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Seeing Seeing

Abstract

This paper discusses several key issues concerning consciousness and human vision. A brief overview is presented of recent developments in this area, including issues that have been resolved and issues that remain unsettled. Based on this, three Hilbert questions are proposed. These involve three related sets of issues: the kinds of visual experience that exist, the kinds of visual attention that exist, and the ways that these relate to each other.

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The past few decades have seen considerable 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 improvement in our understanding of how we see, and the way that attention and consciousness enter into it.

Amidst all this, however, confusion has arisen on several fronts about particular issues, and even to some extent about the bigger picture that is emerging. Part of this stems from inconsistencies in several of the technical terms used, which have retained some of the vagueness and ambiguity found in their original use in everyday life. Another cause is the fact that many results were converged on by researchers from different traditions, bringing with them different terminologies and different 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 highlight several of the important questions that still need to be answered.

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Rapid Vision

When discussing human visual perception, a natural place to begin is *rapid vision*, which comprises those processes occurring within the first few hundred milliseconds of stimulus onset (see e.g., Rensink & Enns, 1995, 1998). This aspect of vision is dominated by a "first wave" of feedforward information flow, which reaches all areas of cortex within 150 milliseconds (e.g., Lamme & Roelfsma, 2000). Rapid vision itself can be further decomposed, based on distance from the initial retinal input. Processes at the lowest levels involve retinotopic representations; at higher levels, they become increasingly spatiotopic, involving relative rather than absolute quantities. 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*, that is, 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). It has been found, however, 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 identification of shadows (Rensink & Cavanagh, 2004). Although earlier studies suggested that attention was needed to bind together simple properties at this level, the existence of these more sophisticated properties shows that this is not the case. Indeed, immediate access of attention (and perhaps consciousness) appears limited to these proto-object properties, with access to the underlying image properties requiring 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, likely 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.[2] Each

[2] 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

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, about 10^3 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 invariant 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 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 judgments involve complex stimuli presented for a time insufficient to attend to more than 2-3 items, suggesting 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, that is, 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 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 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. Inattentional blindness, however, can be induced even for stimuli that are expected (Rensink, 2005), indicating that this, too, corresponds to a failure of perception. It, therefore, appears that all forms of induced blindness do indeed support the claim that attention is necessary for visual experience.

Meanwhile, it remains somewhat unclear as to whether attention is sufficient for such experience. Part of this is due to an ambiguity regarding whether the entities involved are

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represent the range 1-10. Larger ranges can be represented by D^2, D^3, and so forth. In the interests of simplicity, the dimension of time has not been explicitly handled here. 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 level of precision.

physical or psychological. For example, it is believed that an object must be attended to be seen to change (e.g., Rensink et al, 1997, Simons, 2000). But consider the word "object." If it is taken to refer to a structure in the external world, then attention is clearly not sufficient for change perception: An observer can easily miss changes in an attended structure in the environment if the changing properties are not represented (Levin & Simons, 1997). If, however, an object is taken to be an internal representation of such a structure, then attention is sufficient, assuming that the creation of such a representation is what attention does (Rensink, 2000b, note 13; however, see Schankin & Wascher, 2007).

But what does attention really do? An important issue here is whether there exists just one kind of attentional process, 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 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 failure to perceive the structure of an object, even when its constituent properties are experienced (*integrative agnosia*). The different characteristics of these two deficits suggest that two kinds of attention may exist: one dealing with selective access to unstructured visual "stuff" (*ambient attention*), and one with selective creation of structure (*focused attention*), This may explain why observers in some experiments report detecting "something" in stimuli that were not given focused attention (Neisser & Becklen, 1975): ambient attention was still being applied. It can likewise explain why 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, attention has been posited to enable change detection by creating a coherent "circuit" of information that connects higher and lower processing levels (Rensink, 2000c). The formation of such a circuit for each item in a display (possibly resulting in visual short-term memory) 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 (*coherent attention*), 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). 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 visual object with up to three or four parts.[3]

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

The amount of information associated with an item receiving coherent attention is unknown, but some studies (e.g. Hayhoe et al., 1998; Vogel et al., 2001) suggest something less than 10 bits per item. Given the existence of three to four items, the total amount of information held this way is therefore likely to be less than 30-40 bits, compatible with other estimates of conscious experience (see e.g. Norretranders, 1998).

Note that even in that absence of attention (and visual experience) of any kind, considerable processing still takes place. For example, the meanings of unseen words and pictures can affect other aspects of perception by 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 valence. Such *implicit perception* can take place rapidly (within 100 milliseconds), showing that rapid vision and visual attention are largely independent systems that operate 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 the 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 in great detail. Such an impression, however, gives rise to a problem: If visual attention is needed for conscious perception, and if visual attention is limited to about 30-40 bits, 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 (or coherent) attention to create object representations whenever they are requested (Rensink, 2000c). This 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, since this kind of representation is too fragmentary. What is needed for this is a second system involving more structured and sustained representations created by visual attention, containing about 30-40 bits of information. This connects higher-level structure with lower-level detail (especially at the level of V1) and thus could support “seeing” in the usual sense, providing an experience of structure and even individual objects. Meanwhile, a third system, involving properties such as scene layout and gist, could use high-level knowledge and low-level salience to guide the allocation of attention, creating the right coherent representation at the right time. Note that if ambient attention is a separate kind of attention, 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, may not even have any visual content per se. It might be thought that such "guidance mechanisms" would contain a great deal of information. A relatively sparse system, however, 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 for its maintenance. Such a representation could contain information from D x 10 items, each needing perhaps 20 bits to describe its properties (color, shape, etc) and location. In accord with this, experiments indicate that at least four items may be kept in such a memory, along with the four items being attended (Rensink, 2000d; Tatler, 2002). Newer estimates raise the total number of items to 10 (Hollingworth, 2004), and this estimate may climb higher yet. But even if 50 such items existed, such a representation would still be relatively sparse: The total information content would be unlikely to exceed 1000 bits, less than one 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 nonvolatile representation.

The existence of representations without any manifest visual content may also explain 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). An increase in the false-alarm rate, however, 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 treating 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 and on event-related potentials appears to provide additional support for this position (Busch et al., 2009; 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, sparse and volatile, or sparse and nonvolatile. Contrary to subjective impression, however, they cannot be both dense and nonvolatile. Scene perception is based on the co-ordination of attention rather than the construction of dense, long-lasting representations. The belief that a dense, nonvolatile representation is formed (Levin, 2002) is a "meta-illusion," an illusion that ascribes properties of the world (dense, nonvolatile) 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 strands above, some important conclusions emerge about conscious and nonconscious processing in visual perception. First of all, 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, many of which take place relatively quickly. Third, different kinds of attention may exist, corresponding to different kinds (or aspects) of visual experience. Finally, the impression of seeing a great deal of information in dense, coherent form reflects only the nature of the world. Its underlying representation appears to involve 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 coordinated 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 can be placed into one of just a few experiential categories. These might best be viewed as submodalities (or *modes*) of visual perception, which operate at least somewhat independently of each other:

1. *Structural experience*. This is the experience of coherent structure, for example, 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 it is not present 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 object at a particular location in space.

2. *Ambient experience*. This is the experience of unstructured (or fragmented) qualities, namely, 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*, that is, the 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) 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 it would rely on nonattentional or subattentional mechanisms. One form of this might be the rapid estimation of statistical quantities or gist, which do not involve a strictly visual quantity. Another might be the sensing of change that can apparently occur in the absence of visual experience. 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 experience we have of the world is less unitary than traditionally believed, a set of important new questions arises. As in the case of the original Hilbert questions in mathematics, answering these will likely take considerable work. But the answers have the potential to greatly increase our understanding of both consciousness and human vision:

1. **What are the different modes of visual perception, and how are they related to each other?** If there are distinct modes of visually experiencing the world (e.g., structural experience, ambient experience), it is important to determine how many of these exist, along with the characteristics of each (speed, sensitivity, information content, etc.). It would also be important to determine how these relate to other distinctions that have been made, such as access consciousness and phenomenonal consciousness (Block, 1995).[4] Related to this will be the determination of whether these modes are truly independent of each other or whether dependencies of some kind exist between them (e.g., whether structural experience requires ambient experience).

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, possibly because several different processes have been lumped together under this name (Allport, 1992). An important issue is, therefore, 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 may exist in human vision. The goal here would be taxonomy of attentional processes, complete with a description of what each process does, and how they relate both to each other and to other selective processes, such as visual short-term memory.

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 visual experience. Some recent proposals have suggested that this may not be the case (e.g., Lamme, 2003). Given that distinctions have not been made, however, between different modes of

[4] Ambient experience may be related to "raw qualia," or phenomenonal consciousness (or "P-consciousness"), while structural experience may correspond, at least to some extent, to access consciousness (or "A-consciousness"). Better operational definitions of the modes, however, will likely be needed before such correspondences can be firmly established. Also, a simple correspondence will be unlikely if more than two modes exist.

experience or between different kinds of attention, close associations 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. Once determined, however, these relations will likely give us important new insights into the nature of attention and consciousness.

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