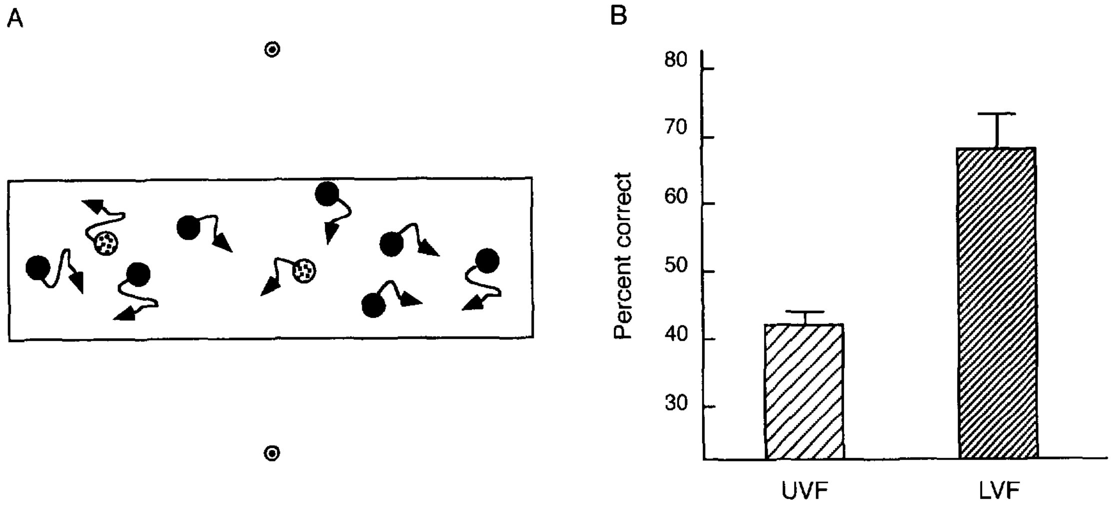


Fig. 4 Attentional tracking task and accuracy data. (A) Observers fixated 10 degrees above or below the center of a rectangle area in which nine green moving balls were presented. At the beginning of each trial, two of the balls were changed to red for 1 s, and then turned back to green. The observers' task was to keep track of those two balls with attention while keeping their gaze steady on the fixation dot. After 5 s, all nine balls stopped moving, and observers indicated which two balls were the ones that had turned red at the beginning. Chance performance is 21.1%. **(B)** Observers performed much better when the balls were presented in the lower visual field. LVF, lower visual field; UVF, upper visual field. (From Ref. 33.)

ones (except for a brief color change for identification at the beginning of the trial), performance in this task depends critically on the ability to use attention to track the selected targets, that sometimes move very close to the distractors.

Differences between the upper and lower visual field were also found in several other tasks involving attention[38]. Previc proposed two attentional systems, one for extrapersonal space that favors the upper visual field, and one for peripersonal space that is directed towards the proximal lower visual field[38]. Although this distinction is still a subject of debate, much of the evidence is consistent with a finer attentional resolution in the lower visual field. In contrast, there is very little evidence of differences in visual resolution between the upper and lower field within a large range of eccentricity as measured by contrast sensitivity using gratings[39]. The recent finding that the lower visual field is better at perceiving subjective contours[40] may be unrelated to the different attentional resources of the two hemifields, although Gurnsey, Poirier and Gascon[41] have argued that subjective contours may not be seen without attention.

The lower visual field advantage in attentional resolution may partly be due to the fact that the lower field is represented in the upper part of the primary visual cortex, which is anatomically adjacent to and projects more heavily[42] into the occipital–parietal regions that are often linked to spatial attentional control[43,44].

The second inhomogeneity is that attentional resolution is also anisotropic in the radial or tangential dimension. There is significantly less interference between items when they are arranged tangentially, rather than radially, relative to the eyes' fixation[45,46]. It seems that the shape of the smallest regions to which we can attend is ellipsoidal, elongated along the radial lines from fixation. Although the receptive fields of many visual neurons[47–49] tend to be slightly elongated along such radial lines, this factor alone is not sufficient to explain the large difference between radial and tangential configurations in the lateral interaction which is observed behaviorally. The difference in attentional resolution may contribute to many observed radial orientation advantages including that for grating resolution[50], phase discrimination[51] and motion sensitivity[52].

Temporal resolution of attention

Under bright light, luminance fluctuation can be perceived as a flicker at frequencies as high as 50 Hz, suggesting that the initial stages of our visual system can resolve fast changes. In comparison, attentional processes appear to be much slower, and to have a coarser temporal resolution. In a direct analogy to the resolvable but not individuable bars of the grating, demonstrated in Fig. 1, a spot flickering at slow rates can be perceived as appearing and disappearing (individual temporal events). However, at a higher rate, the spot is no longer seen as turning on and off discretely, but instead seems to be present continuously as a flickering spot (one cannot index a particular appearance or count the number of appearances of the spot). The rate (~4-6 Hz) at which the spot's phenomenal existence becomes continuous has been called the Gestalt flicker fusion rate by Van de Grind and his colleagues[53]. In an experiment performed by He and MacLeod[54], a grating with its contrast changed from a high to a low level or from a low to a high level could be perceived as an obvious change, but if the rate of change was higher than 4 Hz, observers could not distinguish between the two sequences of change.

Reduced performance with rapid serial visual presentation (RSVP) may also reflect the poor attentional resolution in time[55]. For example, when detecting a probe that occurs between 100 ms and 450 ms after a correctly identified target in an RSVP sequence, observers show a marked decrease in their ability to detect that probe. This loss of performance has been labeled the attentional blink[56]. The limited temporal resolution of attentional selection may be one of the factors that contribute to this phenomenon.

General discussions and future questions

Visual information is processed at multiple stages. We cannot be aware of everything at any one time, but only the things we are attending to or things that capture our attention. In this sense, attentional resolution is the bottleneck of our awareness and one might even argue that studying attention amounts to studying awareness. Although, in this article we have used the word attention as if it were a single process, it is not necessarily so[57,58]. Exogenous and endogenous shifts in attention may be controlled separately[59]. Moreover, the systems for shifting attention from one object to the next[60,61] may be very different from those used to keep track of moving targets[62].

A central goal in the study of attention is to identify the neural structures mediating attentional processes and the study of neuronal responses to crowded stimuli may have much to offer here. For example, in many cortical areas the response of a cell to its preferred stimulus is strongly reduced when the stimulus is flanked by identical stimuli[63–66]. However, based on what has been found psychophysically[45,46], the signature of a cell which participates in attentional selection should be that the response is almost completely suppressed when the target and flanking stimuli are aligned radially from the foveal, whereas less suppression should be seen when target and flankers are aligned tangentially at equal eccentricity.

For many years the question of early vs. late selection has been the center of debate in studies of attention[67–69]. It remains an unresolved question today. The adaptation experiment described earlier demonstrates an effective method for evaluating the processing of unselected features and the results indicate that the site of attentional selection is later than the site of orientation analyses. The advantage of this method lies in the degree to which stimuli are rendered inaccessible to attentional selection. Traditionally, the fate of unattended information is studied with brief, masked presentations. This masking may reduce the available signal enough to prevent accurate recognition but it is always possible that bits and pieces of the stimulus may reach awareness; these may be sufficient to prime or otherwise influence later measures[70]. However, with an optimally crowded display (Fig. 2A), the target stimulus remains inaccessible to awareness, even with unlimited viewing, making the argument that unreported information is unavailable to awareness much more compelling. The same paradigm can be extended to study the level of processing of many other properties of the crowded/inaccessible stimulus.

Finally, the pattern shown in Fig. 1 raises the question of when a pattern is no longer an arrangement of elements but a texture. The pattern on the left seemed necessarily a texture since its individual elements could not be accessed. However, the pattern on the right could be thought of as either a sparse texture or an arrangement of individual lines. Studies of texture segmentation may, therefore, also be related to attentional resolution. The factors that support segmentation may change qualitatively when the pattern density crosses the limit of attentional resolution[71].

The concept of attentional resolution may help us in understanding many diverse phenomena, such as contextual effects, crowding, masking, some aspects of subliminal perception and perception in RSVP sequences. Moreover, the measurement of an individual's attentional resolution may turn out to be a more salient factor than visual resolution in predicting that individual's performance in attentionally demanding tasks such as driving, piloting airplanes or air traffic control.

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