# Seeing Seeing

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The past decades have seen great progress in our understanding of human visual perception.  Important advances have occurred both in the techniques used and the conceptual frameworks developed.  The result has been a great increase in our understanding of how we see, and the way that consciousness enters into it.

Amidst all this, however, confusion has arisen on several fronts about particular issues, even to some extent about the bigger picture that is emerging.  Part of this is due to inconsistencies in several of the technical terms used, which have retained some of the vagueness and ambiguity found in their original use in everyday language.  Another source of confusion is the fact that many of the discoveries were converged on by researchers from different traditions, bringing with them different terminologies and styles of analysis.  Finally, a certain amount of confusion is inevitable simply because progress has been so rapid, and our understanding still so incomplete.  There are conceptual gaps and inconsistencies yet to be addressed, hindering our ability to obtain a clear picture of the situation.

But although some of this confusion cannot be dispelled at the moment, much of it can. The goal here is to present a reasonably consistent (although necessarily incomplete) account of several key issues concerning conscious and nonconscious processes in vision, and to discuss some of the questions that still need to be answered.

## Rapid Vision

When discussing visual perception, a natural place to begin is *rapid vision*, which comprises those processes occurring within the first few hundred milliseconds or so of stimulus onset (see e.g., Rensink & Enns, 1995, 1998).  This aspect of vision is dominated by feedforward information flow: within 150 milliseconds this “first wave” can reach all areas of cortex (e.g., Lamme & Roelfsma, 2000).  Rapid vision itself can be decomposed further based on distance from the initial input at the retina.  Processes at the lowest levels involve retinotopic representations; at slightly higher levels, they become increasingly spatiotopic, involving relative rather than absolute spatial locations.  All these processes are highly parallel, with operations carried out concurrently at many—and perhaps most—locations in the visual field.  Processes that are both rapid *and* low-level constitute what is known as *early* vision.

Historically, early processes were identified as “preattentive”, i.e., acting before attention had a chance to operate.   In this view, simple features were formed at this level (such as bars or colored patches) and then combined by visual attention into more complete objects (e.g., Treisman & Gormican, 1988).  However, it has been found that relatively complex “proto-objects” of limited extent (a few degrees of visual angle) can be formed at this level, involving combinations of features that are evidently obtained without attention (e.g. Rensink & Enns, 1998). The result is a “fragmented” representation (or sketch) of the type proposed by Marr (1982): a patchwork that covers the visual field, but with little interaction to knit these local structures into something more coherent. Proto-object properties can be quite sophisticated, involving grouping, estimates of three-dimensional orientation, and the identification of shadows (Rensink & Cavanagh, 2004). Interestingly, immediate access of attention (and perhaps consciousness) appears limited to these more sophisticated properties, with access to the underlying image properties requiring more time and effort. As well as a limited extent in space, proto-objects are also believed to have a limited extent in time—they are continually regenerated as long as a visible stimulus is present, and are quickly overwritten by any subsequent stimulus at their location. If a stimulus disappears, the corresponding proto-objects will fade away over the next half second or so, possibly accounting for iconic memory (Rensink et al., 1997).

The neural mechanisms at this level include the retinotopic system formed of the retina, lateral geniculate nucleus, and primary visual cortex (V1). Also included are the associated “V areas” (V2, V3, V3a, V4, etc), which carry out specialized processing at levels progressively less tied to retinal location. Early representations appear to form a “cascaded system”, with their contents distributed across several areas, and with dense connections between the corresponding locations in each. During rapid processing, these connections are mostly in one direction—from the more absolute to the more relative—although there is still enough time to establish some re-entrant feedback connections between these areas (Di Lollo et al., 2000).

As might be expected from the physiology, early representations are inherently dense. A retina has 120 million photoreceptors; as such, it contains D x 10^8 bits of information [note 1]. Each optic nerve is composed of about a million nerve fibers, indicating a reduction in information content to D x 10^6 bits. The density at higher levels is more difficult to estimate. If a proto-object extends about 2 degrees and doesn’t overlap excessively with its neighbors, about10^3 of these would exist. Computational models of human performance posit D x 10^2 bits for the simple properties of each proto-object (e.g., Itti & Baldi, 2005), yielding a total of at least D x 10^5 bits. Thus, even if much of the incoming information has been discarded at these levels, a considerable amount remains, re-packaged into a dense representation concerned more with properties of the world than with the retinal input per se.

Other kinds of rapid processes also exist. For example, the average size of several disks shown for 100 milliseconds can be estimated quite accurately (Ariely, 2001; Chong & Treisman, 2003). Another capacity—possibly related to this—is the ability of observers to determine the abstract meaning (or *gist)* of a briefly-presented scene (e.g., whether it is a harbor, airport, or farm) within about 150 milliseconds (e.g., Thorpe et al, 1996). Other aspects of scene composition can also be obtained this way, such as how open or crowded it is (Oliva, 2005). Importantly, such judgements involve complex stimuli presented for a time insufficient to attend to more than 2-3 items, indicating that most if not all such processing is done without attention.

## Visual Attention

Visual attention is perhaps the aspect of vision most closely associated with conscious visual experience, i.e., the "picture" we receive of our surroundings. Various induced failures of visual experience have been attributed to the absence of attention: the attentional blink (Raymond et al., 1992), binocular rivalry (Blake, 2001), change blindness (Rensink et al., 1997), inattentional blindness (Mack & Rock, 1998), motion-induced blindness (Bonneh et al., 2001), and repetition blindness (Kanwisher, 1987). All of these have been taken to support the claim that attention is necessary for visual experience.

An important concern was raised by Wolfe (1999; cf. Dennett, 1991: pp. 115-119): Does the failure to report an experience correspond to true *blindness* (i.e., a failure to perceive the unattended items) or to *amnesia* (i.e., a failure to remember them)? For change blindness, this would appear to be a genuine failure of perception, since an observer can be prepared to respond to a target stimulus as soon as possible (Rensink, 2000a). This argument also holds for all other forms of induced blindness except inattentional blindness, which typically relies on unexpected stimuli. However, inattentional blindness can be induced even for stimuli that are expected (Rensink, 2005), indicating that this, too, corresponds to a perceptual failure.

Meanwhile, it is somewhat unclear as to whether attention is sufficient for conscious visual experience. Part of this is due to an ambiguity in the word "object". If an object is taken to be a structure in the external world, the answer is clearly "no"—an observer can miss changes in an attended structure if the changing properties are not represented (Levin & Simons, 1997). But if an object is taken to be a representation of a structure in the environment, the answer may be "yes", at least if the creation of such an internal structure is what attention does (Rensink, 2000b: note 13; however, see Schankin & Wascher, 2007).

But what exactly does attention do? An important issue here is whether there exists just one kind of attention, or several. "Attention" is notoriously difficult to define, and it has been suggested that this may reflect the lumping of different processes under a single label (Allport, 1992). All attentional processes can be characterized in terms of selection (Rensink, 2003). But selection can be for different things (e.g., selective access, selective construction), and it is unclear whether these all involve the same neural mechanisms.

Some insight into this can be obtained by comparing the kinds of perceptual failure caused by different kinds of cortical damage. For example, damage to the right posterior parietal cortex can cause an outright failure to experience part of the visual input (*neglect*). Note that this need not be the entire mechanism responsible for conscious experience—other parts may also be involved, such as area V1 (Lamme et al, 2000). In contrast, damage to the inferior temporal lobe can cause a different kind of deficit—a failure to perceive the structure of an object, even when its constituent properties are experienced (*integrative agnosia*). The different characteristics of the two deficits suggest that two kinds of attention may exist: one dealing with selective creation of structure (focused attention), and one with selective access to unstructured visual "stuff" (ambient attention). This may also explain why observers in some experiments report detecting "something" in stimuli that were not given focused attention, even though it was "not really seen" (Neisser & Becklen, 1975). Likewise, observers can perceive some unstructured aspects of an image (e.g. the presence of simple properties, and perhaps scene gist) while their focused attention is occupied with other tasks (Braun & Sagi, 1990; Li et al, 2002)

Meanwhile, the attention that enables change detection has been posited to create a coherent "circuit" of information flowing between higher and lower levels (Rensink, 2000c). The formation of such a circuit for each item in a display requires about 300 ms (Rensink, 2001), a value comparable to the "attentional dwell time" encountered in studies of the attentional blink. The similarity of these estimates suggests the possible existence of a third kind of attention, one concerned with individuation rather than structure per se. Indeed, the capacity of this kind of attention appears to be 3-4 items, similar to that encountered in tracking studies (where individuation is paramount). And as with tracking, these items are not entirely independent of each other, but in many ways act as a single complex, corresponding to a single object with 3-4 parts [note 2].

The amount of information associated with an item receiving such attention is unknown, but some studies (e.g. Hayhoe et al., 1998; Vogel et al., 2001) suggest a minimal amount, corresponding to less than 10 bits per item. Given the existence of 3-4 items, the total amount of information held this way is therefore likely to be no more than 30-40 bits, compatible with other estimates of conscious experience (see e.g. Norretranders, 1998: ch. 6).

Note that even in that absence of attention (and visual experience), considerable processing still takes place. For example, the meanings of unseen words and pictures can affect other aspects of perception—for example, speeding up conscious recognition—even if the stimuli are not themselves visually experienced. Meanings perceived under these conditions can include both semantic aspects (i.e., associations with other concepts) as well as emotional connections. Such *implicit perception* can take place rapidly (within 100 milliseconds), showing that rapid vision and visual attention are independent systems operating in tandem with each other.

## Scene Perception

The interaction of conscious and nonconscious processing is perhaps best seen in the context of scene perception. This is not quite the ultimate stage of vision, since it does not deal with the perception of dynamic structure, nor does it appear to underlie on-line control of movement (Goodale & Milner, 1992). Nevertheless, it is highly comprehensive, providing a percept intended to encompass everything of significance in the environment.

One of the more striking qualities of scene perception is the impression that we see everything in front of us. However, such an impression gives rise to a problem: If visual attention is needed for conscious perception (as many researchers have argued), and if visual attention is limited to about 3-4 items (as many studies have shown), why does our impression of a scene appear to contain so much information?

Part of the answer may lie in the idea of a "virtual representation"—a representation that allocates focused attention to create object representations whenever they are requested (Rensink, 2000c). Such a representation could be based on the interaction of three systems. The first is early vision, where representations are dense, rapidly formed, and volatile (i.e., lasting less than a few hundred milliseconds). Although D x 10^5 bits may be available, they cannot on their own support "seeing" in the usual sense: such a representation is fragmentary, at best supporting an impression of unstructured stuff. The second system is focused visual attention, involving more structured and sustained representations containing perhaps 30-40 bits of information. Connecting some of the higher-level structure with lower-level detail (especially at the level of V1) could support "seeing" in the usual sense, providing an experience not only of stuff, but also structure and individuation. Meanwhile, a third system—driven by rapid vision, and involving properties such as scene layout and gist—could use high-level knowledge to guide the allocation of attention, creating the right coherent representation at the right time. And if ambient attention is separate from the focused attention that underlies the perception of structure, observers may also have concurrent access to unstructured stuff (i.e., the properties of proto-objects), which would then form a kind of background visual texture.

Thus, a critical role in the creation of visual experience appears to be played by representations that are not themselves consciously experienced—and in fact, do not even have any visual content. It might be thought such representations would involve a great deal of information. However, a relatively sparse schematic system could suffice (Rensink, 2000c). For example, information could be collected on the basis of eye movements or attention into a visual "medium-term" memory that does not require attention to be maintained. Such a representation could contain information from D x 10 items, each with perhaps 20 bits describing something of its properties (color, shape, etc) and location. In accord with this, experiments indicate that at least 4 items may be kept in such a memory, along with the 4 items being attended (Rensink, 2000d; Tatler, 2002). Newer work raises this estimate to 10 items (Hollingworth, 2004), and the number may climb higher yet. But even if 50 such items existed, such a representation would still be relatively sparse: the total information content would not exceed 1000 bits, less than 1 percent of the D x 10^5 bits present at low levels. Indeed, although thousands of images can be stored in long-term memory, only 20 bits appear to be stored for each image (Brady et al., 2008), consistent with a relatively sparse representation.

The existence of representations without any visual content may also account for the reports of some observers that they can "feel" or "sense" a change, even though they do not have an accompanying visual experience of it (Rensink, 2004). It has been argued that such sensing may simply be due to observers experiencing a near-threshold state of regular visual perception; support for this has been taken from the finding of increased false-alarm rates for observers that often report sensing (Simons et al., 2005). However, an increase in the false-alarm rate could be due to a variety of causes, and so on its own is not conclusive. Furthermore, several results appear to provide positive support for seeing and sensing as distinct aspects of visual perception. For example, the durations of sensing and seeing are completely uncorrelated in individual trials, a result unlikely to arise from a single mechanism, but one that is consistent with separate mechanisms for sensing and seeing. Recent work on comparative visual search appears to provide additional support for this position (Galpin et al., 2008).

In any event it is clear that a simple principle holds for the representations involved in scene perception: they can be dense and volatile, or sparse and nonvolatile, but they cannot be both dense and nonvolatile. Contrary to subjective impression, scene perception is based on *co-ordination* of focused attention rather than *construction* of dense, long-lasting representations. The belief that a dense, nonvolatile representation is formed is a "meta-illusion"—an illusion that ascribes properties of the world itself (dense, nonvolatile detail) to the representations involved. In a way, this is a side-effect of a successful representation—it should only convey information about the world, and not about its own nature.

## Modes of Visual Perception

Drawing together the various strands discussed above, some important conclusions emerge about conscious and nonconscious process in visual perception. First, attention of some kind is strongly associated with conscious experience, which can take several hundred milliseconds to emerge. Second, attention is not required for at least some aspects of perception, much of which can take place relatively quickly in a concurrent processing stream. Finally, the impression of seeing a great deal of information in dense, coherent form reflects only the nature of the world, and not the underlying representation, which involves a dense, volatile component that may provide an impression of unstructured “stuff”, along with a much sparser, nonvolatile component that provides more structured percepts.

These results suggest that our visual experience may not be as unitary as casual observation indicates, but may involve the co-ordinated interplay of several different experiential components. Moreover, these components may go beyond the simple dichotomy of conscious and nonconscious perception. Little is yet known as to what these components might be, but virtually all results to date on visual perception can be placed into one of just a few experiential categories. These might best be viewed as submodalities (or modes) of visual perception, which may operate somewhat independently of each other:

1. Coherent experience. This is the experience of coherent structure, viz., particular combinations of particular properties at particular locations. Focused attention appears to be needed for this, along with an intact area V1. As such, the informational density involved is likely low. This type of experience is relatively slow to emerge, and so is not experienced during briefly-presented displays. The failure of this mode results in integrative agnosia, where the structure of an object is not perceived, even though the constituent “stuff” is still experienced. Note that a further subdivision of this mode may also exist, with the experience of a structured item being separate from the experience of an individual at a particular location in space.

2. Ambient experience. This is the experience of unstructured (or fragmented) qualities, viz., relatively simple properties at particular locations in space (Iwasaki, 1993). Ambient attention—posited to be distinct from and simultaneous with focused attention—may be needed for this; an intact area V1 is also required. This type of experience can appear relatively quickly. As such, it may accompany some kinds of rapid visual processes. It can also extend over relatively large areas of space, and so may be involved with the collection of information concerning global aspects of an image.

3. Implicit perception. This form of perception occurs rapidly and without any conscious experience whatsoever, although several kinds of operations can take place. These include things such as determination of meaning (including emotional valence), as well as the formation of groups and other structures. No attention of any kind appears to be involved. At least some of these processes may be carried out via neural pathways quite separate from those underlying the production of conscious visual experience. This may

explain why some patients with damage to V1 have *blindsight*, i.e., to ability to perceive properties such as color, orientation and emotional expression, even in the absence of any visual experience.

4. Nonvisual experience. In this type of perception there is a conscious experience (marked by a sense or feeling of something happening), but no accompanying visual experience. The existence of this as a separate mode of experience is still controversial. If it is a separate mode, it would likely involve neither focused nor ambient attention, but would rely on nonattentional or subattentional mechanisms. Interestingly, some blindsight patients can "sense" an unseen event (blindsight type II). If this is related to the sensing reported by normal observers, it would suggest that V1 is not involved.

**Hilbert Questions**

If the visual experience we have of the world is less unitary in its qualitative aspects than traditionally believed, a set of important new questions arises as to the nature of consciousness in visual perception. As in the case of the original Hilbert questions in mathematics, answering these will likely take considerable work. But the answers may have the potential to greatly increase our understanding of both consciousness and attention:

1. **What are the different modes of visual perception, and how are they related to each other?** If there are several distinct modes of visually experiencing the world (e.g., coherent experience, ambient experience), it is important to determine how many of these exist, along with the characteristics of each (speed, sensitivity, etc.). It is also important to determine how these relate to other distinctions that have been made, such as access consciousness and phenomenonal consciousness (Block, 1995) [note 3]. Related to this will be the determination of whether these modes are truly independent of each other, or whether dependencies exist between them (e.g., whether coherent experience requires ambient experience as a necessary precondition).

2. **What are the different kinds of visual attention, and how are they related to each other?** In some ways, this is the behavioral analog of the question above. Traditionally, visual attention has been difficult to define and characterize; it has been suggested that this may be largely due to the lumping of several different processes under this name

(Allport, 1992). An important step in understanding the nature of visual perception is therefore to determine whether there are different kinds of attentional process. This might be approached by defining “attention” in terms of selective processing (Rensink, 2003) and seeing how many different forms there may exist in human vision. The goal here would be a taxonomy of attentional processes, complete with a description of what each process does, and how they relate to each other.

3. **How do the modes of visual perception relate to the kinds of visual attention?** There has traditionally been great interest in the relationship between attention and consciousness—in particular, whether attention is both necessary and sufficient for conscious awareness to occur. Some recent work has suggested that this may not be the case (e.g., Lamme, 2003). However, given that distinctions have not been made between different modes of experience or between different kinds of attention, a close association may still exist between particular kinds of attention and particular modes of experience. Given the number of relationships possible, this will likely take considerable work. However, once determined, these relations will likely give us new insights into the nature of attention and consciousness.

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## Notes

1. The notation here is intended to improve upon the usual order-of-magnitude estimates by providing the range as well as magnitude. Here, D represents variation over a factor of ten (or *decade*); more precisely, it is used to represent the range 1-10. Larger ranges can be represented by D^2, D^3, etc.

   In the interests of simplicity, time has not been explicitly handled in this treatment. Instead, it is assumed that whatever the information rate, sufficient time has passed that the representation at any point has built up to its asymptotic precision.

2. Some authors (e.g. Hollingworth, 2004) fail to distinguish between "item" and "object". While 3-4 items can be held in attention (or visual short-term memory), these are not completely independent; rather, they are linked into a higher-level structure, perhaps by pooling their properties into a single nexus (Rensink, 2001). Because of this, the number of relevant structures is either 1 or 4, depending on the nature of the task. The possibility of such a structure was pointed out by Yantis (1992), who noticed that a set of 3-4 tracked items gave rise to a single "virtual polygon" that could affect tracking efficiency.

3. Ambient experience may be related to "raw qualia", or the phenomenonal consciousness (or "P-consciousness"), while coherent experience may correspond—at least to some extent—to access consciousness (or "A-consciousness"). However, better operational definitions of the modes will be needed before these correspondences can be firmly established. Also, a simple correspondence will be unlikely be to complete if more than two kinds of modes exist.