Challenges of Visual Experience

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**Introduction**

 Many major advances in science have resulted from the rigorous exploration of unexplained

phenomena that challenge contemporary beliefs. At any time, there are some scientific questions that are unapproachable and others that are unsolved and present direct challenges to existing paradigms. The general mind-body problem is known to be intractable and currently mysterious (35). This is one of many deep problems that are universally agreed to be beyond the modern purview of science, including quantum phenomena, etc. But all of these famous unsolved problems are either remote from everyday experience (entanglement, dark matter) or are hard to even define sharply (consciousness, free will, etc.).

 In all of science, but particularly in Cognitive Science, theory and experiment needs to be done at multiple levels of abstraction. A critical challenge is establishing consistency across levels of investigation. In this paper, we will consider some ubiquitous aspects of vision that arise every time that we open our eyes and yet are demonstrably **incompatible** with current theories of neural computation (20) and thus present the kind of challenge that could lead to significant progress. The focus will be on two related phenomena, known as the *neural binding problem* and the *illusion of a stable visual world*. I, among many others, have struggled with these issues for more than fifty years (1, 2, 3, 34).

 Somewhat paradoxically, the continuing progress in scientific methods and knowledge reveals that these are both unsolvable within current neuroscience (36). By considering some basic facts about how the brain processes image input, we will show that there are not nearly enough brain neurons to compute what we experience as vision. These facts should induce humility about the prospects for our current neuroscience to yield a complete reductionist account of even concrete aspects of vision and other thought processes. More constructively, the demonstrations and discussion below suggest possible new theories, models, and experiments.

**Demonstrations**

 The visual system can only capture fine detail in a small ( ~1 degree) part of the visual field; this is about the size of your thumbnail at arm’s length. “The Illusion of a detailed full-field stable visual world” refers to our subjective experience of a large high-resolution scene. Let’s first consider Figure 1a. Your vision is best in the center of gaze and the small letters in the center of the figure are easy to read when you look directly at them, but not when you look to the side. The letters away from the center are progressively larger and this describes how much coarser your vision becomes with eccentricity.



Figure 1a. Size for Equal Visibility with Eccentricity

You can experience this directly using the line of text in Figure 1b. Cover or close one eye and focus on the + in the center from a distance of about 12 inches. While holding focus, try to name the letters to the left. You should be able to do much better with the progressively larger letters to the right of the +. In ordinary vision, there is no problem because we change our gaze several times a second, as you can experience in viewing Figure 2.

Figure 1b. Demonstration of Visibility with Eccentricity

 **U Q C G O** + **C O** **U** Q G

 A possibly more striking demonstration can be seen in Figure 2 below. There are 12 black dots at various junctions in the grid, but you cannot see them all at once. You do see black dots when you are focused near one, again because your vision is much better there. However, no one fully understands why you perceive some imaginary grey circles outside the focus area.

 Figure 2. There are 12 black dots, but you cannot see them all at once (39).



 More generally, representing more information requires more hardware, which is why new phones are marketed as having cameras with more megapixels. This is also believed to be true for the neurons in the brain and will play a major role in the discussion. There is a great deal known about how the human brain processes visual information, largely because other mammals, particularly primates, have quite similar visual systems. We will focus on what is called primary visual cortex or V1. Looking ahead, Figure 4B shows a flattened and projected view of the human brain with V1 on the far left.

 Unsurprisingly, the brain realizes this high central resolution using many, densely packed, neurons. The central portion of the retina in the eye is called the fovea and the downstream target of these foveal neurons in V1 of the brain is called the foveal projection.



Figure 3. Tootell et al. Experiment (4)

An important aspect of this architecture can be seen in Figure 3. The upper part of the figure depicts an oscillating radial stimulus, also with more detail in the center, which was presented to a primate subject. The lower half of the figure shows the parts of visual cortex that responded strongly to the input. As you can see, by far the most activity is the foveal projection on the far left, corresponding to the detailed image in the center of the input stimulus (red arrow). So, vision is most accurate in a small central area of the visual field and this is achieved by densely packed neurons in the corresponding areas of the brain (4).

 However, our visual experience is not at all like this. We experience the world as fully detailed and there is currently no scientific explanation of this. But there is more - we normally move (saccade) our gaze to new places in the scene about 3 or 4 times per second. These saccades help us see and act effectively and are not random. But again, our experience does not normally include any awareness of the saccades or the radically different visual inputs that they entail. Taken together these unknown links between brain and experience are known as “the illusion of a detailed stable visual world” and this is universally accepted, if not understood.

There is extensive continuing research on various aspects of visual stability (6, 7, 8, 9, 10, 11). None of this work attempts to provide a complete solution and it is usually explicit that deep mysteries remain. Reference 9 is an excellent survey of behavioral findings and reference 11 has current neuroscience results.

We are attempting here to establish a much stronger statement. These stable world phenomena and a number of others are **inconsistent** with current theories of neural processing (20). The demonstrations below require combining findings from several distinct areas of investigation, as an instance of Unified Cognitive Science (12).There is always the possibility of a conceptual breakthrough, but it would entail abandoning some of our core beliefs about (at least) neural computation. Before digging in to the computational details, we consider some consequences of establishing that there is presently no explanation of such visual experiences.

**Why Inconsistency is important**

Throughout the history of science, crucial instances of inconsistency have led to profound reconsiderations and discoveries. One of the best-known cases is the fact that Rutherford’s planetary model of the atom entails that electrons rotating around the atomic nucleus would radiate energy and eventually crash into it. This was one of a number of deep inconsistencies that led to the development of quantum theory.

If there really are fundamental inconsistencies between visual experience (mind) and the neural theory of the brain, this presents a major challenge to the (currently dominant) theories that the mind is constituted entirely from the activity of the brain (38). As usual, Dennett is unequivocal: “Our minds are just what our brains non-miraculously do “(42, Preface). No one has suggested how this postulated mind/brain interaction would work, and we will show here that the examples above cannot be explained within current theories. There is always the possibility of a conceptual breakthrough, but it would entail abandoning some of our core beliefs about (at least) neural computation.

There is a plausible functional story for the stable world illusion and the related binding problem to be discussed below. First of all, we do have an integrated (top-down) sense of the space around us that we cannot currently see, based on memory and other sense data – primarily hearing and smell. Also, since we are heavily visual, it is adaptive to use vision as broadly as possible. In fact, it would be extremely difficult to act in the world using only the bulls-eye images from Figure 1 and separated information on size, color, etc. The mind (somehow) encodes a more accurate version of the world than can be directly captured by our limited neural hardware.

We should not be surprised that our subjective experience deviates from the information captured and processed by the visual system. Our senses and the nervous system in general evolved to help our bodies function effectively in a physical and social world that we cannot directly observe (34, 44). There might well be some equivalent “illusions” in the brains of other animals that exhibit intelligence.

At a much deeper level these visual illusions might be related to the postulated “illusion of Free Will” (43). Everyone agrees that we all act as if we had Free Will, even determinists who deny that they have this power – hence the illusion story. More generally, given that such mental illusions are evolutionarily fundamental, what can we know about their physical realization?

**Computational Limitations**

We will now prove that some everyday visual experiences cannot be explained within current science. The basic form of the argument will be computational. There is no way that brain neurons, as we know them, could represent or compute the substrate of our visual experience. The constraint of explaining visual experience also **rules out** many proposed and speculative theories of neural computation in the human brain, as discussed below. To explore the details, we turn next to Figure 4 A, B.

Figure 4 Flat map projection of the Human brain (5)



Figure 4A is a standard flattened projection of one hemisphere of the human brain with the various areas colored. The numbers refer to the traditional Brodmann classification of brain regions from their anatomical details. Modern methods have further refined this picture and elaborated the basic functions computed in different areas (32). Figure 4B provides more detail on the functional specialization in the visual system, which is the core of the neural binding problem, one of our mysteries.

The visual area V1, our main concern for the stable world illusion and the subject of Figure 3, is shown as the yellow area on the left of Figure 4A (as area 17) and as the magenta area in Figure 4B. Notice that V1 is by far the largest of the visual areas; this will be important for our discussion.

 There are two additional lessons to be gleaned from Figure 4 above. First of all, 4A shows that the functionality of the cerebral cortex is basically known (5, 32) – there is no large available space for neural computation of currently mysterious phenomena. Also, various aspects of our visual experience are primarily computed in distinct and often distant circuits. For example, color calculation is based in the bright green area V4v and motion calculation involves several areas: V3, V3A, MT, etc. In spite of this extreme separation of function, we see the world as an integrated image with objects that combine all visual properties and even associate these with other senses like sound when appropriate. The mystery of how this happens is called the “hard binding problem” (3, 40).

 Two immediate challenges to be addressed in “the illusion of the stable visual world” are the apparent stability over saccades and the detailed perception of the full visual field. One popular idea is to suppose that the perceived full field is pieced together as a mosaic of “bull’s-eye” views (Figure 3) from many saccades. There are two serious flaws in this story, one temporal and one spatial, as an explanation of the illusion. We only make about 3~4 saccades per second – this is too slow for stable vision (movies are ~ 20 frames per second). Also 3 or 4 such images would not yield nearly enough detailed information to build a detailed full field view.

 In addition, it would require a huge area of visual neurons to encode the detailed full field view that we subjectively perceive. We can give a quantitative estimate of what is involved. There are a number of alternative calculations, but they all confirm the basic point that fine resolution over a large visual field would require brain area several times larger than V1 (Figure 4).

Stan Klein, who has looked extensively at this issue (14), suggests the following analysis focusing on the retinal ganglion cells –RGC. The key equations from (14) are:

Thr(Ecc) = Thr(fovea)\*(1 + Ecc/E2) or

Sep(Ecc) = Sep(fovea)\*(1 + Ecc/E2)

where Thr (or Sep) is threshold (or separation) in minutes.

and Ecc is eccentricity in deg

and E2 is the eccentricity at which Thr or Sep double.

E2 is the number of degrees of eccentricity at which the spacing of V1 neurons or ganglion cells double. They found E2=0.7 deg for cortical cells and is about 1.0 deg for ganglion cells. That is, for ganglion cells the spacing would be s = 0.5 (Ecc + 1) min so at Ecc=0 the spacing is about 0.5 min and at 20 deg it is about 10 min, 20 times as much. This calculation suggests that it might require 20 times as much V1 area to capture the precision of the fovea out to 20 deg of visual angle.

From a slightly different perspective, the cortical magnification factor says that the resolution at 20 degrees eccentricity is 20 times worse than at the foveal projection. This is because of retinal under-sampling in the periphery; the detailed information is only captured at the fovea of the retina (13). Also, the dense neural circuits in the V1 foveal projection have about 200,000 cells per square mm, while at 20 degrees out it is more like 4,000 cells per square mm (15). This is a factor of 50:1 denser in the V1 fovea than in the periphery. The V1 foveal projection occupies about a quarter of region on the left in Figure 4. For the brain to encode our detailed perception out to 20 degrees would require an area roughly 12 times the size of V1. There is no way that an area nearly this large could fit into Figure 4.

 We can also consider the evidence from the hundreds of full-brain scanning experiments that are exploring which brain locations are active for various vision tasks (16, 17, 18). This precludes the possibility that a network large enough to capture a detailed image could remain undetected. The remarkable recent advances (32) describing a much more detailed parcellation of human cerebral cortex provides even stronger evidence against unknown visual areas.

 In summary, as long as we believe that more detail requires more neurons, there is no place in the brain that could encode a basis for the detailed large field image that we experience. This analysis disproves more than the idea of unknown brain circuitry that underlies our stable world illusion. It also refutes any plausible substrate for other proposals such as complete “remapping” which suggest that all of the information from one saccade is (somehow) mapped to the input coming from the next saccade (7, p.557).

 The binding problem is a closely related mystery of vision that we should consider, also based on Figure 4. Although the full computational story is more complex, it is basically the case that different visual features are largely computed in separate brain areas. The problem is that we experience the world as coherent entities combining various properties such as size, shape, color, texture, motion, etc. As before, there is no place in the brain that could encode a detailed substrate for what we effortlessly perceive. This also suggests that our subjective perception (somehow) intrgrates activity from different brain circuits. Various forms of the binding problem are also the subject of ongoing research (3,19)

**Alternative Theories of Brain Computation**

The discussion above is based on the standard theory (20) that information processing in the brain is based on complex networks of neurons that communicate over long distances mainly by electrical spikes and learn mainly through changes in the connections (synapses) between neurons. This theory also includes a wide range of other chemical and developmental factors, but none that would affect the basic results above. The standard theory is continuing to yield scientific and clinical progress, so any new proposal should be consistent with it.

There are a number of alternative proposals that deny the centrality of standard neural computation and several of these are being actively discussed (21, 22, 23). Two good sources for a wide range of alternative models are the Journal of Consciousness Studies and <http://consciousness.arizona.edu>.) . One reason for this interest in alternative theories is that almost everyone agrees that the standard model does not currently support a reductionist explanation of historic mind-brain problems like subjective experience and consciousness.

Alternative ideas on the basis for brain information processing include quantum effects and central roles for the glia, for the neuropil, or for microtubules. More general architectural suggestions include a global workspace model and the Tononi information model (21). Hameroff and Penrose (37) continue to develop their ambitious theory based on quantum effects in micro-tubules. Many proposals suggest some unspecified mass action of neural assemblies, following a long tradition (23). Edwards (28) suggests another approach – unified perception (and consciousness) are based on wave patterns in the membranes of individual cells. All of these presuppose that there is some substrate (NCC) for subjective experience in the brain, but there also more radical theories like that of Alva Noe (22). He claims to explain how "we enjoy an experience of worldly detail that is not present in our brains". Since the deep mind-brain phenomena of most common interest are not well defined, it has not been straightforward to evaluate any of these suggested alternatives to the standard model of neural computation, although none have been shown to even match the coverage of the standard theory.

The findings described earlier in this paper could yield concrete *touchstone* problems for proposed theories of representation, computation, and communication in the brain. Both the binding problem and the illusion of a detailed stable visual scene are omnipresent in daily experience, are functionally necessary, and have clear informational requirements. We could ask proponents of speculative brain models how their theory could account for these two concrete phenomena. That is, assume your theory is true and show how it helps explains these (or other) touchstone tasks. I have done this informally with several leading proponents of alternative models and have never heard even a vague claim of adequacy. Community acceptance of some such touchstone tasks could sharpen the discussion of information processing in the brain. Of course, the deep mind-brain problem remains a mystery, but we could require that proposed models of brain function address some of the concrete touchstone problems.

**Experiments**

 One major problem is a complete separation into careful experimental work on tractable problems and unfettered speculation on the deep mysteries of the mind. We need research on the omnipresent, but currently unexplained, everyday visual experiences. As mentioned above, there is a large range of experiments that explore various aspects of the binding problem

(3) and on the stable world illusion (6,7,10,11). None of these has yet helped with the core mysteries, but there is some recent work that has illuminated the boundary between the known and the unknown in related areas. These examples might suggest ways of approaching the problems raised in this paper. In the Fall of 2014, a seminar series and course at Berkeley (33) explored a number of such promising approaches to unsolved problems in visual experience.

 The general mind-brain problem is the deepest and most famous mystery involving the neural substrate of subjective experience. No one has proposed a general solution, but there are some recent experiments that constrain the possibilities. Cohen et al (24) explore the relation between awareness (consciousness) and attention. The mechanisms of (visual) attention are extensively studied and relatively well understood. An important aspect of attention are the saccades discussed above, which are often triggered without awareness. On the other hand, these unnoticed saccades show that there is no evidence of awareness in the absence of attention. This all suggests that attention and awareness are neither inherently linked nor doubly dissociable.

Another visual mystery that has been somewhat demystified is *postdiction*, in which a later stimulus seems to causally affect the percept of an earlier input. For example, a flashed letter can be masked by a somewhat (~100-200 ms) later image in a nearby position. Apparent motion is also postdiction since the trajectory cannot be computed until after the second flash. Shinsuke Shimojo has done extensive work on postdiction, recently summarized in (25). In one experiment, an artificial scotoma induced by TMS (Transcortical Magnetic Simulation) was filled in with the color shown later. The paper describes four compatible plausible neural substrates for rapid postdiction and also considers memory effects like “hindsight bias” that makes events seem more predictable after the fact.

This analysis is then extended to address the well-known controversy concerning action before awareness and its relation to the mystery of free will. The article suggests that the “sense of agency” is another instance of postdiction, resulting in an illusion of action before awareness. This does not solve the mystery of free will versus determinism(43), but does greatly sharpen the question.

Perhaps the most directly relevant research is that of the von der Heydt lab (26) on ambiguous figure-ground scenes like the duck/rabbit and face/vase images and the Necker cube. Employing wide range of behavioral, neural, and computational findings they have established that *border ownership* is the basis for these and a number of related phenomena, including object identification. They also describe in detail a plausible neural substrate. Convincing evidence was found for the requirement of top-down input in early visual areas V1 and V2 (Figure 4). Border ownership was also shown to be central to *filling-in*, as with the blind spot. The effects of border ownership were also shown to extend across saccades and to affect attention. Their finding of increased spike synchrony between neurons whose border ownership preferences are consistent with the stimulating object, even when the neurons are widely separated in cortex, is strong evidence for feedback grouping circuits and is relevant to aspects of the binding problem.

More generally, Simons and Rensink (30) have a deep and thoughtful discussion of the prospects and perils of scientific research on problems at the boundary of subjective experience. Their story on the developments around the phenomenon of “change blindness” suggests guidelines for the explorations suggested here.

There are also possible experiments more directly related to the binding and stable world phenomena. Other mammals seem to have visual behavior similar to ours and they might have some internal representations analogous to our subjective experience. With all of the multi-faceted work on, e.g., the mouse, there should be a way to explore this possibility.

**Towards a Science of Mind**

Since the concept of “Mind” inherently involves 1st person subjective experience, any science of mind must be able to incorporate such experience as evidence. We do not need to start with formal definitions of science, mind, experience, etc. – conventional understandings will suffice. The crucial idea is that science involves explaining and predicting evidence and that mind involves first person evidence. Looking back and ahead, the demonstrations in this article are examples of combined 1st/3rd person science.

For obvious reasons, we cannot base a science just on individual subjective experience. But it is feasible to define the 1st/3rd person notion of “consensual subjective experience”, abbreviated CSE. This is already done informally in several fields of psychology, etc. For example, our starting demonstrations rely on an implicit consensus that people normally experience the illusion of a detailed visual world and the illusory unity of perception. While correspondence with 1st person experience is sometimes a motivation for scientific studies (24, 25, 26, 30, 34), there is usually no explicit statement of the underlying CSE – this is what needs to be improved.

One immediate issue is how should the CSE be established. First notice that experimental methodology is always an issue in science – are the data being explained reliable and relevant? My suggestion is that the CSE under study be explicitly described in the research proposal or report. Part of evaluating the study is the reviewers agreeing that they experience the CSE as well. Similarly, readers of a 1st/3rd person research study should also expect to experience the presented phenomena. The proposed formulation of experimental studies of 1st person experience are compatible with both no-report and standard report (29) methodologies.

Another great advantage of studies based on explicit CSE, is that they can be used to show inconsistency between subjective 1st person experience and proposed explanations for the substrate of its realization. This article is claimed to include such a demonstration.

**Conclusions**

 There is general agreement that there are mysteries about the world and our place in it that are not yet understood. Even radical materialists will concede that there are questions (e.g. free will) that might never have scientific solutions. But it is not widely understood that, every time we open our eyes, we experience phenomena that cannot be explained with current neuroscience.

 As thinkers we must acknowledge that we do not know and may never know the answers to many deep questions about the world and ourselves (27). There are two basic ways to learn about the physical and social world, investigation and stories. Science is a uniquely powerful social tool of investigation, but is limited in scope at least at present. Of course, there remains a vast amount that can and should be explored and exploited scientifically.

 Carlo Rovelli (31) has expresses this more elegantly:

*“The confusion between these two human activities – inventing stories and following traces in order to find something is the origin of the incomprehension and distrust of science shown by a significant part of our contemporary culture. The separation is a subtle one: the antelope hunted at dawn is not far removed from the antelope deity in that night’s storytelling.*

 *The border is porous. Myths nourish science and science nourishes myth. But the value of knowledge remains. If we find the antelope, we can eat.”*

Stories can provide insights that are not directly testable, and this is certainly also important in science (38). The stories in art, mythology, religion, etc. have been and will remain powerful sources of guidance about how to live.

Everyone is entitled to their own (religious or other) beliefs, but there is nothing about our current ignorance that privileges one faith over all others. Belief in the inevitability of complete scientific answers (38, 42) is one such faith. There are beliefs (e.g. about the age of the Earth) that contradict established scientific knowledge and cannot be taken seriously. Somewhat surprisingly, there seems to be little support in cognitive and neuro science for "we simply don't know". This is despite the fact "we simply don't know and may never know" is the accepted response in physics for some fundamental questions. What has been most surprising is how many people prefer believing there must be an (inscrutable) reductionist answer rather than accepting the agnostic stance. This might be related to recent findings suggesting an innate human drive to find answers for unanswerable questions (44).

 But in the face of all that is unknown, we (following the physicists) would do well to appreciate both what is scientifically known and also the mysteries that remain. Ideally, results like those above will encourage theory and experiment on questions at the boundaries between the known and unknown.

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