

Introduction

Science is a crowning glory of the human spirit and its applications remain our best hope for social progress. But there are limitations to current science and perhaps to any science. The general mind-body problem is known to be intractable and currently mysterious. This is one of many deep problems that are universally agreed to be beyond the current 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 (phenomenology, consciousness, etc.).

In this note, we will consider some obvious computational problems in vision that arise every time that we open our eyes and yet are demonstrably **incompatible** with current theories of neural computation. The focus will be on two related phenomena, known as the neural binding problem and the illusion of a detailed stable visual world. I, among many others, have struggled with these issues for more than fifty years (1, 2, 3) and I now believe that they are both unsolvable within current neuroscience. By considering some basic facts about how the brain processes image input, we will show that, under the standard theory, there are not nearly enough brain neurons to compute what we experience as vision. These facts should induce skepticism and humility about the prospects for current science to yield a complete reductionist account of even concrete aspects of vision and other thought processes. More constructively, the demonstrations below suggest possible new theories 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 perception of a large high-resolution scene. Let's first consider Figure 1. 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 further from the center are progressively larger and this describes how much coarser your vision becomes with eccentricity.



Figure 1. Size for Equal Visibility with Eccentricity

You can experience this directly using the line of text in Figure 2. 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 viewing, there is no problem because we change our gaze several times a second.

Figure 2. Demonstration of Visibility with Eccentricity

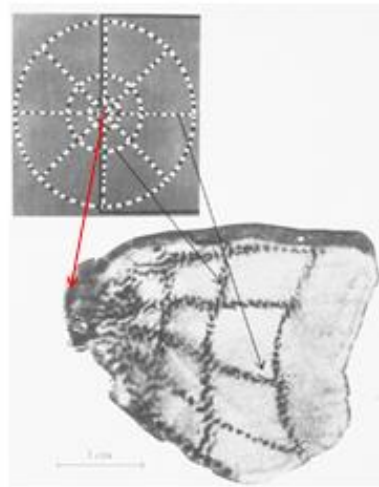


More generally, representing more information requires more hardware, which is why new phones are marketed as having cameras with more megapixels. This is also believed to be true for the neurons in the brain and will play a major role in the discussion. There is a great deal known about how the brain 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 its 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 standard theories of neural processing (20). The demonstrations below involve 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 is a major challenge to the (currently dominant) theories that the mind is constituted entirely from the activity of the brain. As usual, Dennett is unequivocal: "Our minds are just what our brains non-miraculously do" (30, 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 (32). 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" (31). 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)

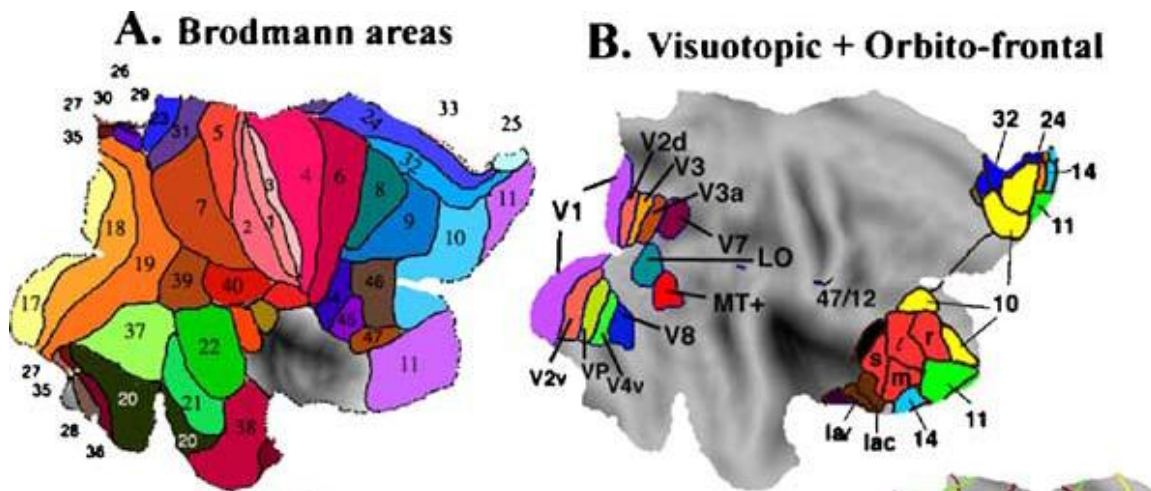


Figure 4A is a standard flattened projection of one hemisphere of the human brain with the various areas colored. The numbers refer to the traditional Brodmann classification of brain regions from their anatomical details. Modern methods (27) have further refined this picture and elaborated the basic functions computed in these different areas. Figure 4B provides more detail on this functional separation in the visual system, which is at 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 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, 27) – 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 interacting circuits. For example, in Figure 4B 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 experience 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).

There are two immediate challenges to address in “the illusion of the stable visual world”: 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:

$$\text{Thr}(\text{Ecc}) = \text{Thr}(\text{fovea}) * (1 + \text{Ecc}/\text{E2}) \quad \text{or}$$
$$\text{Sep}(\text{Ecc}) = \text{Sep}(\text{fovea}) * (1 + \text{Ecc}/\text{E2})$$

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 $s = 0.5 (\text{Ecc} + 1)$ min so at $\text{Ecc}=0$ 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 has 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 foveal projection 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. The remarkable recent advances (27) describing a much more detailed parcellation of human cerebral cortex provides even stronger evidence against unknown visual areas.

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.

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 can 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. However, 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) integrates activity from different brain circuits. Various forms of the binding problem are also the subject of ongoing research (3, 19)

A Touchstone for alternative brain theories

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.

However, 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 everyone agrees that the standard theory does not currently support a reductionist explanation of historic mind-brain problems like subjective experience and consciousness. The standard theory continues to yield scientific and clinical progress, so any new proposal should be consistent with it.

Alternative ideas on the basis for brain information processing include quantum effects (28) 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). Many proposals suggest some unspecified mass action of neural assemblies, following a long tradition (23). Cohen et al. (26) show how known results on summary statistics and peripheral vision explain some of people's ability to get the "gist" of a scene without capturing all of the detail of subjective perception.

Edwards (25) 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 are 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.

The findings described above 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 ubiquitous 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 explain these (or other) touchstone problems. I have done this informally with several leading proponents of alternative models and have never heard even a vague claim of adequacy. The general 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 neural computation address some of the concrete touchstone problems.

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 and possibly not with any science.

As thinkers we have no choice but to acknowledge that we do not know and may never know the answers to many deep questions about the world and ourselves (24). There are two basic ways to learn about the physical and social world: investigation and stories. Science is a uniquely powerful 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. Stories can provide insights that are not directly testable, and this is certainly also important in science. The stories in art, mythology, religion, etc. have been and will remain powerful sources of guidance about how to live.

Initial attempts to convey the ideas in this note have not been very successful. I find that scientists have a strong negative reaction to my simple demonstrations and philosophers and humanists welcome any attack on reductionism. But it seems like both responses are mainly territorial defenses. It does not appear to be too much of a stretch to view the (Eastern or Western) religious practitioners as another special interest group. It is certainly true that all these groups have emotional/spiritual as well as financial/power stakes in the big questions, but there might not be any support for "we simply don't know". What has been most surprising is how many people prefer believing there must be an (inscrutable) reductionist answer to accepting the agnostic stance. This might be related to the current theories (32) of a basic human drive for answers to unanswerable questions, underlying religions, etc.

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 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. 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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