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by

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HOW MIGHT THE BRAIN GENERATE CONSCIOUSNESS?

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Abstract

Anyone contemplating consciousness might well have some sympathy with a wasp, attempting sortie after sortie against an impenetrable glass window. What is the survival value of consciousness? How did it evolve? Could a machine be conscious? How can we even define the term? But perhaps the most tantalising question of all, and indeed one that might help elucidate this host of other problems, is: what is the physical basis of consciousness? The brain is an organ of the body like any other, but somehow it must, in addition, have some sort of seemingly magic ingredient that enables billions of its banal-seeming cells to provide the pivot and inspiration of your outlook, your personality, your life.

The issue of how a "mind" might emerge from a brain is hardly new (Metzinger, 1995). Yet still we have no idea what type of answer to expect that would be unequivocally acceptable. There are those, for the most part scientists, who believe that the solution lies in a "special" physiological mechanism that could act as a magic bullet (Crick, 1984; Llinás and Paré, 1991); an alternative more sophisticated approach, favoured by some philosophers, is to frame reasons to devalue the question (Dennett, 1991). In this paper I would like to suggest a third, alternative strategy.

I need to start with two disclaimers that could be discussed at length, but which, for our purposes, can be summarily put to one side. First, consciousness is impossible to define. However, I know that I am conscious and I assume that people would agree that they were conscious. Perhaps then it is simply best to give a hazy description of the phenomenon, something like consciousness being "your first person, personal world", and leave it at that. Secondly, let us assume that the brain generates consciousness and that it is not beamed in from outside. Rather, the physical brain is the only starting point. From a Yorrick-like position then, almost holding the brain in one's hand, I would like to explore here how far scientists, in particular neuroscientists, can make a contribution to understanding consciousness.

The problem for me arose 25 years ago now. I remember -while performing a dissection of a human brain- wondering whether if I'd got a bit of tissue underneath my fingernail, would that have been the bit that someone loved with? Would that be the bit that made someone fidget when they spoke? Would it be the memory of a hot summer day? How would the boring-looking, banal stuff relate to my special fantastic, personal and unique character?

The most obvious feature of the brain is that it is not homogenous, but composed of different regions (Greenfield, 1997). There are no intrinsic moving parts, nor no obvious way of knowing where to start to understand what is actually happening, what functions are taking place. Some scientists who are interested in consciousness have looked nonetheless at the workings of different brain regions, and if they found some novel mechanism, they have then effectively said "Ah ha! This is a novel mechanism not found before. Consciousness is novel. Therefore, one must relate to the other."

Although, by following this path, you might be acting as a good scientist and looking at different aspects of the way the brain is functioning, you would nonetheless be ignoring, - and this is why philosophers are often so dismissive of scientific approaches, so called "qualia", - the feel of the first person experience to you.

In my view any scientific explanation of consciousness is of course going to be very objective and embrace physical phenomena in the brain: but at the same time it must, nonetheless, somehow take account of the subjective. This is why consciousness has been such an anathema to scientists, because the whole essence of science is objectivity. And yet we are going to deal with a phenomenon that is subjective, so how can we proceed? The third alternative, that I personally favour, is to develop a means for, on the one hand, looking at various events in the brain that somehow marry up with, on the other hand, subjective feelings. But before we start at the science, we should look at what we expect of consciousness. Are there any properties that we could try and work out, which we could then use to go back to the brain and see if we can accommodate them?

As an initial step, I shall try to develop some possible properties of consciousness. The first might be location; if we are conceding that the brain is the physical basis of consciousness, then it must occur somewhere. So where is the consciousness centre? This is one of the recurring problems in neuroscience in general, namely, the difficulty of "location of function." People have, for a long time, tried to relate events in the outside world directly to certain brain structures.

Now, however, the functions manifest in the outside world, memory, vision, movement seem almost certainly not to be related in a modular way to single respective brain regions. We now know that many different brain regions all play roles in different aspects "in parallel" to generate a connected whole. So may it be too for consciousness. Since there is no committed brain tissue, it seems more likely that non-committed neuronal populations in some way contribute to the final process. Hence one property could be that consciousness is spatially multiple. On the other hand, one is only conscious of any one state at a time. The first possible property of consciousness might be then that it is spatially multiple, but temporally unitary. What about a second property?

If a dog is trained to put its paws to its ears at the sound of a violin, does that mean that it is having the same consciousness as a human being would who exhibited the same behaviour, putting hands over the ears: or would the dog have been trained like some Pavlovian automaton? What kind of consciousness, if any, would a dog be experiencing? And whilst we are thinking about dogs, let us also turn to rats. Rats are masters of survival. In potentially hostile conditions they are chillingly efficient; for example, they will not eat new foods. Instead, they will wait and see if a small sample has deleterious effects, and then go back only after three or four hours once no gastro-intestinal mishap has occurred. It is very hard to think of rats therefore as little automata. But is a rat really conscious in the same way that a dog is or, indeed, as a primate? It is very easy and dangerous to anthropomorphise, but anyone looking at enchanting pictures of a chimpanzee staring at itself in a mirror would be hard pressed to say that such an animal (who has only a one percent difference in its DNA from ours) is a computer or an automaton. But, again, is this consciousness the same as that of someone like George Bernard Shaw? How do we handle animal consciousness therefore, particularly when compared to our own?

In my view an unnecessary problem arises here because consciousness is often thought all or none: either you are conscious or you are not. A more plausible scenario, however, is that consciousness is more like a dimmer switch that grows as the brain does. The more complex the brain, the deeper the consciousness. If you go along with that idea, it circumvents many of the problems we have normally with animal consciousness. Think of a continuum of consciousness, ranging from minimal through to very profound, and that in turn will be reflected in the sophistication of the brain. Such a continuum of consciousness would help us with child consciousness, and indeed that of the foetus.

Foetal consciousness has in the past posed quite a conundrum. If a foetus is not conscious, then that suggests that a baby is suddenly conscious as soon as it is born, even though the brain does not undergo any sudden, conspicuous changes at all at birth. Alternatively, we have to assume a baby is conscious only at two or three months, say or at an even older age. Try telling any mother that her new born child is not actually conscious, effectively therefore a vegetable. Alternatively, a foetus would have to be conscious in the womb, in which case we would have to imagine what it might be *conscious of*. I think one can get round this riddle by saying that consciousness is emerging or growing as the brain is growing in the womb. Therefore the second property of consciousness is that it is continuously variable: it is a continuum. The corollary of this idea is that it is not just with seeming dichotomies: animals versus humans, children versus adults, where consciousness is actually placed along a continuum: but even you, as an adult, will have moments when you are more conscious than at other times. We are, of course, already used to talking in everyday parlance, about "raising" our consciousness, with drugs, religious experiences, or simply by listening to music.

What about a third property of consciousness? I suggest it derives from the fact that you are always conscious of something. You are not always conscious of everything, and it is a paradox in terms to say you are conscious of nothing. I would suggest you are always conscious of some kind of focus, epicentre or trigger: the third property of consciousness would then be that it derives from a specific stimulus.

These are three fundamental properties of consciousness that, if we are to posit any kind of physical basis of consciousness, we will have to somehow accommodate in the physical brain. But first, we need to bring them together. Here then is a formal description of consciousness, incorporating the three properties:

Consciousness is spatially multiple, yet effectively single at any one time. It is an emergent property of non-specialised groups of neurons that are continuously variable with respect to an epicentre.

We will take an "emergent property" to signify a property of a group of components that is not attributable to any individual component. For example, the sound of a symphony is not directly attributable to any one instrument; the flavour of a curry could not be attributable to any one single ingredient, but it is something that emerges collectively from a group of components that cannot be attributed to any single component. Simply, the whole is more than the sum of its parts.

I am suggesting then that consciousness is somehow an emergent property of a transiently recruited group of neurons that are not specialised, (because after all we know there is no consciousness centre), but rather it will depend on how many neurons are entrained around some kind of epicentre. Imagine a stone thrown in a puddle, and the rings that would spread out over the surface of the water. The extent of these neuronal "ripples" would determine your degree of consciousness at any one time. What scientific grounds are there to justify such a scenario?

Instead of thinking straightaway about the whole neural assembly, let us turn first of all to the simpler idea, that of an "epicentre", the stone in the puddle, the focus of consciousness. It is a simpler concept because in itself this epicentre is not going to generate any consciousness at all. On the other hand, we need to assign it some neural correlate as it plays an important part in initiating the steps that will lead eventually to a conscious state. The most obvious candidate for the neuronal epicentre, is the neuron, of which there are 100 billion in the brain. So is it the case that you have one neuron that becomes active when your brain receives a visual signal relating to your grandmother, for example? Although the starkness of this idea renders it attractive, it is nonetheless not the case that you simply have one neuron that will represent one object in the outside world. After all, it would be a rather precarious state of affairs since we know that one loses neurons throughout one's adult life: how sad for your grandmother if you lost the cell that registered her.

Instead, it seems it is not so much the single neuron that relates to a specific object in the outside world, but rather, circuits of neurons. By far the most dominant feature of brain tissue is the extremely dense network of fibres. You have some 10-100,000 connections between each of your 100 billion brain cells. Imagine the awesome number of permutations and combinations of different neurons that results to give the greatest possible flexibility and versatility in your brain. The same cell, which according to the simple model would have just slavishly been activated at the sight of your grandmother, can now participate in all number of circuits responsible for different objects.

Neuronal connectivity is a very important feature of the brain (Greenfield, 1997). As we develop in life, and learn to recognise different objects, circuitry will develop, connections between neurons will form that will relate to objects in the outside world. We know that post-natally, and especially in the case of human beings, it is the connections, not the neurons themselves, that are established as a result of experience. Hence these, experience-related connections account, to a certain measure, for your individuality, your particular fantasies, hopes, and prejudices.

However, once established, these connections are not necessarily fixed, but are subject to change over a fairly rapid period of time. For example, it has proved possible to take time-lapse shots of a neuron growing out to make connections, eventually, with other neurons. But in one particular experiment, a chemical has been introduced that is actually a well known chemical messenger in the brain, acetylcholine. At 60 seconds after acetylcholine has been introduced, there is a clear divergence of the neuron from its original path, in favour of that in the direction of the transmitter. By 90 seconds it is unequivocal in that the presence of this chemical has actually changed the destiny of that future neuronal connection. This sort of event, in itself, has nothing to do with consciousness of course, but simply shows how plastic your brain is during development, how it can be modified by the availability of certain chemicals, how it is not necessarily preordained or intransigently "hard-wired" (Zheng et al., 1994).

Even in adulthood, the brain remains adaptable and sensitive to the experiences of life, as seen clearly in a particularly elegant study with adult owl monkeys. In these animals, Michael Merzenich and his team recorded from different groups of brain cells responsible for each digit of the hand. The hands and mouths of all primates are very sensitive; both these parts of the body are exquisitly controlled in the brain. After all, compared with, say, the small of your back, you need much more dexterity in your hands and your mouth for day to day activities. The hand has a very extensive representation in the brain in terms of numbers of neurons that serve each digit. Merzenich mapped out how many neurons were allocated in each case; he then asked the monkey to perform a simple task of rotating a little disk with selectively two of the digits. Then he looked again, some months later, to see if the situation in the brain had changed.

In the area of the brain that is responsible for hand movements, it was the two digits that were manipulating the little disk, where there was an enlargement of that territory of the neurons. Hence, experience will change the number of neurons, the connectivity, in your brain, according to whatever circuits are the most stimulated and thus the most active (for a review of the critical experiment, see Kandel and Hawkins, 1993, pp.41-53).

Where does that leave us with the physical basis for an epicentre? I should like to suggest to you that the epicentre, the stone in the puddle, that which is going to trigger your consciousness at any one moment, is mediated not by a single neuron. Instead a group of neurons are responsible, the connections between which are relatively long-lasting. It takes a while to establish such contacts - seconds or so, if not longer - but once they are there, then they are fairly robust. However, such adaptive events are not at all over a time scale that we are going to want for consciousness, which is much faster. These neuronal configurations and re-configurations will enable associations to be built up during your experience. They are not the centre of consciousness, but they are going to trigger it. Such circuits are simply the neural substrate for certain objects for our sensory perceptions. If your grandmother comes into view, that hub of neurons will become activated, but you will not be as yet actually conscious of your grandmother.

What we really need to do now is to see how the activated hub of neurons could act as a stone in the brain puddle. How might this epicentre, once stimulated, corral up, transiently and temporarily, a much larger group of neurons that is going, in turn, to determine your degree of consciousness for that moment. Here our task is much harder because we have to think now in a time scale of subseconds. Somehow we have to think of a way of neurons banding and disbanding, very fast. Here is a quote from Ad Aertsen, which sums up the situation very well (Aertsen & Gerstein, 1991).

"Instead, we should distinguish between structural and anatomical connectivity on the one hand and functional or effective connectivity on the other. The former can be described as quasi-stationery, whereas the latter may be highly dynamic with time constants of modulation in the range of tens to hundreds of milliseconds. It appears that dynamic co-operativity is any emergent property of neuronal assembly organisation in the brain which could not be inferred from single neuron observation. ".

Our task then is to try to work out exactly how groups of neurons can be swiftly and temporarily recruited into an extensive congress. But first, perhaps we need to be convinced that it occurs. Let's consider an experiment by Frostig and colleagues, who made use of a powerful experimental tool that cannot be used in humans, voltage sensitive dyes (Frostig et al, 1991). When a brain cell is active, its voltage will transiently change. Certain dyes are sensitive to this phenomenon, in that they fluoresce when the neurons become excited. Instead of looking at simply one cell, as in conventional electrophysiological studies, a whole group of cells can be monitored instead.

Frostig shone a light at a frog and then studied the number of neurons in the brain that responded to that flash of light. They found something very interesting. A conventional way of looking at the brain would be to shine a light and note how the brain responds in a certain way at a certain time: end of story. But interestingly, over 500 milliseconds (which is quite a long time in terms of brain operations), Frostig observed that gradually there is an enhancement in the activity of large numbers of cells (Frostig et al, 1991) . It is not after all a simple light on-brain response - end of story, but rather a gradual recruitment of neurons occurs over about half a second. Of course, we do not know whether a frog is conscious or not, so what happens in humans?

A different type of experiment has been done by Benjamin Libet in California, with human subjects (Libet et al, 1979). Libet pricked the skin of these volunteers rather gently and recorded the activity of large parts of the surface of the brain using an electroencephalogram (EEG) via electrodes on the scalp. He found that there was a huge amount of activity in the area of the brain associated with the sense of touch. The experience, however, was not reported as consciousness. The subjects did not feel anything, although their brain was registering signals via the spinal cord of a certain part of the body being touched. It is this early component in the response that I would suggest is the equivalent of the "epicentre" in my model. But then over, once again 500 milliseconds, the activity evoked by the prick spreads away from the committed area (the somato-sensory cortex) to much larger areas of the brain. It is only at this stage, after 500 milliseconds, once the activity has spread extensively, that the person says "I am feeling a tingle."

If we consider these two experiments together, the slow lighting up of the frog's brain and the late dawn of consciousness in the human, it indeed suggests that we are validated in thinking of consciousness in terms of growing populations of neurons, the relatively gradual recruitment of neurons over about half a second that will only be linked to appreciable consciousness when they have reached a certain quantity.

However this scheme as it stands presents a problem because you could easily say, "Well, that's fine, but if that occurs consistently all the time, that suggests we'd have the same consciousness every time and I know that I never have the same consciousness, apart from very rare occasions perhaps of déja vu". It is possible to overcome this objection, but to do so we will find it easier to take recourse in yet another metaphor.

Instead of a stone in the puddle, imagine the epicentre as a boss who only has power via the number of managers he can contact on a telephone network. Such a boss would need to be powerful enough to sustain conversations with many managers and the managers to telephone sub-managers and therefore establish a buzzing network. At the moment the current model would be represented by the rather static arrangement of the same old boss, same old managers all behaving in the same stereotypic old way, like a sequence on video repeated over and over.

More realistic, however, would be the idea that the boss is trying to make phone calls, but that some of the managers are chatting, some have a hangover, some cannot be bothered to answer the phone, some are very keen to get a pay rise and pick up quickly: in general, there is a variability in the extent to which these managers and sub-managers will respond to the corralling, recruiting signals of the boss. This scene would inspire a more plausible model, because on no two occasions would the same number of neurons be corralled up to exactly the same extent in exactly the same way. How might we then go back and accommodate such a varying arrangement in the brain? Is there any neuronal mechanism which responds that fast, which can somehow modulate the activity of vast banks of brain cells?

In the traditional view of neuronal communication, electrical signals pass from one cell to another one at a time, a little like a baton changing hands in a relay race. What we need, if this model is valid, is to have an increasing number of batons changing hands all at once, over an ever larger group. We need something, let's say a chemical, that can bias large number of neurons to be activated simultaneously. Such a chemical will not in itself make neurons excited, but it will make cells more receptive to the recruiting signals of the stimulus epicentre, as these spread progressively out in all directions.

If we look at the brain it seems that there might be the machinery for just that scenario. Some chemical messengers, transmitters, have a fountain-like distribution in the brain, so that the transmitter in question is very well equipped to access large target areas and intercept other messages. It would therefore be appropriate for our purposes if just these very chemicals were somehow able to bias, 'modulate' neuronal activity. Indeed, many electrophysiological experiments have shown that they can. When any of these particular chemicals are present, the response of a neuron to a given stimulation, is far greater than when the same stimulation is given alone.

It is precisely these chemicals that are targets for drugs such as prozac, amphetamine, LSD for example - drugs that are well-known to modify consciousness. Furthermore, it is these chemicals that are associated with changes in biorhythms, changing with the sleep-wake cycles. If these chemicals can be manipulated by consciousness changing drugs, then it could be that the way they modify consciousness is to modulate the degree of neuronal corralling up that will finally determine the depth of your awareness at any one time.

To summarise the model so far: an epicentre, the hard hub of cells that are more long-lasting in their connectivity, are activated by, let us say, one of the senses - the prick on the skin, looking at something - that in itself will not generate consciousness. But if, at the same time, your arousal levels are such that chemicals are reaching a large group of cells, these target cells will be more sensitive transiently to the corralling signal of this epicentre. If enough neurons are recruited, consciousness will ensue for that moment.

In my view, therefore, the critical factor is not qualitative, after all it is very hard to find how you might miraculously turn water into wine of consciousness. It is much more sensible to think in terms of quantity of neurons. I cannot at this stage describe exactly how a large number of neurons has the emergent property of consciousness. On the other hand the model offers an appropriate framework, a kind of Rosetta stone, for marrying up these two sides of the coin, the physiological nuts and bolts of the brain, and what you are actually feeling, the phenomenology.

Let us see how far we can go with this model in extrapolating from the physiology, the physical brain, to subjective sensations. We can then go back again, taking a phenomenological experience, and see how we might explain it once more in terms of physiology. A good approach, as always in science, is to start with caricatures. So instead of trying to think simply of a "typical" consciousness, let us think of what kind of consciousness you might have if, for whatever reason, your neuronal assemblies (which reflect the extent of your consciousness) were abnormally small. What kind of consciousness might one have?

Starting with the physiology, the following factors would be important. First, the actual strength of the epicentre. One reason for a small assembly would be if the epicentre was weak. Is there any situation when we could be almost sure that it would not be very strongly driven? Common sense has it that when you are asleep you are not conscious, but that is not quite true. There is a certain form of sleep when you are not conscious. Your EEG, the brain waves, discharge as synchronous "slow waves" (hence the term, 'slow wave sleep'). But what is exciting, and perhaps unexpected, is that when you are dreaming and not kicking off your blankets, your EEG reverts to being identical to when you are fully awake. Hence dreaming, although we traditionally think of it as a form of sleep, appears instead to be a form of consciousness. We all know that when we dream we are certainly experiencing something; it can sometimes be extremely vivid and realistic. So could it be that dreams would be an example of a very, very small neuronal assembly? If we are talking of a continuum, could it be that dreams - because they have only a very weak hub, because in turn there is no strong external stimulus to drive or to excite a large group of neurons - could it be that dreaming is an example of the lower end of the continuum of consciousness?

In my view this is an attractive idea because no one has really come up with a very satisfactory concept to date of what dreaming is. Although people have reasons why we dream, I have not found anything particularly convincing to try to explain it in terms of consciousness. According to the current model, however, it would seem that as you are dreaming, there is a kind of meandering over your brain where, because there is no strong drive from outside, they are rather flimsy, fragile little bits of consciousness. This explanation would account for how somehow you can be on a beach and then suddenly in a house; suddenly your mother is there and suddenly she is somewhere else. At the time, that is all very real of course, but is not like the consciousness of reality, of being awake, when you have a continuity provided by the sobering input of your senses flooding in from the external world.

So much for when a neuronal assembly is small because of weak neuronal recruitment. What about if it was small because connectivity was modest? What examples are there in the brain when the connectivity of the brain would be abnormally sparse? We saw earlier that the new-born brain has very modest connectivity. In this case then, for potentially small neuronal assemblies, childhood would be a good example. For a child a toy placed in front of it, will be the centre of attention, the epicentre. But as soon as the toy is hidden, it no longer "exists" for that child, whereas someone with a more sophisticated or mature brain would have been able to internalise and have a name for that little toy and continue thinking about it. When a child is crying, we give it a bar of chocolate or point out a bird: it is a relatively easy matter with a child, if it is upset about something, to distract it with another sensory stimulus. But for an adult it is harder to stop someone being miserable simply by saying "Look at that bird", "Have some chocolate". I would suggest that less mature brains have smaller potential for large assemblies and therefore are much more dominated by whatever epicentre is triggered from the outside.

The common physiological base of a small neuronal assembly would suggest that in a sense, although dreaming and childhood are of course very different, they might in some way after all be similar in some regards. Interestingly enough, at about 26 weeks in utero, the foetus spends all its time in dreaming: this generous allocation gradually decreases in the early stages of post-natal life. Such an observation would suggest that the immature brain in the first year of life, and to a certain extent in the further nine years, is very different from our brains: because the connectivity is modest in one scenario and under-activated in the other, perhaps dreaming and childhood are not that dissimilar.

Could there be any further causes of abnormally small assemblies? We have seen the consequences of a weak epicentre or sparse connectivity. The other factor that we have not mentioned yet is how many of the modulatory chemicals are available. We have seen that these substances are related to arousal levels and biorhythms: therefore, perhaps if you are highly aroused or you are moving around a lot (both of which often entail each other), then there are so many potential epicentres bombarding you, that you do not have time to form an extensive neuronal assembly. Any nascent assembly would be competed for, elbowed out of the way by other assemblies: so although in this particular case, you have the connectivity and although the stimuli are very strong, they do not have time to form because they are jostled out of the way by the competition. The sort of scenario one can imagine to fit into this category are downhill skiing or bungy-jumping. In such activities, very powerful sensations are coming in in rapid succession and giving very little time for reflection on anything else. I would suggest that this is an extreme example of small neuronal assemblies, due this time to very high turnover.

One could therefore actually start to draw up a profile of neuronal assemblies that were abnormally small. I would suggest that the kind of consciousness that would dominate would be raw phenomenal consciousness - that is to say, an absorbing awareness of the outside world. This outside world would impinge very heavily on you, you would be very much at its mercy. You would not have a lot of "internal resources" of reflection and memories and thoughts; rather you would just be very reactive to whatever crossed your path, a passive victim of your senses. In a way this is precisely the situation in dreams, when one is very much at the receiving end of experiences, for instance in nightmares where one is being chased. Things happen to you, you observe things, but you are not really in control. When you are in such a state, you cannot reflect, think or rationalise away the fear.

Interestingly enough, such a profile also could be applied to another condition: schizophrenia. Schizophrenia can be characterised by abrupt shifts in logic, often by the person thinking themselves divine because the outside world appears glowing and special. The patient is dominated by external events and images. Frequently, they will feel at the mercy of outside forces, completely out of control, mere victims. Here too then the underlying consciousness might be one of abnormally small neuronal assemblies. Indeed, we know in schizophrenia, by inferring from the efficacy of certain types of medication, that there is to a certain extent a problem with the fountaining chemicals, in particular with the modulatory transmitter dopamine.

Having looked at the profile for small neuronal assemblies, it would follow that it is the opposite for an abnormally large neuronal assembly. Here the outside world would be more remote, in extreme examples it might appear very grey, very distant, the opposite of the glowing bright colours of the child's perspective and indeed that of the schizophrenic. There would be a strong continuity, a certain logic to what was happening, or a perseveration in what you were thinking about, and finally reduced movement because you would not be having the competition from lots of epicentres bombarding.

I would suggest that most of our normal lives are lived with a mix between small assemblies and large assemblies. You are walking home from work, plotting revenge against someone who has offended you and then suddenly a car screeches around the corner and you are thrown back into the immediate world again, and so on. But if we are thinking of caricatures, is there a scenario we can think of where overly large neuronal assemblies would dominate? I would suggest clinical depression offers a good example, where the patient will often sit in a slumped position. Frequently in clinical depression the patient will indeed say that the world seems grey, remote, and people a long way off.

In general, there is no single factor in determining the neuronal assembly size and, hence, your degree of consciousness. Rather, your consciousness is always varying, because it is controlled by a combination at any one moment of the available neuronal connectivity, the strength of the epicentre, how many neurons are wired up together, how strongly they are stimulated, your arousal levels and therefore how quickly these neuronal assemblies are turning over, resulting in the particular size they have time to achieve.

So much for the physiology. But if the model is a true Rosetta stone we should be able to use it in the other direction. Can we take a phenomenon, some experience of consciousness that we have, and cater for it by explaining it in terms of a neuronal assembly? One experience we all have, is pain.

There is an experiment showing a very interesting aspect of pain. What happened was that at different periods of the day, the subjects had cold stimulus or electrical stimulation applied to their teeth, either for different periods of time or, in the case of the electrical current, at different intensities, until they said it hurt: this is called "the pain threshold" (Winfree, 1987). What is really interesting, apart from the fact that such individuals exist who would volunteer for such an unpleasant experience, is that the pain threshold varies enormously. In both cases, what they thought of as painful in the early hours of the morning or the middle of the night, was very different from what they would recognise as painful in the middle of the day. So your pain threshold changes enormously throughout the day. Your pain fibres do not change, they are still conducting pain signals into your brain in the same way. Rather, something in your head is changing: your consciousness is changing to this seemingly straightforward stimulation. What, of course, is changing is your biorhythms and your fountains of chemicals: I would suggest therefore that variable pain thresholds could be something to do with the recruitment of neurons that is possible at different times of the day, according to the availability of your modulatory chemicals.

We can list interesting features of pain, that could be viewed as "phenomenology". First, we have just seen that it is variable. The second is that quite often we refer to pain in metaphorical terms. We talk about it as "burning", "pricking", or "stabbing" - always in terms of something else. Another interesting feature is that pain is absent in dreams (at least in my dreams). You can see things happening, you can fear pain, but you never actually feel pain in your dreams. The actions of morphine, the well known analgesic, are also very interesting. People taking morphine do not necessarily claim that the pain goes away: they are still aware of it, but it does not matter any more to them. Finally, there are the well known cases of phantom limb pain, when amputees will still feel the pain of their absent limb within their brain.

These are all interesting aspects of the sensation of pain and, to a certain extent, they fit with the idea that perhaps the extent of pain could be again related to the extent of the neuronal assemblies available to you. Could it be that morphine, for example, modifies how easily neurons can be corralled up in the brain and therefore would give you a subjective sensation of a reduction in its importance? Similarly, in dreams, if you have a small neuronal assembly, could that account for why it is not of sufficient size to be associated with pain?

In conclusion, I think that there is no magic ingredient in the brain that mediates consciousness. A critical factor could be the number of neurons that are corralled up at any one time and it is the extent of those neurons that are corralled up that will determine your consciousness. The most valuable approach would lie in brain imaging - being able to image the brain in conscious volunteer subjects very precisely just as they were undergoing different tests that one could predict would modify their neuronal assemblies in certain ways. But at the moment the time and space resolution, although awesome in what has been developed over the past 10 years, is still not sufficient for consciousness.

At the moment, only voltage sensitive dyes (which cannot be used in humans) showing up areas of activity in response to an epicentre, such as a light at 152 milliseconds compared with 300 milliseconds, can be used. By virtue of such fine temporal resolution, such studies show, for example, that a second assembly will not form because the first is acting as a rival. That is the kind of precision, the sort of timing we are going to need to characterise how neuronal assemblies relate to consciousness. We are also going to need a very much finer spatial resolution of refined groups of cells, before we could really look at consciousness and its regulation in human subjects. However, there is no conceptual reason why the time and space resolution of brain imaging should not progress ever onwards and better. By using models such as that suggested here, we might then have some purchase on a true science of consciousness.

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