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## What is it Like to be Boring and Myopic?

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I see before me sitting on the laboratory bench a human brain – or rather a preserved human brain, readied for dissection, sporting a halo of straight pins and cheery red flags. I await the bell. When it rings, I will have one minute to identify whatever neuroanatomical structure is marked by the red flag bearing the numeral “8” – and around me stand thirty odd other students in front of “their” brains, similarly at the ready. Surveying the room, I cannot help but wonder: did any of these dear souls, whose brains now sit before us, ever foresee that one day *they* would be central players in this Kafka-esque scene?

Yet even as I ponder this question, I cannot quite grasp it. Looking at this very brain – cold, gray, and granular, stuck with pins and flags – it seems odd to think that *this* was once a *someone*, a thinking and feeling person. Stranger still to realize that there but for the grace of God go I, our roles reversed, this brain’s and mine. I know, of course, that this is true. This brain was once very much a person and, in some sense, I as an experiencing subject, am just such a brain as well. Still, I cannot quite comprehend this fact. How exactly is it possible?

### 1 Resolving a Tension

The problem of consciousness, simply put, is that we cannot understand how a brain, *qua* gray, granular lump of biological matter, could be the seat of human consciousness, the source or ground of our rich and varied phenomenal lives. How could that “lump” be conscious – or, conversely, how could I, as conscious being, be that lump? Moreover, because we cannot comprehend how a brain can be conscious at all – *the very fact of physically embodied consciousness* – it makes little intuitive sense to think that any *particular* facts about the brain would prove helpful in this regard. We now know, for example, that the brain is not an amorphous mass but an entity of enormous physiological and anatomical complexity, that the human brain has (by a low estimate)  $10^{12}$  neurons with an estimated  $10^{15}$  connections running between them. This piece of knowledge, however, does not meet with our intuitive problem.

In virtue of learning that the brain is quite complex, we do not thereby understand how the brain could be conscious. Similarly, if it were discovered that the human brain has certain unique functional properties (say, a capacity for self-referential reflection) or that a certain kind of neural event occurs only during episodes of awareness (perhaps the synchronous firing of neurons in the visual areas of the brain in response to visual stimulation) these would be intriguing discoveries. *But they would not dispel our sense of mystery.* How could these neural events, no matter how unusual or unique, bring about phenomenal experience? Physiological facts and the puzzle of consciousness seem to pass each other by. This is one side of the story, the problem of consciousness as portrayed by common intuition.

On the other side of the story, we, in our various materialist guises, believe that science must surely tell us *something* about consciousness. Granting the tenet that the mind *is* the brain, it surely follows that many facts about the brain are also facts about conscious experience. Moreover, there are certain cases in which purely physiological facts *do* seem to give us insight into the experience of other subjects. For example, because we know that the retinal cells of the macaque monkey are insensitive to light in the infra-red range, we think it unlikely that these mammals experience any visual phenomena resulting from perceived infra-red light. Just as we *Homo sapiens* cannot see the infra-red light, we can be relatively certain that the macaque’s visual experience does not contain episodes of this type. Similarly, when we realize that certain species of animals do not have the kind of retinal receptors necessary for trichromatic color vision, we no longer attribute to them visual perceptions of a “colored” world – perceptions, say, of the red, pink and orange hues of the setting sun.<sup>1</sup> Scientific facts, it seems, *can* tell us something about conscious experience, although exactly what science can say is not clear.

It is this tension, between our inability to comprehend how a material brain can be conscious at all (and hence to understand how physical facts could give us insight into phenomenal experience) and the realization that facts about consciousness both ought to be, and to some extent *seem* to be, accessible from the natural sciences, that is reflected in Nagel’s work on consciousness (1979a, 1986). In his famous article “What Is It Like to Be a Bat?,” that is, Nagel’s primary concern was with the first side of this tension: he sought to justify our intuitive sense of mystery by drawing a distinction between objective and subjective facts. Roughly speaking, objective facts are those with which science is concerned: the way things are in themselves, a way that is independent of our (or any other subject’s) perceptions of them. Thus to give an objective or scientific characterization of an event is to transcend its mere appearance, to abstract away from how the event is perceived given the particularities of the individual observer (e.g. where the individual stands relative to the event observed) and of the type of perceptual process used (e.g. human vision). The essential property of an objective characterization, says Nagel, is thus not intersubjectivity *per se* but externality or detachment: “the attempt is made to view the world not from a place within it, or from the vantage point of a special type of life and awareness, but from nowhere in particular and no form of life in particular” (Nagel, 1979b, p. 208).

In contrast, subjective facts – facts about phenomenology, conscious experience, “what it is like” for a certain creature – are essentially tied to a point of view. Unlike, say, the phenomenon of lightning, which has both an objective nature that can be apprehended from many different points of view (i.e. as a sudden discharge of

electrical energy) as well as a subjective one (its appearance *to us* as a blinding flash), conscious experience admits of no distinction between its appearance and the experience in and of itself. Conscious experience exists *as* appearance and hence as an appearance *to* some subject. (Says Nagel, 1979a, p. 173: "It is difficult to understand what could be meant by the *objective* character of an experience, apart from the particular point of view from which its subject apprehends it. After all, what would be left of what it was like to be a bat if one removed the viewpoint of the bat?") Of course, if, as Nagel claims, there is no objective nature to phenomenal experience – nothing that can be observed from several different points of view – then it is clear why the third person perspective of science is of little help in understanding phenomenal experience. Says Nagel, "any shift to greater objectivity – that is, less attachment to a specific viewpoint – does not take us nearer to the real nature of the phenomenon: it takes us farther away from it" (Nagel, 1979a, p. 174)<sup>2</sup>

The other side of the tension – the conviction that science *can* explain certain aspects of consciousness – surfaces in Nagel's suggestion about an "objective phenomenology." Perhaps, ventures Nagel, there might be properties of phenomenal experience that admit of scientific or objective scrutiny. On the face of it, of course, this is a very odd position for Nagel to advance: how could there be a third-person understanding of that which admits of only first-person experience? It was, after all, this very property of the subjective, its existence as appearance, that was to explain why we cannot comprehend embodied consciousness.

In explaining an "objective phenomenology," Nagel puts forward two different ways to incorporate the results of science. First, in "What Is It Like to Be a Bat?," he speaks of the "structural features" of our perceptions, presumably in contrast with their qualitative or intrinsic properties. If we could provide a description of these structural properties, Nagel says, then some kind of neurophysiological or reductive account might then be given.<sup>3</sup> (For example, one might give a description of the *logical* space of colors and then map that logical space onto a scheme for its physical realization, say as in Paul Churchland's (1989) color state space.) In *The View from Nowhere*, however, the project is a bit different: by abstracting away from the particular features of the human experience, we are to derive a conception of a point of view that, while still essentially perspectival, admits of many different instantiations. What we want to construct, in other words, is a general description – a picture of what it *is* to have a point of view, whether one's own or that of the bat.

Note that, on either conception, an objective phenomenology is intended only to give science its rightful due, *not* to entirely bridge the gap between the objective and subjective. No matter how far advanced, says Nagel, an objective phenomenology will always leave something out, namely the "particularity" or "specific qualities" of an individual's experience. *That* we could never comprehend. So it is this promise of a permanent explanatory gap that is intended to reconcile an objective phenomenology with the special nature of conscious experience. Some aspects of conscious experience must forever lie beyond our grasp.

The problem Nagel's view encounters in making room for scientific explanation – its apparent inconsistency – arises, I think, from the very nature of his task. Confronted with the tension between two *prima facie* competing intuitions, Nagel begins with a justification of our sense of puzzlement, with a general argument about the limits of scientific knowledge. Consider, however, exactly what this would require, the demands of the project. On the one hand, in order to justify the

essential mysteriousness of consciousness, the theory must show that the mystery is, *in principle*, one that science could never diffuse. It must give us good reasons to believe that there are some facts about conscious experience that will remain inaccessible to scientific investigation. On the other hand, in protecting such facts from scientific scrutiny, the theory must be careful not to deny the explanatory contributions science *can* make, the very insights scientific investigation will provide. What the theory must justify, in other words, is a certain principled divide – between those facts about consciousness that will be accessible to science (and hence human understanding), and those that will not.

Part of the problem with establishing such a divide is just that science itself has little to offer, at least not by way of present evidence for the broad negative claim. That is, in order to establish that certain properties of phenomenal experience would still be unexplained even with all the possible scientific evidence in hand, one would need, at the very least, a small but representative subset of data on which to draw. But the sciences that seem likely to shed light on the nature of consciousness (neurophysiology, neuroethology, neuroanatomy, and the like) are still in their infant states: they have yet to produce anything like a "complete" body of data on any species whose members are vaguely plausible candidates for conscious experience. (Surely neither the sea slug nor the leech!) So to date, we have not been in a position to judge – not even in a single case – what kinds of facts about conscious experience withstand empirical investigation and what kind do not. Such a divide must be discerned, then, on *a priori* grounds.

What, then, are the problems of an *a priori* argument? A theory that attempts to delineate what we can and cannot know about phenomenal experiences must inevitably take sides on any number of fundamental philosophical issues. It will necessarily prove to be (what one might call) "metaphysically expensive." Looking back at Nagel's theory, for example, the reader is asked to grant the following: the distinction between objective and subjective facts (as opposed to objective and subjective *descriptions* of the world), a characterization of science as trying to obtain a non-perspectival, sense-independent account of the physical world (a characterization that seems dubious for the sciences at issue, namely for biology, neurophysiology, neuroethology), the assimilation of phenomenal experience or "what it is like" with having "a point of view" (a pivotal notion that is left largely undischarged). The point here is not that only a conservative philosophy will do – on the contrary. Rather, the point is that, if progress can be made without the requirement of characterizing the nature of scientific practice, our knowledge of the world, the nature of the phenomenal realm, and so on, then *that* would be the more plausible strategy to adopt. Perhaps, for the present, we should simply set aside our puzzlement about how physically embodied consciousness is possible and approach the problem from the other side.

The strategy of this paper is to take the other route available: to follow our suspicion that science has something to say, and to simply ask what that might be. If one examined an admittedly incomplete body of scientific data – in this case, all the available literature on the neurophysiology and behavior of the bat – what would we learn about this particular case? What would we come to know about a bat's phenomenal experience – what it is like to be a bat – and what would we understand about phenomenal experience in general? The alternative route, in other words, is to accept Nagel's challenge – to pursue an "objective phenomenology" whatever

that turns out to be – to see how much we can learn about the phenomenal world of the bat.<sup>4</sup>

The advantage thereby gained is that we can avoid, at least temporarily, the metaphysical entanglements to which the more *a priori* approach is prone. For example, there is no need to discern the nature of scientific practice as a whole, in order to draw any conclusions about the particular case at hand, the phenomenology of the bat. We can simply *use* the results of science as given. Similarly, we can remain agnostic about the existence and character of any explanatory “gap” and concentrate upon what *can* be known, given the evidence currently available. And, finally, this empirical route allows us to investigate the kind of undischarged notions that often arise in discussions of human consciousness: for our purposes, Nagel’s notions of a “point of view,” the “structural” and “qualitative” features of conscious experience, “subjective” and “objective” facts and so on. In other words, the strategy allows us to see how these abstract notions meet with the concrete case, and to ask whether they hold up to the explanatory task. These are the theoretical advantages of the strategy. Now let us turn to the bats.

## 2 The Informational Problem: The Auditory World

When we think about the sonar system of bats – not about “what it is like,” phenomenologically, to have echo location but rather about the information-processing task that is performed by the sonar system – the temptation is to think of sonar perception as being somehow similar to human vision.<sup>5</sup> Since the early 1930s, when Donald Griffin first thought to plug the ears of a bat, we have known that the bat’s self-produced cries and its auditory system are essential to its perception of the external world: without its ears for guidance, the bat flies about, colliding at random with various objects.<sup>6</sup> For the airborne bat, echo location is a primary means of spatial perception. Hence it is natural to think that the information that the bat gains through auditory processing is probably very similar to what we obtain by visual means. What the bats’ ears do for them, our eyes do for us. Richard Dawkins in *The Blind Watchmaker* provides a good illustration of this intuitive view. In describing the bat’s sonar system, he writes:

[the bat] uses sound to perceive, and continuously update its perception of, the position of objects in three-dimensional space, just as we use light. The type of internal model that it needs, therefore, is one suitable for the internal representation of the changing positions of objects in three-dimensional space . . . Bats and we *need* the same kind of internal model . . . The fact that bats construct their internal model with the aid of echoes, while we construct ours with the aid of light, is irrelevant. (Dawkins, 1986, p. 34)

In other words, the intuitive view starts with an assumption about human vision, namely that its central task (although probably not its only one) is the perception of objects in three-dimensional space. Roughly speaking, light from a source (the sun or an artificial source) falls upon objects in the world and is reflected and absorbed by those opaque surfaces; then, via that reflection, some of this light arrives at our eyes, producing an image on the back of the retina. From there, the task of the

visual system is a kind of “reconstruction.” It tries to figure out, from the properties of the retinal image (plus, presumably, some tacit assumptions about the nature of the world), what the world is like – the nature of the environmental surfaces from which the light was originally reflected – and from there, the shape, location, and identity of any objects within the visual field.<sup>7</sup> (This is a view of vision that is more or less in accord with our understanding of ourselves: with what we think we see, when we stand with our eyes open, surveying the world.) The second premise of the intuitive view is simply that, because the bat also requires spatial perception to maneuver about the world, it too must have a sensory system concerned with the location and identification of the world’s furniture. Here, it is the bat’s own sonar signal that is reflected from the distal objects, and hence, the auditory system that must discern the various properties of any objects within the sonar field.

No one, I take it, would want to claim that bat audition is *exactly* like human vision – that it performs precisely the same information tasks. Based upon only the crudest of considerations, namely the size of the bat’s brain (the size of an aspirin tablet!), it seems clear that there must be *some* disparity between the computational powers of the two neural systems. And given this disparity, there are probably many aspects of human visual processing that are not tractable given the bat’s limited computational space. Something must be given up. So, what the bat must have, most people would probably say, is some kind of “downgraded” version of the human visual process. Perhaps it is a system that yields an “image” that has less spatial acuity than our own (like the difference between, say, a sharp photograph and one that is out of focus), or less detail (the difference between a photograph and a sketch of the same scene), or perhaps with a narrower field of “view” (like a picture taken through a keyhole instead of through the “wide-angle lens” of human vision), or . . . Still, it seems plausible that the purpose of the bat’s audition is object perception, the construction of representations of the shape, location, and category of objects in three-dimensional space.

When one stops to think about it, however, there is something very puzzling about this claim, something about the bat that requires explanation. Look around you. Among all the fuzzy (and not so fuzzy) creatures both vertebrate and invertebrate that inhabit the earth, the bat is a rarity.<sup>8</sup> Even for nocturnal species, evolution has “chosen” vision as the primary system of spatial perception. Most nocturnal animals (think here of the cat family, of owls, and rodents) have specialized visual systems to guide their activity in the dark – to detect prey, to maneuver about, to obtain information about the distal environment. Bats, on the other hand, rely upon sonar navigation in their nocturnal flights: while they also have eyes – they are not blind even if somewhat myopic<sup>9</sup> – they use audition as a central means of spatial perception. So why, one ought to ask, are bats so unusual? All things being equal – if sound and light were equally suited to the task of spatial perception – one would expect to find as many species adapted for echolocation as for vision. There must be some *reason*, then, why the bats are such an anomaly of adaptation. Thus, before we simply assimilate the function of the bat’s auditory system to the human visual system, we need to solve this puzzle – to ask about *spatial perception through auditory processing in the bat*. We need to find out about the specific problems that arise in using sound (as opposed to light) to gain spatial information and about the kinds of spatial information the bat’s behavioral repertoire requires.

Begin, then, by adopting the physicist's view of the world, a world that is not inhabited by the human ontology of middle-sized objects, of tables and chairs, but by more basic "furniture" and its interactions – the properties of sound and light, the variety of mediums they might pass through, the kinds of surface properties sound and light make contact with, and so on. Given this starting point, consider what the world of sound is like, how it differs from the visual world, and the informational problems inherent in auditory spatial perception in virtue of those properties.<sup>10</sup>

Most obviously, sound and light are quite different commodities. Light is electromagnetic energy, the narrow section of the electromagnetic spectrum between about 380 and 780 nanometers in wavelength, to which human visual receptors are responsive. It can be interpreted as either a transverse waveform or as a stream of photons, depending upon the phenomenon to be explained. In virtue of these properties, it is easy to see why light (on earth) makes a good source of spatial information.

For one, the sun provides a single light source that is reflected and absorbed by surfaces in the environment. The sun produces, as it were, a "bath" of light particles that surrounds the objects of the world, one that is directed and predictable in its spectral properties. Moreover, within the spectral range of electromagnetic radiation to which mammalian eyes are receptive, there are very few natural phenomena or objects that self-produce light that can interfere with the sun's illumination (fire and luminescent organisms being notable exceptions). The pattern and spectral characteristics of the light that reaches the receptors, then, can be used for, among other things, discerning object shape and texture (from shading information given the directedness of sunlight) and material composition (using the spectral composition of the reflected light).

Secondly, because light has such short wavelengths, in the nanometer range, it will be reflected by even very small objects, thus rendering them visible to the observer. Short wavelengths also guarantee a minimum of diffusion – the scattering of light – except under those conditions when the air itself is filled with small particles, say, in a fog or in a dust storm.

Thirdly, given the organic building blocks widely provided by nature, the development of a receptor for light is a fairly small investment, neurologically/evolutionarily speaking. There are many organic molecules that are sensitive to (change their shape in response to) electromagnetic radiation, thereby providing the first link in an electrochemical neural system.

Finally, the wave property of light allows light to be easily focused through a lens or small hole. This latter property is extremely important for spatial perception because it allows the position of the light receptor to receive information about the spatial position of the light source. In the normal course of events, that is, a receptor embedded into a flat surface receives light travelling towards it from all directions (except from behind it); so the receptor response does not indicate the angular direction of the light source. The addition of a lens (or a pinhole opening), however, eliminates this problem: light travelling through a lens in a straight line must fall in a specific spot given the lens properties. Thus the spatial position of the receptor indicates the spatial position of the light source in the visual field. What is important here is that this simple informational relation can easily be taken advantage of by

even the most neurologically simple organism. For example, the proverbial "fly detector" of the frog is a retinal ganglion cell activated by any small circular area of neural activation that moves across the retinal receptors; a looming shadow or predator detector can be made by monitoring the retina for any areas of "darkness" (lack of activity) that grow rapidly larger (a pattern that occurs when a large creature looms closer) and so on. Importantly, this simple correlation – between the position of the retinal receptor and the position of light source in the world – is an easy source of spatial information (position and depth plus shape) as well as of (rough) object categorization. When the fly goes by, that is, the frog "knows" where to swipe with his tongue as well as that he ought to.

Sound, on the other hand, makes for a fairly messy world. Unlike light, sound is vibration that originates with the deformation of an elastic solid (e.g. a tuning fork) and then propagates through a medium (such as air) in longitudinal waves. (The vibrations to which the human ear is sensitive are long compression waves with frequencies between 20 and 20,000 hertz.) The first problem, then, is that sound does not originate, like most natural light, from one reliable, principal source – there is no analogous homogeneous "bath" of sound that surrounds minute objects on the earth's surface.<sup>11</sup> For example, stop right now and concentrate on the many sounds occurring in the room around you. Even in a deserted and seemingly quiet office, I can now hear the hum of the air conditioning, a telephone ringing one floor above, a chirping bird outside my window, the computer's fan, rustling noises as I shift in my seat, etc. There is, when one stops to listen, an entire world of sound – sounds emanating from multiple directions, of numerous frequencies and intensities, that come into being each time an appropriate deformation occurs.<sup>12</sup> One consequence of this is that an organism that uses sound to retrieve spatial information must actively produce its own sound instead of relying on a passive receptive system, in order to ensure the kind of constant and predictable sound signal from which spatial information can be discerned. (Think here of an underground miner, finding his way around with only a head lamp for illumination.) Moreover, the organism must send a sound signal *out* to the environment and then wait to receive it *back*. Finally, the organism also faces numerous problems of interference from all the sounds that fall within the sensitivity range of its receptors – from random background noises and the signals of conspecifics in close roosting quarters, plus interference from its very own signals (one hears, as it were, the sound on the way out, as well as on the way back). These are all problems that need solution.

Secondly, because the propagation of sound waves involves the vibration of a medium, an actual movement of mass, sound waves have a high absorption rate – one that depends upon the nature of the medium, and the intensity and wavelength of the signal. Short wavelength (high-frequency) signals and low-intensity signals are most easily absorbed by a medium of propagation; longer wavelengths and high-intensity signals fare better. What this means then is that the frequency characteristics of the signal, plus an organism's ability to alter the intensity of the sound, will have a significant effect on the range over which a sonar signal can travel and on the nature of the echoes that return. (If one projected, say, a signal containing a number of different frequencies at a uniform intensity, one could lose, through absorption, all the high-frequency information in the returning

signal.) So, what goes around, comes around. The characteristics of the signal that the organism sends out will determine, in part, the kind of signal that the organism gets back.

Thirdly, sound vibrations, given their comparatively long wavelengths, are subject to high diffraction and diffusion. They bend around barriers instead of bouncing off them, they disperse in random directions (in fact, given a smooth enough surface, the scattering will be so complete as to make the barrier "invisible" to an echo-locating system – the auditory equivalent of glass). This is a fact that has a number of consequences for spatial processing, most of which are not particularly good. On the positive side, sound, unlike light, can travel around corners. One can hear what one cannot see, certainly an advantage for avoiding predators or tracking prey. On the down side, there seems to be no simple or informationally *immediate* way to precisely discern the spatial location of a sound source given the signal. For one, it is no simple task to focus a sound signal, the way a lens or pinhole can focus light.<sup>13</sup> Given a small aperture, for example, sound waves simply bend as they pass through the opening. Thus, when sound waves enter the ear, squeezing through the narrow canal opening, they diffract in all directions. Where a sound wave lands, once in the ear, gives no immediate information about where in the external world it originated from. Hence, unlike the retina, on which the position of an active receptor correlates with a position of the light source in visual space, auditory receptors do not yield immediate spatial information. Such data must be extracted by neural computation, based upon other features of the auditory signal.

High diffraction is also problematic because it tends to hinder echo formation. In order for a wave to be reflected from a target, its wavelength must be smaller than the size of that object (or, given that most objects are not spherical, smaller than the leading edge of the object). This makes life difficult for an organism that preys on small flying insects. One might think the trick would be to use sonar signals with a very short wavelength, so that they will be reflected by even the smallest objects. But the problem is that short wavelength signals do not make good travellers – even at high intensity, short wavelength sound waves are easily absorbed by the atmosphere. So, the selection of any particular broadcasting frequency will always involve a trade-off between range (how far the signal can travel) and "grain" (the spatial resolution that will be possible given the size of the objects that reflect the sound wave). There is no one signal frequency, even at high intensity, that will provide fine spatial information for small distant objects.

Fourthly, the type of medium that carries a sound wave vibration makes a difference to the signal, to its velocity of propagation. (This is the principle behind ultrasound.) For example, the velocity of sound through dry air at STP is 331.4 meters per second, in sea water it is 1,540 meters per second, and in fresh water, the velocity of sound is 1,401 meters per second. In this respect, sound does not differ from light. Indeed, this is the very fact about light that allows it to be focused by a lens: the "inner" edge of the light wave strikes the lens surface and slows, while the "outer" edge continues at its airborne velocity until it makes contact with the lens, thus causing the light to bend towards the slower moving side. (Think here of a treaded army tank, moving along in a straight line, when suddenly it hits a patch of mud with one tread.) For sound, however, this same property has none of the beneficial consequences, at least for the average small creature (see note 13 above). Moreover, if a sound signal is to be used for fine-grained information about range –

i.e. a calculation of the distance to an object based upon the time that it takes for the echo to return – any change in the medium of propagation must be considered. In this particular case, the case of bats, changes in air pressure, temperature and in humidity (say, if there is rain or fog) will affect the signals of bats that prey on airborne insects (such as moths), while bats that hunt for fish (by flying over the surface of the water and using sonar to detect fish just under the surface) must contend with signals that use dual mediums, water and air.<sup>14</sup> One can see, now, why evolution failed to fasten upon sound as its central strategy for spatial perception: compared to the relative compliancy of light, sound presents many problems.<sup>15</sup> The question about the bat's auditory function, then, is this: how does the bat overcome the inherent difficulties of this information-processing problem? What is the strategy that makes tractable, in only a bat-size brain, the extraction of spatial information from sound?

### 3 The Behavioral Strategy and the Signal Characteristics

The central strategy used to extract spatial information from sonar signals by echo-locating bats is the parallel sequencing of signals and behavior: the signal characteristics of the bat's outgoing cry are matched to the informational requirements of each stage of the bat's behavioral sequence. The bat's present behavior and its perceived state of the world, in other words, determine the kind of cry it makes, and this affects the type of information received in response. As a consequence of actively producing the sonar signal, what the bat *says* will determine, in no small part, what it *hears*.

#### *The Behavioral Strategy*

Across all species of echo-locating bats (and there are quite a number of different species, exemplifying a variety of sonar systems), sonar is used primarily during the pursuit of prey: in order to locate and track insects, moths, and other airborne prey, or to catch a fish swimming just beneath the surface (Simmons, 1989). Moreover, the behavior of each of these species during "the hunt" follows a similar pattern: initially the bat flies around *searching* for something of interest, say by flying around in the open air and "looking for" insects (the Search phase); then, once some prey is located, the bat must approach the insect and track it until the bat gets close enough to grab it (the Approach and Tracking phase); finally, once the prey is within reach, the bat must somehow make the final approach and get the insect into its mouth (the Terminal phase) (Griffin et al., 1960). Each of these stages of behavior (for any species) follows a fairly set routine (altered, of course, to fit the specific movements of the prey in each case). For example, the Little Brown bat (*Myotis lucifugus*), as it enters the Terminal phase of pursuit, often uses a somersault maneuver to grab the prey, a moth or, as in figure 7.1 a mealworm tossed into the air by the experimenters. The bat makes the final approach in such a way that its wing makes contact with the moth/mealworm. It then hits the mealworm with its wing, while somersaulting backwards, catching the prey in its tail pouch. And finally – dinner! – it bends over and eats the mealworm. The Little Brown bat also uses a number of alternative Terminal techniques: "the mouth catch" and "the tail membrane catch"

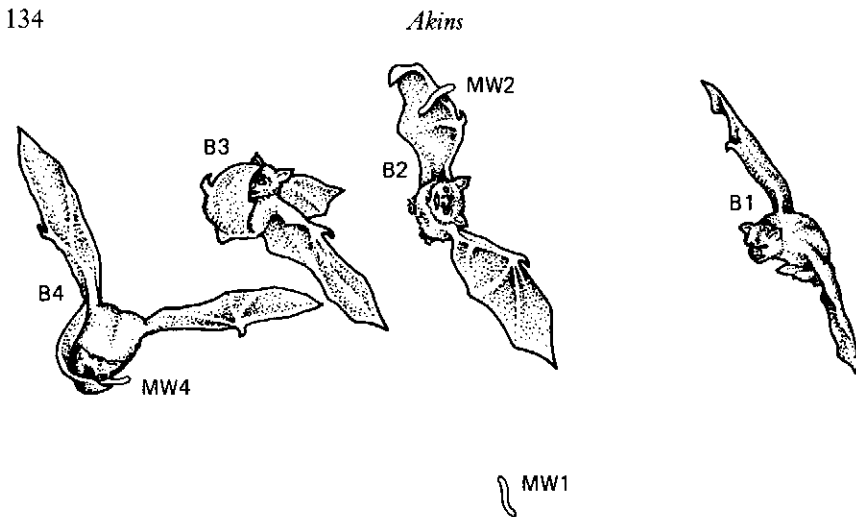


Figure 7.1 The filmed sequence of the Little Brown bat using a somersault technique to capture a mealworm. The sequence progresses from right to left, with the bat marked B1 and the mealworm MW1. (Reproduced with permission from Camhi, 1984; taken from Webster and Griffin, 1962.)

are two examples (Webster and Griffin, 1962; Webster and Durlach, 1963; Webster and Brazier, 1968). This is the standard behavioral pattern of the hunting bat – a stereotypic sequence of activities performed over and over again. Hence, the “boring” bat.

### The Signal Sequence

During each of these three hunting phases, the bat’s sonar signal is altered to meet the informational needs of the moment. What, then, are the sonar characteristics and how do they change with the behavioral sequence? First, the general properties of the sonar signal.

*There are two signal types, CF and FM signals* The two kinds of sonar signals used by bats are *constant frequency* (CF) signals, in which the cry is broadcast at one unchanging frequency or unchanging frequency combination, and *frequency modulated* (FM) signals that involve a “sweep” through a range of frequencies, starting with the highest “note” and progressing down through a series of signals to the lowest frequency sound. The constant frequency signal is ideally suited to measuring the *relative velocity* of the bat and its prey using the phenomenon of Doppler shift. This is the phenomenon whereby the frequency of the sound increases when the source and the observer are moving towards each other (a positive relative velocity), and decreases when the source and observer move apart (a negative relative velocity). (Thus the familiar sound of a train as it approaches the railway crossing and then crosses and travels away – a high pitch growing louder

followed by a low one becoming softer.) Relative velocity is calculated by comparing the frequency of the outgoing signal (the *broadcast frequency*) with the frequency of the echo – a calculation that is made easy by the unchanging frequency of the CF sonar cry. The FM signal, on the other hand, is better suited to determining fine-grained *range* information, the *distance* to the target calculated by measuring the time between the outgoing cry and the echo’s return (how long the echo takes reflects how far the sound has traveled). In an FM signal, each specific frequency marks a distinct place within the sweep, such that it can be used as a timing marker for the outgoing and incoming cries. The first occurrence of a certain frequency in the cry can serve to “start the timer,” as it were, while the next occurrence of that frequency in the echo “stops the clock.”<sup>16</sup> In this way, fine-grained timing information is possible.

*FM and CF signals contain harmonics* When a bat emits a CF or FM signal it contains a fundamental frequency plus two or three harmonics.<sup>17</sup> This means that the frequency range of the signal – and hence its informational value – is greatly broadened. It gives the bat the best of both worlds: high-frequency sounds for more fine-grained spatial information about near objects and lower-frequency signals for coarse-grained information about more distant ones. Moreover, by selectively altering the intensity of the various harmonics (the “loudness” of the parts of the cry), the bat can “focus” the signal towards specific aspects of the environment (e.g. by putting energy into the higher harmonics, the return signal will contain more information about the texture of a close object). Actually, this makes the situation sound better than it is, for despite this widening of the frequency range by the use of harmonics and even though the sound is emitted at the deafening intensity of about 100 decibels, the bat’s sonar signal still cannot travel very far. Even on a good day – when there is low humidity and an uncluttered field of “view” – even when the lowest harmonics are intensified, the bat is rather myopic: the furthest that most bats can “see” is about 3 meters.

*The type of signal used is species-specific* Both the CF and FM signals are used alone and in combination, the species of bat determining the basic type of signal used. There are numerous species of bats, living in diverse environments, pursuing a variety of prey. Some species hunt for insects in dense forests, while others forage in the open air; the diet of bats ranges from nectar and fruit, to insects, small vertebrates (such as reptiles and rats), and surface-feeding fish (Schnitzler and Henson, 1980). Compare the informational requirements of these diverse “lifestyles,” e.g. the sort of motion analysis required to intercept a fluttering moth with the requisite pattern analysis of waves on a lake’s surface needed to locate a surfacing fish; or the demands of high-speed navigation through a tangle of branches in pursuit of an insect as compared to the far less hairy demands of searching above an open field for a moth. Thus one finds species of bats that have FM signals, others with CF signals, and other species that use a combination signal, a long CF signal followed by a short FM “tail.” For example, the Little Brown bat, *Myotis lucifugus*, which catches insects in the open air, has an FM cry; the Mustached bat, *Pteronotus parnellii*, which pursues insects in dense vegetation, emits a CF-FM cry (the CF component is thought useful in identifying a fluttering moth against the high background clutter of the vegetation); and the fish-catching bat,

*Noctilio leporinus*, uses a CF and CF-FM signal while searching for prey (presumably for detecting surface ripples) and an FM signal for pursuit (Suga, 1990).

These are the general characteristics of the bat's sonar signals. When a particular bat approaches a target, as I said above, it changes its sonar signal in response to the phase of the pursuit, but exactly what changes are made and what are their consequences? In what follows we will look at the Mustached bat, *Pteronotus parnellii*, that emits a combination CF-FM signal, and examine the changes to its signal throughout its hunt. (Much of the material that follows is drawn from Schnitzler and Henson, 1980.)

*The search phase* As the Mustached bat flies around searching for an edible insect, it emits a rapid sequence of short signals known as "chirps." In the search phase, these chirps are emitted at a relatively slow rate 8–12 chirps per second. During this time, the CF-FM signal has a long CF component and a short FM tail. The fundamental frequency is just under 30 kHz, but the second harmonic, at about 59.5 kHz, receives the most energy. Thus, as a low-frequency signal, the cry is biased towards information about distant objects – what one would expect during the search phase.<sup>18</sup>

*The approach phase* Once an insect comes into "view," the Mustached bat points its head at the target, directing its cry, and follows its prey. As it does so, its cry alters along a number of dimensions. For one, the bat increases the number of chirps (short cries) per second in inverse proportion to the distance to the target – the closer the bat gets, the more frequently it chirps. Thus, as the bat closes in on its target, the signals become more physically dense – and presumably informationally rich as well. For another, the composition of the CF-FM signal changes: the CF component is shortened in length and the FM "sweep" is broadened, passing through a wider range of frequencies. In effect this shifts the informational focus of the signal. The signal becomes better suited to the extraction of fine-grained information about distance and texture (Simmons et al., 1975) but less well suited to information about velocity. Thirdly, the bulk of the signal's energy, which in the search phase resided in the second harmonic, is now shifted to the third and fourth harmonics. This means that it is the high-frequency sounds – those signals that have high spatial resolution but that travel only short distances – that are emphasized. In this way the content of the echo quickly shifts to fine-grained spatial information about nearby objects.

The approach phase also sees a change in the broadest frequency. As the bat makes progress towards its prey and as its relative velocity increases, the sonar echo comes back at a *higher* frequency (the Doppler effect). In response, the bat *lowers* its outgoing call (this is known as Doppler compensation), and by lowering the cry, the echo always returns with a frequency (for the second harmonic) at or slightly above 61.0 kHz. So no matter how quickly the bat overtakes its prey, the frequency of the signal remains almost constant. On the other hand, if the frequency of the cry comes back substantially *lower* than broadcast frequency, the Mustached bat does *not* respond with an increase in frequency. (The bat lowers its voice, as it were, but never raises it.) Evolution, it seems, has determined that anything that flies faster than the bat – that gets away from it – is probably not catchable. (Or for that matter, edible!) So it does not pay to track those objects with a negative relative velocity.

*The terminal phase* In the last stages of the pursuit, as the bat slows down to approach the insect and grab it, it emits a rapid burst of shortened chirps, up to 100 per second in the Mustached bat. These are cries that consist almost entirely of a brief FM tail. As soon as the prey is captured, the signals entirely cease.

While this gives the general sequence for the progression of the signal throughout the hunt, it should be noted that, within this basic framework, the bat adjusts its signal to the situation at hand. For example, if the moth makes a number of evasive movements and manages to lose the bat briefly, the approach phase continues until once again the bat has its prey almost within reach. Or if, at the last moment, the moth side-steps the bat, either the rapid chirps of the terminal phase continue or else its signals might revert back to those of the approach phase. Moreover, the Mustached bat also tailors its signal to the *kind* of objects/targets approached. Bats then, while they have stereotypic behaviors and signal sequences, are not genuinely "boring," for they adapt their signals and behavior to the situation at hand.

### Sender/Receiver Properties

Like any well-engineered system, there is a symbiotic relationship between the properties of the bat's sonar signals and the properties of the mechanisms that receive them. The bat's auditory system, in other words, is such that the transduction/sensory mechanisms "match" the sonar signals: they act as signal filters to either reduce the noise in the known incoming signal or to "shape" those sounds in some other beneficial way. In this way many of the problems inherent in the sound world begin to find solution, right at the transduction level or in the initial sensory steps. The following are some examples of these sender/receiver compatibilities.

1 When the bat tracks its prey, say a moth fluttering in front of it, the bat follows the prey with its nose. It directs its sonar signal in a high-frequency, intense and directed beam towards the moth, keeping the signal aimed on its prey throughout the moth's evasive movements, with the beam firmly focused just *below* the midline of the target. Given the way the bat's vocal system is constructed, this small sound field, focused upon the moth, has a center circular region of high sound intensity plus midlobes on either side of softer sounds (Figure 7.2A). When this signal is received back by the bat, the sound field is filtered first by the bat's outer ears or pinnae. The low-intensity "lobes" around the circular area of the sound fields are absorbed by the ears, leaving only the circular region of sound, rather like the visual field (only smaller) of a single eye (Grinnel and Schnitzler, 1977; Schnitzler and Grinnel, 1977). At the mid-brain level of sensory reception this signal is further refined. Here the receiver is maximally sensitive to signals returning just *above* the midline (Henze and O'Neill, 1990). This serves to balance the skewed sender properties so that the sound field becomes, in effect, a circular region with the highest intensity sounds directly in the middle, with decreasing concentric regions (Figure 7.2B). Filtering at the mid-brain also changes the composition of this sound field. The neurons of the mid-brain area are tuned such that sharp borders between the rings of decreasing intensity are produced. In effect, the sound field is now a circular region, the central area of highest intensity being focused upon the moth, with sharp concentric regions of decreasing intensity. The bat thus achieves its own

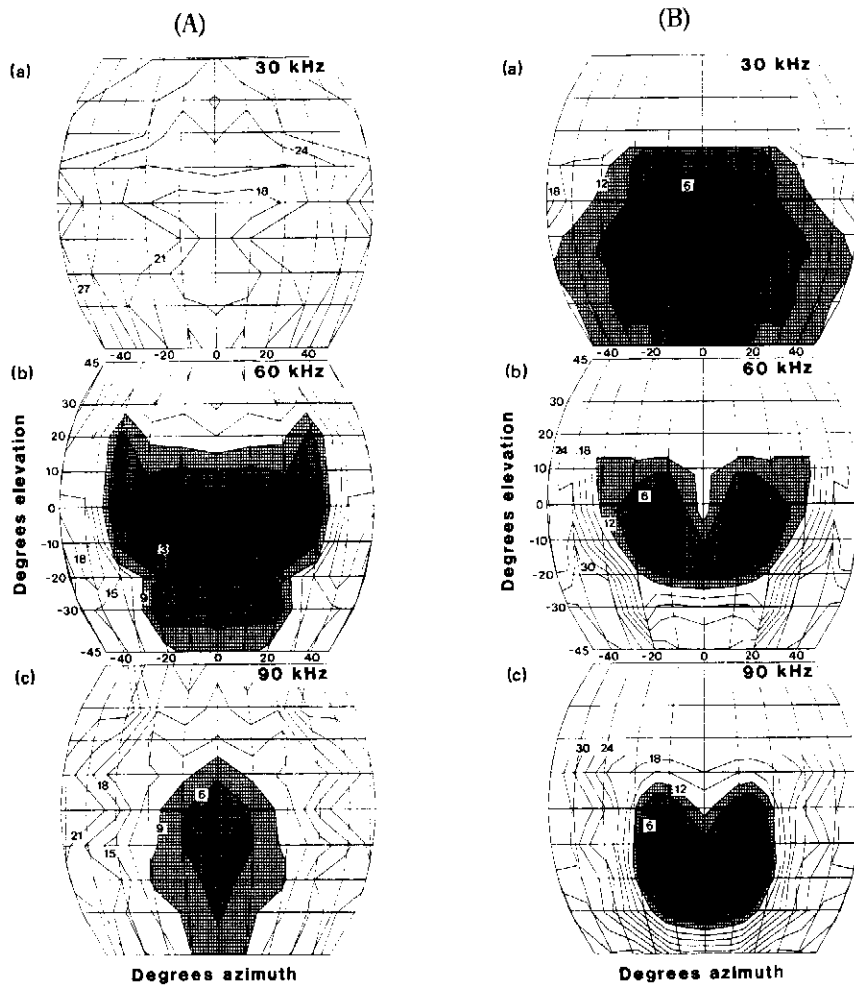


Figure 7.2 (A) The sound patterns of the emission signal measured at the fundamental frequency, (a) 30 kHz, (b) 60 kHz, and (c) 90 kHz. (B) A projection of sound contours for the combined emission and reception of the sonar system. (Adapted with permission from Henze and O'Neill, 1991.)

private version of our public "sun" – a directed "flashlight" beam of sound with uniform "spectral" and intensity properties.

2 The basilar membrane in the inner ear of the bat (the transduction mechanism) is selectively tuned to – most sensitive to – the second harmonic of the echo, to returning sounds somewhere between 61.0 and 61.5 kHz. It is least sensitive to frequencies around (and below) 59.5 kHz or the second harmonic of the vocalization, the resting broadcast frequency. Exactly which frequencies are filtered

or enhanced is a function of the individual bat: the basilar membrane is "personalized" to accommodate the slightly different broadcasting frequency of each individual. Like us, a bat has its own distinct voice (and, yes, on the whole, male bats have the lower voices) (Suga et al., 1987). As a result of these factors, the basilar membrane serves to filter out the sound of the bat's cry (below 60 kHz) and selectively enhances the echo of its own voice as it bounces back from distal objects. Thus the bat reduces interference from its own voice and from the cries of others.

3 Although the basilar membrane acts as a selective filter, this alone could not solve the interference problem. The Mustached bat, as I said earlier, issues a deafening cry – at its most intense – at about 100 decibels. (By way of contrast, this is louder than a symphony orchestra, about the same as a rock concert or the pounding of a jack hammer, and somewhat quieter than a jet engine.) Needless to say, this is a difficult interference problem: one cannot solve the problem by having an insensitive receiver, transducer neurons that respond only to sounds above 100 decibels, for this would create a bat that was "blind" to everything but its own voice (the echo always returns at a diminished amplitude)! Nor given the frequency similarity of the outgoing and incoming signals, would a "notch" filter be physically feasible. Rather, some sort of "intermittent" mechanism is needed, one that works during the production of the cry. This is, in fact, the sort of mechanism in play. The middle-ear muscles contract in tandem with the call, effectively blocking the tympanic membrane during that time. In effect, the bat is intermittently deaf but it enables the bat to process the signals returning from the world. It should be noted, however (the reasons for this will soon be made clear), that the middle-ear muscles take time to relax. After the chirp is complete, there is a period of 5–8 ms during which the muscles relax back to their uncontracted state (Henson, 1970; Suga and Jen, 1975).

#### 4 The Beginnings of Subjectivity

Out of the physicist's view of the auditory world, the bat's signal characteristics and its sender/receiver properties, the "subjective world" of the Mustached bat, begins to emerge. We can see how the informational character of the signal changes over the course of the hunt and start to understand what that probably means for the bat's auditory experience. More specifically, at this stage, without access to most of the details of how the bat processes the neural signals, several strong negative constraints can be discerned: we can infer, with fair reliability, what information the bat lacks given the properties of the physical world and the signals produced. For example, if we know that a sound signal with a certain frequency  $F$  can travel only about 6 feet, then we know that an echo of frequency  $F$  does not provide any information about objects at a distance of greater than 3 feet (i.e. 6 feet there and back). We can also make some reasonable assumptions about the positive characteristics of the bat's auditory perceptions given only these kinds of "external" facts. For example, one can assume that if the bandwidth of the signal suddenly broadens, then the bat probably makes use of this increased informational capacity, for otherwise it is unlikely that such a change would have taken place. Because we have a general picture of the kind of information the bat will need (e.g. the velocity, range, and type of target) and we have some idea about how such information is ded



to the characteristics of the signal, we can make a reasonable judgment about what information is going to be used by the bat and when this is likely to occur.

We know, for one, some general characteristics of the bat's auditory field. For example, we can infer that when the bat is using sonar navigation, its "auditory field" is a small circular area directly in front of the bat's nose. Like our own visual field which shifts position whenever the head, eyes, or body move, the bat's auditory field also moves along with its nose and head. Moreover, the mid-brain processing produces in the bat's auditory field an analogue of the human retinal fovea, that central area of our retina densely packed with sensory receptors that produces a high-resolution image of the world. In the bat, the mid-brain processing produces a central area of high intensity in the auditory signal and this in turn yields a central area with increased "depth of field" – the bat will be able to "see" further in this central region. However, unlike our visual system in which the decreased acuity (and increased rod density) of the peripheral retina causes our visual image to "fade towards gray" in the peripheral regions, the mid-brain filtering of the bat produces sharp boundaries between the intensity regions of the auditory field. For the bat, the auditory field will have a number of distinct concentric intensity regions. We also know that although the chirp of the bat is *very* loud, it is not deafened by its own outgoing cry. In fact, its own voice, in the outgoing phase, is heard only indistinctly given the middle-ear muscle contractions. On the other hand, because the bat's basilar membrane is "personalized," it hears its own returning cry far more distinctly than the chirps of anyone else. The sound of its own signal is, in one sense, more interesting than any other.

The data also give us a picture of how, specifically, the bat's auditory access to the world changes across time as it pursues its prey – as it searches for prey, then tracks the "edible," and finally comes close enough to grab its dinner. We know, for example, the following facts about the bat's sensory state as it closes in on the prey:

*Myopia* The closer the bat gets to its target, the smaller becomes its depth of field. In the search phase of the hunt, recall, it is the second harmonic (low-frequency, further travelling FM sound waves) that receives the greatest energy. But as the bat gets closer, particularly in the final phase, the energy shifts to the high-frequency harmonics, sound waves that are more easily absorbed. So as the bat nears the target, the echoes contain information about only progressively closer objects. The bat can "see" furthest in the search phase, then, shorter and shorter distances thereafter.

*Detail* In the last moments of the approach, there is an increase in range and texture information about the target. Because the bandwidth of the FM tail broadens in the terminal phase, the bat receives very fine-grained range information. In addition, because the higher harmonics (short wavelengths) are emphasized, there is high spatial resolution as well – two things which when taken together give the bat detailed information about the *texture* of the target.<sup>19</sup> Again, this is something like human vision. The closer the bat gets, the more detail it can discern.

*Constant frequency* Because the bat compensates for the Doppler shift by lowering its voice, the frequency of the echo remains constant. So, contrary to what one might guess (this is certainly what I guessed), the bat does not keep track of how fast

it is going by listening to the rising or lowering frequency of the echo: increasing frequency does *not* indicate higher speed. Rather, it is the comparison between the outgoing cry and the returning constant frequency signal that determines velocity.

*Intensity and object size* As the bat closes in on its target, the echo becomes louder and louder. Not only do the sound waves have less distance to travel (hence suffer less absorption), but the subtended angle of the target increases (the target surface area looms larger). (Think of playing a trumpet against a wall.) One might imagine then that the bat has an auditory analogue of visual looming. In vision, the closer you get the *larger* the object appears; perhaps in echo location, the closer the bat gets, the *louder* the echo sounds. This is not, however, how it is for the bat: target size and target range are disambiguated. Remember that after the bat emits its cry, there is a period of 5–8 ms during which the contracted middle-ear muscles relax. During this time – before the muscles have fully relaxed – echoes from nearby objects will return. The cries bouncing back from objects at a distance of about 2 meters will take about 8 ms to return, so they will arrive when the muscles are almost entirely relaxed. Echoes from nearby objects, on the other hand, return sooner – they will make it home around the 5 ms mark or when the muscles are still almost fully contracted. The net effect, then, is that the muscles are *more* contracted – admit less sound – for the echoes of near objects and are *less* contracted – admit more sound – for the echoes of far objects. Hence, closeness of the object alone will not effect the loudness of the echo. Increased volume is accounted for only by object *size*, or subtended angle.

*A disappearing world* Because Doppler compensation in the bat occurs only in one direction (the bat lowers its voice but never raises it) objects moving away from the bat will produce echoes that are well below 61 kHz (in the second harmonic). This means that the echo will fall in a frequency range to which the basilar membrane (the "receiver") is least sensitive, so objects that move away from the bat will simply *disappear*. Indeed, the faster the object moves away from the bat, the more quickly it will "evaporate." (Consider how odd our experience would be if human vision had an analogous mechanism. Imagine standing by the side of the road watching cars go by. The car comes towards you, getting bigger and bigger, but when it passes, the car almost instantly vanishes! Cyclists, however, take a little longer to disappear while pedestrians simply fade slowly away.) Unlike for us, however, this mechanism makes sense in the bat because the sonar system is used primarily during flight. It is always flying *forward*, directing the sonar signal in a small beam ahead of itself, *towards* the objects in its path. Hence, most objects will have a positive relative velocity and be potentially "visible."

All these facts about the bat's auditory access to the world have been deduced almost in the absence of the neurological facts, of the details of signal processing. How then do things look once we know something about the bat's auditory cortex?

## 5 Cortical Processing

The auditory cortex of the Mustached bat, as you can see from Figure 7.3a, takes up a large portion of its brain. Figure 7.3b shows an enlargement of this area, a

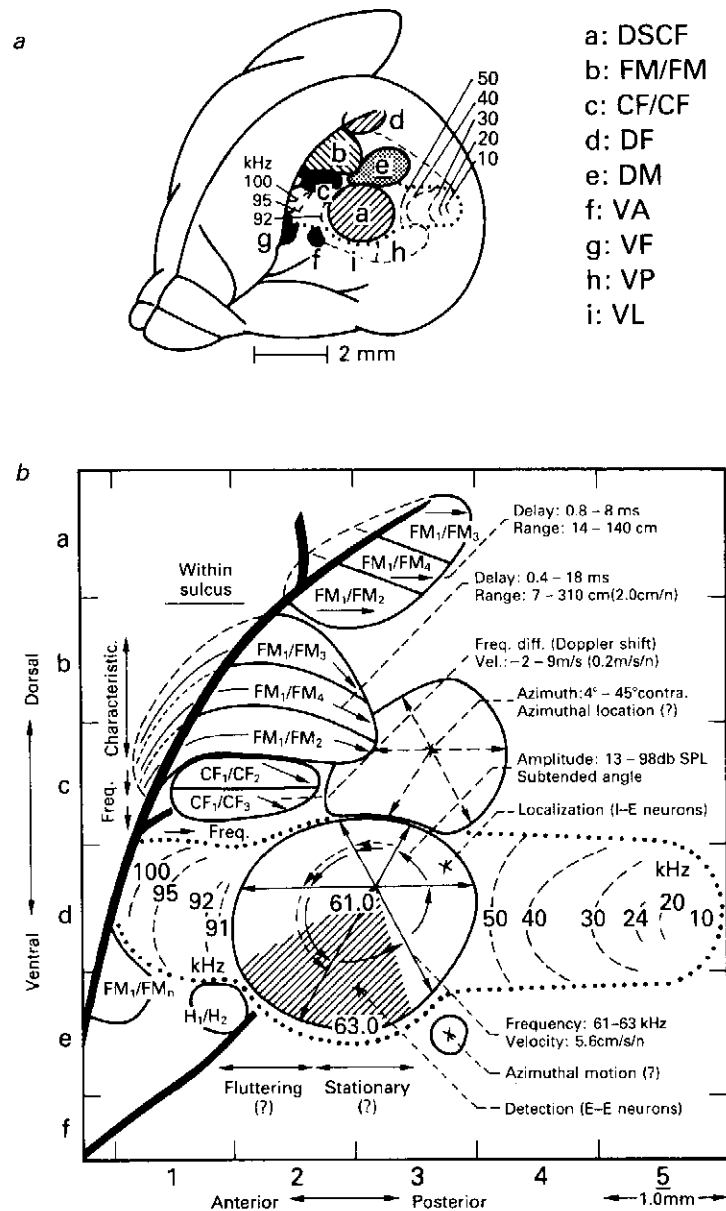


Figure 7.3 Functional organization of the auditory cortex of the Mustached bat. (a) The dorsolateral view of the left cerebral hemisphere. Note the large amount of cortex devoted to sonar processing. (b) An enlargement of the auditory cortex, showing, among other areas, the FM/FM areas, the DSCF area, and the CF/CF areas. (Reproduced with permission from Suga, 1988.)

more detailed picture of the various neurophysiological maps that have been found. This is not, of course, what the brain looks like to the naked eye (if only nature were so accommodating). Rather, these cortical areas are determined by electrophysiology: an electrical probe is inserted into the brain, the bat is presented with various auditory stimuli, and then, by recording the rate at which a given neuron fires, the “preferred” stimulus for each neuron is determined. For example, when a neuron is responsive over a range of sound frequencies, there will be one particular frequency that provokes the most vigorous neural activity.

In many sensory areas, such as the ones shown here, the neurons form an orderly “map” based upon their preferred stimuli. One might find, say, an area of cortex, all of the cells in which respond to sound amplitude, where the neurons are arranged along an axis in order of increasing preferred amplitude. Other maps are “two dimensional”: they contain neurons that respond along two different dimensions of the stimulus, again with a preferred value for each property. Such maps, spread along the surface of the cortex, come in a variety of kinds: some use roughly polar coordinates, some have vaguely Cartesian coordinates, while others use non-orthogonal coordinate systems. For the most part, such maps are irregularly shaped, with “skewed” or “stretched” spatial dimensions. (While the irregularity of such maps may initially seem confusing, such skewed arrangements usually make functional sense: they allow proportionally larger areas of cortex to be devoted to signals of greater importance to the organism. In this way the irregularity of the map facilitates fine-grained processing of more salient properties – a feature we will see in the various cortical areas of the Mustached bat.)

In the primary auditory cortex of the Mustached bat, a number of such maps have been discovered.<sup>20</sup> Here we will look at three major kinds of area: the Doppler shift constant frequency (DSCF) area, the constant frequency (CF/CF) areas, and two areas that contain FM/FM neurons (the FM/FM area and the DF area) (Figure 7.3b).

### The DSCF Area

The DSCF area covers about 30 per cent of the primary auditory cortex. Using roughly polar coordinates, the map plots signal frequency against signal amplitude. Using an analogy of Suga’s (1990), think of a bicycle wheel. Radiating out along the spokes, the preferred frequencies of the neurons start at about 61 kHz and extend out to about 63 kHz at the periphery; going around the wheel – going around in both directions out from one particular spoke – the preferred amplitudes increase. (The cortical areas to either side of the DSCF area serve to extend the frequency range, out to over 100 kHz in one direction and down to about 10 kHz in the other direction.) The DSCF, then, is devoted to frequencies at and just above the reference frequency of the bat’s cry.

Despite the name of this area, the DSCF is probably *not* used for calculating prey velocity (from the Doppler shift of the constant frequency signals). Instead, the central circular region seems to play some role in the bat’s ability to make fine-grained frequency and amplitude discriminations, discriminations needed for a variety of functions. One theory here, is that because the CF signals carry information about the wingbeat of insects, the DSCF might be used to locate fluttering prey against background clutter or to determine the orientation and

species of the prey (these are all capacities of the Mustached bat that have been confirmed by experimental observation). When the constant frequency sonar signal is reflected by the beat of an insect's wings, both the amplitude and the frequency of the echo changes. As the insect flies towards or away from (i.e. perpendicular to) the bat, the beating of the wings acts like an "acoustic mirror" resulting in sharp amplitude peaks or "glints" in the echo. Also, as the wings beat back and forth, there is a small repetitive change (AC component) in the frequency of the echo caused by Doppler shift (in effect the wing movement serves to very slightly increase or decrease the relative velocity). Both these modulations carry information about the species of insect being pursued because each species has a characteristic wingbeat rate. Here, the repetition rate of the amplitude glints encodes the frequency of the insect's wingbeats, while the small repetitive frequency shifts carry information about insect wingbeat plus the size of the insect's wings. Further, the pattern of echo glints carries information about the target orientation (Schnitzler et al., 1983). It is thought that this DSCF area, with its fine-grained processing of frequency and amplitude of the echo around the reference frequency, might contribute to these processing tasks. (This hypothesis has been confirmed in part by the presence of neurons in the DCSF that respond in a phase-locked fashion to the beating of the insect's wings – a synchronous discharge of neurons to the upper and lower frequencies of the Doppler shift.)<sup>21</sup>

Apart from this hypothesized function, however, the DSCF has some better-established features. For one, these neurons, by responding to the amplitude of the signal, indicate the *subtended angle* of the target – the size of the target. (Recall the dissociation of range and size brought about by middle-ear contraction.) For another, the neurons of the DSCF are "wired" in two distinct ways so as to create specialized areas. All neurons in the DSCF, that is, receive an excitatory input from the opposite or contralateral ear. (There is a DSCF area in each of the brain's two hemispheres. So all neurons in the right hemisphere DSCF area receive excitatory input from the left ear and all neurons in the left hemisphere DSCF are excited by input from the right). Input from the same ear, however, can either excite or inhibit. Neurons with excitatory input from both ears (E-E neurons) (shadowed section of DSCF in Figure 7.3b) multiply the signals and thus prove optimal for detecting weak echoes; neurons that receive one excitatory input from the contralateral ear but inhibitory signals from the ipsilateral ear (E-I neurons) will respond preferentially to sounds from one side, the localization of echoes. Thus, there are two distinct areas of DSCF, one for the *localization* of the sounds and the other for the *detection* of weak echoes.

### CF/CF Area

It is here, in the two parts of the CF area (CF<sub>1</sub>/CF<sub>2</sub> and CF<sub>1</sub>/CF<sub>3</sub>), that the neurons record information about the velocity of the prey, through maps that plot frequency against frequency: the frequency of the outgoing stimuli and the frequency of the incoming echo. Each neuron in this area responds to a *pair* of stimuli, a combination of two CF signals: first a fundamental (or CF<sub>1</sub>) tone of the bat's cry, then either second or third harmonic signal (the CF<sub>2</sub> or CF<sub>3</sub> component) from the echo. Neurons in CF/CF areas do not respond to the single components alone, but only to a specific paired combination. (This explains, in part, why the fundamental tones

are so important. As I said above, the fundamental component of the cry is emitted at very low intensity – so low, in fact, that only the bat itself can hear its own fundamental tones. Because neurons in the CF/CF area require a paired signal (the fundamental and the harmonic), there is less chance of interference from the signals of other bats in the cave – of responding to your neighbor's sonar signal instead of your own.) For most of these neurons, the relation between the CF<sub>1</sub> and CF<sub>2</sub> component is not a perfect harmonic difference. The neurons are tuned to specific frequency *differences*, differences that translate into relative velocity measures (e.g. a CF<sub>1</sub>/CF<sub>2</sub> neuron tuned to signals of 30 kHz and 61 kHz respectively is therefore tuned to a relative velocity of 2.84 ms<sup>-1</sup>). The range of velocities represented in the CF/CF area as a whole is between 8.7 and -2 ms<sup>-1</sup>, with the largest number of neurons devoted to the important range of 0-4 ms<sup>-1</sup>.

### The FM/FM and DF Areas

Neurons in these two FM areas are also sensitive to pairs of stimuli. Here they respond to *time differences* – the delay between the first signal of the outgoing cry and the second signal of the returning echo. Hence, FM neurons are tuned to *range*, the distance to the target (e.g. a 1 ms delay correlates with a range of 17.3 c). (Actually FM/FM neurons have a very complex response profile: they are also tuned to the specific frequencies of the two components and most are tuned to specific amplitudes as well – hence target size.) As with the CF/CF neurons, the first signal is an FM<sub>1</sub> signal or a fundamental frequency; the second time-delayed signal can be an FM<sub>2</sub>, FM<sub>3</sub> or FM<sub>4</sub> signal (these pairs are arranged in separate clusters in each FM area). Again, the first and second components are not usually perfect harmonic variants, for even though the Mustached bat uses Doppler shift compensations during flight, the FM echo will commonly arrive back at a slightly higher frequency (a positive Doppler shift.) The frequency of the second component, then, is usually slightly higher than a perfect harmonic of the fundamental tone.

In both these FM/FM areas, the neurons are arranged along an axis of preferred delay; that is, along an axis of *distance* to the target. (So, as the bat gets closer to its target, the activity of the neurons actually shifts across the surface of the cortex.) In the FM/FM area, that range is 7-310 c (practically the full range over which the bat can "see" with sonar signals); in the DF area, distances between 14 and 140 c are represented. These, then, are some of the processing characteristics of the primary auditory cortex of the Mustached bat.

## 6 The Bat's Point of View?

The strategy adopted at the beginning of this essay was to explore the prospects of explaining at least *some* aspects of the bat's subjective experience. Now, having assembled in the last four sections an explanation of the bat's informational problem, facts about the bat's behavior (including the emission of its sonar signal), and a description of the signal processing in primary auditory cortex, the time has finally come to return to Nagel's question, "what is it like to be a (Mustached) bat"? What can we infer about the bat's phenomenal experience?

Recall that when Nagel asked his question about the phenomenology of the bat, he equated the bat's experience – the “something it is like” to be a bat – with having a point of view. If the bat is conscious at all and if it perceives the world by audition (as opposed to by vision), then there is some way that the world seems to the bat – presumably, an auditory kind of “seeming.” This way of putting the matter, however, fails to separate two distinct questions about the bat's experience.

We can all agree, I think, that the bat is located in – flies about – a world of spatiotemporal material particulars, a world of trees and caves and small flying insects; we can also agree that some of the bat's neural states are caused by the properties of those objects or, more specifically, by the spatial properties of those particulars. But this is only to describe the bat *as we see it*, as located in and causally interacting with *our* world of objective particulars. In other words, this description of the bat alone is not sufficient to attribute *to the bat* a certain perspective on an independent world – to ascribe to it a representation of the spatial world, its properties and objects, *as objective, as distinct from the bat itself*. To say of the bat that *it* perceives a world, one that contains objects and properties is to make a further claim about the bat's conceptual scheme.

The two very different questions that we need to distinguish then are these. First, one can inquire about “the very feel” of the bat's auditory phenomenology, whatever it is like to be a bat in virtue of having a sonar system. This is a question which is neutral with respect to the issue of the bat's perceptions of the world: whether or not, for the bat, there *is* a world of objects and properties or, indeed, any world at all conceived of as distinct from the bat itself. Let this be the question “what is it like to be a bat?” The second question is a direct query about the bat's *conscious perceptions of the world*: on the assumption that the bat's conceptual scheme includes an independently existing world of objects and properties, *how does the world, perceived by auditory means, seem to the bat?* In other words, one can also ask about the bat's *species-specific perspective on a world*, one that the bat obtains through its sonar system. It is this latter question – a question that presupposes a certain conceptual ontology – that seems to best sit with Nagel's view that we can equate the bat's *subjective experience* with the bat's *point of view*. That is, if Nagel takes the problem of grasping a bat's acoustic phenomenology as the very same problem as that of understanding a bat's point of view, this seems to presuppose that there is *something on which* the phenomenology *is* a point of view. (Nagel, I realize, would not agree. But we can turn the tables by re-phrasing Nagel's own complaint. Just as Nagel asked “what would be left of what it is like to be a bat if one removed the viewpoint of the bat?”, we can reply by saying: “it is difficult to understand what could be meant by a *point of view* apart from a point of view *on something or other*: after all what would be left of a point of view, if it were on nothing at all?” In other words, if one grants that a subject is necessary for a point of view, then surely an *object* is required as well.) Let this be the question, then, “what is the bat's point of view?”<sup>22</sup>

Both of these questions will be addressed in turn, but in this section I will take up the latter one: what has science told us about a bat's point of view? First, what the empirical data makes plausible – in particular, what the processing properties of the bat's primary auditory cortex strongly suggest – is that what the Mustached bat *hears* is probably not what we *see* – not even what we see, minus little bits and pieces or with less spatial detail or with a narrower field of view. When the bat flies across the night sky, in all likelihood it does not use its sonar system to construct representa-

tions of the objects around it: an image of the large oak tree to the left, another bat over to the right, the ground and bushes below and so on. Even during the chase, when the bat focuses its sonar beam upon the moth, it is unlikely that the bat ever gains a real-time image of its prey: it probably does not “see” an insect of a certain type, a moth about 2 inches across, with a fuzzy body and long antennae, zig-zagging through space, its wings aflutter. Unlike our own visual perceptions, in other words, the bat's sonar experience is probably neither imagistic nor – more importantly – an experience *of* a world of objects and properties. *Hence it seems plausible that the bat may not have a point of view at all.*

To illustrate why science points in this direction, return to the data on cortical processing and a story that draws it together. Imagine that *you* are the bat – or rather, that you are the bat's wingflapper located in the frontal cortex. It is your job to man the motor controls, to steer the bat given the instruments on the control panel in front of you, namely by watching a couple of lights, some digital meters, and a compass-like dial. These are instruments that receive input from the primary auditory cortex alone, that show the summed neural activity of its various regions. You are to maneuver the bat, in other words, on the basis of what the auditory cortex “sees.” But what exactly do the instruments show? How are they wired to the neural activity of the auditory cortex?

The first four instruments are hooked up in various ways to neurons in the DSCF. First, there is a yellow light which is wired to the excitatory-excitatory (E-E) neurons. When the bat is randomly searching for prey, the light remains off. But as soon as the summed activity of the E-E neurons reaches some fixed point (i.e. when the echo rises above a “whisper”), the yellow light starts to flash. The yellow light indicates, in other words, that something or other has come into “view.”

Secondly, there is a compass-like dial on the panel that monitors the activity of the inhibitory-excitatory neurons. By analyzing the pattern of activity across the neural population as a whole, the dial provides a rough read on the direction of the prey. The arrow indicates, in egocentric coordinates (i.e. relative to the bat's nose), the position of the weak echo.

Thirdly, there is a metronome-like instrument, one that is hooked up to the neurons in the central region of the DSCF. Recall that these are the neurons that are phase-locked to the beating of the insect wings. The tick-tock of the metronome, then, beats time with the wings: a sort of “yum-yum” meter from which you can discern the “edibility” of the prey.

And, fourthly, there is a gauge that monitors the amplitude signals of the central DSCF and thereby shows the subtended angle of the insect.

Then there are the digital meters, three in all. The first two meters on the panel are connected to the two large FM/FM areas and – sure enough – they indicate distance to the target. One meter is the “distance meter” because it monitors the FM area, that area which represents distances between 7 and 310 c. So it encompasses all the distances to the prey throughout the chase. The second meter is the “accuracy meter.” As the bat draws nearer to its prey, the accuracy meter (connected to the DF area) gives a more subtle indication of target range.

The third digital meter is a simple speedometer. It is hooked up to CF/CF areas of auditory cortex and thus indicates velocities between  $-2$  and  $+9$   $\text{ms}^{-1}$ , giving

particularly accurate information about speeds at around  $+4 \text{ ms}^{-1}$ , the speed at which you normally fly.

This is what the instruments on the control panel show – or, more correctly, this is how things look from the neurophysiologist's point of view. This is what an outside observer could know about the instrument panel. What *you* see, however, in your role of the wingflapper, is much more simple. You see only the lights and dials, not the wiring behind the scenes, and this is what will guide your behavior.

Most of the time you can spend your time just flapping the wings at random, making the bat circle around, waiting for something to happen on the control panel. More specifically, you are waiting for the yellow "alert" light to come on. When it does, you need to turn your attention to the direction dial. Watch the needle for movement, then flap and orient so that the needle points dead ahead. Of course, this is a little tricky – you have to keep the needle centred on the direction dial while keeping one eye on the "distance meter" (to check your progress), while at the same time adjusting your speed appropriately so as to close in on your potential prey. Now comes the interesting part. Once "that something" is a little closer, you can find out whether it's even worth catching. Is it edible or not? Here, the oscillations of the metronome will tell you whether dinner is in sight.

Of course, it's not the case that things always go as planned. What if the metronome fails to oscillate, if it says *nothing at all*? This means that whatever is out there, it is *not* fluttering, so you'd better put on the brakes. Have a look at the amplitude gauge for subtended angle, check the accuracy meter for distance, and make a guess about the size. How big is that thing anyway? Hmmmm . . . If its *very* big and it's getting closer all the time, you could be in trouble. What's more, the identification of large things is not your kind of job. (Is it a cave wall or *what*!?) So pull the bat sharply up and left and put in a call to another sensory area for help . . . This, then, is the wingflapper's tale.

There are, of course, no lights and dials in the frontal cortex of the bat. Nor is there a bat homunculus, the wingflapper, who reads the instruments and sends out the appropriate motor commands. Still, the story makes for a useful fiction because it makes vivid one essential point, namely just how small the gap between the bat's sonar input and its motor output might be: how little intermediary processing is required to translate (in the mathematical sense) the auditory information of the primary cortex into motor commands.

Looking back at the neural activity of the auditory cortex as represented by the lights and dials on the instrument panel, that is, one sees how closely the sonar sensory system is tied to the bat's motor needs: on the basis of this cortical information alone, we can almost imagine how to "drive" the Mustached bat, or at least, how to drive the bat during the hunt for airborne prey. To put this another way, although you, as the wingflapper, were asked to perform the appropriate tasks – you were asked to imagine *reading* the instrument panel and *deciding upon* the *appropriate* motor responses – all of your decisions and actions might have been performed by a reasonably simple control system. For example, the compass-like dial of the direction instrument could have directly controlled the line of flight using a translation of the compass directions into the suitable coordinates of the motor system. Similarly, one could specify a series of default settings for motor control to be used whenever certain sensory conditions arise; such that, say, in the presence of large looming objects (i.e. for certain values of the amplitude gauge, the accuracy

meter, and the speedometer), the bat would turn sharply, up and away. The story did not require, in other words, an intelligent hand on the controls, an intentional agent who attempts to determine *what is out there* (the state of the external world) and then, on that basis, decides *what ought to be done*. Hence, there is no need to attribute to the bat any intermediary processing steps nor any of the representational capacities that would thereby be required. The input–output "loop" of the bat, it seems, might be very short indeed.

More generally, what we see in the primary auditory cortex of the bat is an extension of the same informational "strategy" employed in the emission of the sonar signal. There, the bat's solution to a complex processing problem was to match, sequentially, the informational characteristics of the signal to the informational requirements of the bat's hunting behavior. In the auditory cortex, we can again see how the bat's behavioral demands tightly constrain the informational properties of the sensory system: for the most part, the cortex encodes only highly filtered information about specific properties of the prey: its relative velocity, size, range, location, and "edibility." What the auditory cortex seems "interested in," one might say, is only that information necessary to locate, track, and catch the bat's dinner. Putting all this together then – the bat's hunting behavior, its signal, and the properties of the auditory cortex – the function of the bat's sonar system, as portrayed by the wingflapper's story, is this: *to secure, sequentially, highly filtered information that can be used, on line, to guide the bat's flight*. By and large, what the sonar system does is to direct the very rapid and stereotyped movements of the bat's prey-catching behavior by providing, "on demand," just that spatial information currently required.

More specifically, if one looks back over the science, there were two aspects of the data that strongly suggest this function for the sonar system. First, there is the "specificity" of the neurons in the primary auditory cortex. To say that a (sensory) neuron is informationally "specific" is to say that when it processes an incoming signal there is information *loss*; because the neuron responds to only particular aspects of a complex stimulus, its signal contains information about only those specific properties. For example, think of the response properties of neurons in the FM/FM areas of bat auditory cortex. These are neurons that will fire whenever there is a pair of stimuli with a certain distinct profile – two stimuli separated by a certain time delay with a particular frequency "mismatch" between a fundamental tone and its harmonic, each stimulus falling within a certain amplitude range. Given a response from an FM neuron, one can infer that a pair of stimuli with roughly those properties has occurred. Then again, the response of an FM neuron does not tell us, say, how many harmonics each signal contained, or their pattern of frequency modulation, or the amplitude of the signals except at a certain point in the signal sweep and so on. Much information about the acoustic properties of the original stimuli (and much of the information about those properties encoded by the basilar membrane in the bat's ear) has simply been lost, discarded in the interest of discerning the distance between the bat and its prey. Hence the specificity of the FM neurons. In the same way, looking again at the neurons in the other areas of the primary auditory cortex, one sees neurons with a similar informational character – informationally specific neurons that "trade" rich information about the acoustic stimulus for specific information about the properties of the prey. As I said above, what makes this property of the cortical neurons "suspicious" is just that the

neurons seem to encode only the information needed by the bat in order to catch the prey, that is, to drive motor control. And this suggests that the bat may require (at least for this aspect of its behavior) little else except this kind of rudimentary information encoding.

In addition, the specificity of the bat's cortical neurons raises the possibility that the bat may not even possess, from its sonar information, the necessary "building blocks" for complex spatial representations. We know, that is, that the information-rich representations of human vision – or, more generally, the complex spatial representations of any neurobiological system – require at least the following three conditions: first, there must be a complex stimulus, one that contains the "raw goods" from which informationally rich representations can be constructed; secondly, the neural system must have a way of encoding the complex properties of stimulus at the transduction level; and thirdly, higher-level "modules" or information processors must have access to this encoding. One needs, that is, a complex stimulus, a way of encoding its complexity, and access to the information thus encoded. What such a system requires at low levels, then, are informationally *general* neurons, ones that respond across a wide variety of properties of the original stimulus and thus jointly encode very detailed information about the original stimulus. (For example, in human vision, the complex stimulus is the visual image on the retina, and the transduction mechanisms – the rods and cones – encode much of the pattern's complexity. At the level of the primary visual cortex, the "simple cells" of layer IV, taken together, still encode most of the properties of the original stimulus.) The suspicion, then, about the bat's primary auditory cortex, is that, even at this very low level of cortical processing, the raw materials of complex spatial representations are no longer present. Hence they are not accessible to higher-level processes. For the various FM/FM areas and the CF/CF regions (although perhaps not for the DSCF), much of the requisite acoustic detail has already been filtered out. Perhaps, then, the bat neither has nor needs the capacity to produce complex sonar representations.

The second telling aspect of the data is that it yields little reason to suppose that the bat's sonar system is designed for the large-scale *integration* of information over time. We know that any system that produces a representation of a stable objective world on the basis of continuously changing input must use massive integration. Again, take our visual system as an example. As you look out at the world, the patterns of light on your retinas are in constant flux. Usually this is the result of your own motion – you constantly shift your gaze, focusing first on this and then on that – but at other times, objects in the world move of their own accord. Somehow or other, amidst all this changing retinal information, the visual system produces a perception of an apparently stable, unified, continuous, and independent world. And this is only possible, I take it, through the system's massive integration of its present informational states with its previously constructed spatial representations.

In contrast, as the wingflapper story illustrates, the bat's auditory system seems designed for sequenced *non-integrated* information processing. First – an old point – as the bat progresses through his prey-catching routine, the informational *content* of the signal changes across time in tandem with its informational *needs*. Information that is not needed at the end of the behavioral sequence is simply "dropped" in virtue of the kinds of signals produced at this stage. (Recall how in the Search phase of the hunt, the bat has broad information about target range, for its "depth of field"

extends past 2 meters, plus information about wingbeat, orientation, and prey size; by the Terminal phase, when the sonar signal consists almost entirely of the FM tail, the bat has very precise information about the target range, but probably little else.) Secondly, simply looking at the bat's behavioral repertoire, it seems that very little of the sonar information extracted during prey-catching will be of any use to the bat at a later time: given its behavioral repertoire, that is, there is very little need for the bat to store and integrate sonar data. For example, there is no reason for the bat to remember exactly where in the sonar field the insect (now in front of him) first appeared; nor will the bat need to recall exactly which evasive maneuvers a certain moth (recently consumed) performed; nor, once the bat has determined that an insect is edible, need it ever recall that *this* moth was of a particular "edible" kind. In fact, it need never remember this moth, *qua* re-identifiable particular, at all. So, for both these reasons – the signal sequencing and the bat's circumscribed use of the acoustic information – it seems unlikely that sonar information is saved and integrated into perceptions of a stable objective world.<sup>23</sup>

To sum up, then, what science suggests is that the sonar system of the bat is probably *not* concerned with the representation of three-dimensional objective particulars.<sup>24</sup> But if this is true, it makes little sense to attribute *to the bat* a phenomenal point of view, conscious mental states which are about objects and their properties. There being, that is, no particulars *for it*, we should not ascribe to the bat perceptions *of* those particulars: a perception of this moth, or of this moth *as* a certain type, or of the bat's favorite landing place, or of the layout of its cave.<sup>25</sup> Because there are no objects that the bat perceives, there are no objects for the bat to perceive *in a certain bat-like way*. So to attribute a point of view to the bat – a species-specific perspective from which to view the world – only imposes an ontology where there is little evidence that one exists.

## 7 But What is it Like?

There are no doubt many readers who, at this point, will feel that the central issue has yet to be raised. After all, even if the bat does not have a point of view in this strong sense, an experience *of the world*, could not the bat have *some kind* of phenomenological experience none the less? Surely it is still like something to be bat, even if the bat's sonar perceptions are somewhat "limited" – or so one might wonder.

Elsewhere I have argued (Akins, 1993) that the above question, for all its appearance, may not be as coherent as it seems. If it is a question about the possibility of a "purely qualitative" phenomenology – about conscious but non-intentional experience – I am not sure that we have even a vague conception of what this might mean. Still, putting this problem aside for now, it does seem that, after having a good look at the available facts, we have come closer to understanding the bat's subjective state, and this regardless of whether such "subjectivity" is consciously experienced by the bat or not.

More specifically, the view of the bat's "inner life" that emerged from the scientific data was not "the view from nowhere" that Nagel feared. Recall that Nagel worried that an objective description of the world moves us, step-wise, away

from the individual's subjective experience – that beginning with the point of view of an individual,

[the] movement toward greater objectivity involves, first, abstraction from the individual's specific spatial, temporal, and personal position in the world, then . . . gradually from the forms of perception and action characteristic of humans, and away from the narrow range of a human *scale* in space, time, and quantity, toward a conception of the world which as far as possible is not the view from anywhere within it. (Nagel, 1979b, p. 206)

On the contrary, what science provided was exactly such an entry into a bat's "subjective world," roughly, an understanding of the kind of sensory access to the "outside" or the external world that is available from the "inside" of the bat (the bat's "subjective world" being a notion that I am using as neutral with regard to the bat's conception of self or of objective, re-identifiable particulars).<sup>26</sup> Moreover, this was a scientific investigation that advanced in exactly the opposite direction, that began with "the physicist's view" and then by steps marched the reader back towards the specific perceptual experience of an individual bat.

The project began, that is, with some basic questions about the nature of the auditory world, the informational properties of sound and the problems those would engender for spatial processing. Then, based upon some knowledge of the Mustached bat's behavioral patterns and the properties of its sonar signal over time, some rough inferences were made about what information the Mustached bat was likely to have and at what times. We could estimate, for example, how far the bat could possibly "see" at different points in the hunt, the spatial resolution of the acoustic field, and how "things" would "disappear" from view under certain conditions. The next move involved a characterization of the first few stages of neural processing, starting at the transduction level. Through this, we gained a further refinement of the bat's "perspective," for it marked the transition between the information we could see as *theoretically* available to the bat given the signal, and the information *actually* retained for use at various levels of neural processing. For example, at the transduction level, we saw how the basilar membrane acted as a signal filter, to enhance the bat's own sonar echoes and to minimize those of its conspecifics and how the contraction of the ear muscles filtered out intensity information. Several cortical connections further down the line, at the level of the primary auditory cortex, our understanding of the bat's "subjective world" was again transformed. We could see that the bat had access to specific properties of the external world (although not *as* properties of objects), properties that included the velocity of the target (between  $-2$  and  $+9$   $\text{ms}^{-1}$ ), its subtended angle, and its distance (up to 3 meters) from the bat. Finally, although the story of the wingflapper was used for a negative purpose – to show that the bat lacks certain representational capacities – and moreover was composed of three parts fiction to every one part of substantiated fact, it none the less illustrated how, theoretically, such cortical information can be used: how the sensory processes of the *species* can be applied to the inner life of a specific *individual*, a single bat located in time and space.

On a less positive note, it was disappointing to see how very little insight into the bat's subjective state was gained by the addition of this neurophysiological data. *Prima facie*, the neurophysiology ought to have been the most important part of the

story; yet it failed to advance our understanding of the bat's inner life very much past what had already been discerned in section 4, "The Beginnings of Subjectivity." Still, the reason so little progress was made stems from what we did not know: the information we gained about cortical processing was unenlightening only because it served to raise complex questions about the global nature of the bat's cortical function – questions about how that information was later used, the relation of the primary cortex to motor control, secondary sonar areas, and other sensory modalities. And without answers to those questions no further story could be told.

Even to construct the cartoon-like fiction of the wingflapper's story, numerous representational questions had to be decided simply *by fiat* in order to gain some semblance of a unified and coherent "perspective" for the bat. For example, in constructing that story, the frontal cortex was arbitrarily selected as the residence of the homunculus, a choice that gave the wingflapper a specific "take" on the world. The same kind of story could have been told from the vantage point of some other cortical area, say from one of the primary auditory areas, one of the other sensory "modules" or from any of the other cortical functional sites. In each case, a different story would have unfolded – another "subjective world" – a story in accordance with the external information available at that particular site.

Certain decisions were also made about how to "string the wires" from the auditory areas to the frontal cortex, about what information would be preserved in transmission and about how the informational properties of the neural population (i.e. as opposed to the properties of the individual neurons) would be processed and represented at the frontal site. Take as an example the activity of the E-E neurons in the DSCF and how that was portrayed, namely by a single yellow light on the control panel. Presumably when a bat is flying around looking for insects, the E-E neurons respond to whatever – and all – objects that reflect the bat's sonar signals. So if there were a number of insects directly ahead of the bat (or some branches of a tree in the background behind a fluttering moth, etc.) the E-E neurons would register this fact: the population would respond to all the echoes present, resulting in a pattern of activity across this area of cortex. In the wingflapper story, however, the yellow light on the instrument panel was assigned a "trigger" level, the threshold of activity for the population which turns on the yellow light. So, on this wiring scheme, the frontal cortex lost a great deal of information available in the DSCF, information about all the "background" activity below the level of the threshold (i.e. the activity caused by various other objects) as well as about the actual rate of firing that triggered the yellow light. In effect, the wiring to frontal cortex reduced the bat's perceptual world to a single sound source, one that was either present or not. Needless to say, some other "wiring diagram" might have been used.

Finally, in selecting the frontal cortex as "the" seat of consciousness, many difficult questions about the bat's world – about a unified perspective or a single subject or a "self" – were avoided. By turning a blind eye towards the difficult representational questions that would inevitably arise, the wingflapper just became "the" bat. No questions were asked about the consequences of interaction between the frontal cortex and other functionally distinct areas, about how motor control might be shared, how different representational schemes might be reconciled, how conflicting and "absent" information might be resolved and so on. No hint was given of how a unified perspective might emerge or, indeed, what this would mean.

And, finally, no problems were raised about how the bat distinguishes itself *as a self*, *as distinct* from the rest of the world. All these very difficult representational questions were simply ignored.

In order, then, to tell a more complete story about the inner life of the bat, numerous representational questions about the nature of cortical function would first need to be answered. Understanding the function of primary auditory cortex did give us some hint of the "subjective world" to come, but being only the very first part of a complex story, it largely served to raise as many questions as it answered. Thus, in the end, it was the objective facts about auditory signals and signal processing that provided our initial insight into the bat's "subjective world," and when the project came up short, it was unanswered questions about representational matters that were responsible. Despite what Nagel feared, science did not take us "further away" from the bat's conscious experiences, nor were the problems that brought the investigation to a (temporary) close, problems about inaccessible subjective facts or the intrinsic properties of the bat's experiences or the phenomenological "feel" of the bat's perceptions.

## 8 Conclusion

This essay began by outlining a tension between two competing intuitions about consciousness. On the one hand, there is our native sense of puzzlement about how it is possible that a subject of phenomenal experience can be physically embodied at all and hence about how physical facts can yield insight into that conscious experience. On the other, given our materialist view that the mind is the brain, it seems plausible that science ought to be able to tell us *something* about the nature of conscious events. In dealing with this tension, the strategy was to set aside the common puzzlement and to begin by taking up the positive project – to see what science would say.

Given the strategy, it was entirely foreseeable that the mystery of physically embodied consciousness would be left unaddressed – and unfortunately this was so. Some physical processes, such as those that occur in the human visual cortex, give rise to conscious events; other physical events such as pouring water into a pitcher or starting the lawnmower do not. And looking at the neurophysiology, behavior, and environment of the Mustached bat did not explain this puzzle. Similarly, the above science shed no light on the question of what *kinds* of neural processes give rise to conscious experience: why it is that some neural events, such as visual perceptions, are present to consciousness while others, such as the neural mechanisms of stereopsis or depth perception, are not. Neither of these problems seem likely to be resolved by this method alone, by looking at the scientific literature about one particular species. Moreover, it was because these questions were not addressed that, in the end, no stand could be taken on whether it is like anything at all to be a bat – whether the "subjective world" of a Mustached bat, acquired in virtue of its species-specific sonar processing and the "particularity" of the situated individual, is sufficient for phenomenal experience. All these are further problems that need to be addressed, but not, I suspect, by examining the data on a single species or even through "pure" scientific inquiry alone. My guess is that these are as

much conceptual problems as scientific and perhaps the very questions themselves must change before satisfactory answers can be given.

What the strategy made readily apparent, however, is that many of the notions commonly used in speaking of phenomenal experience – the notions of "point of view," "structural properties," "self," "subjectivity," "objectivity," and the like – are firmly tied to representational questions. By taking a concrete case and attempting to piece together a coherent picture of a subject's experience, the representational nature of these notions was brought into sharp relief. The bat, we found, may fail to have a point of view, but this is to say that the bat lacks certain representational capacities, a conception of a world of objective particulars. Moreover, given what the bat is missing, it would seem that to understand a creature with a genuine point of view would require asking further representational questions: what would it be to represent objects *qua* objects, to distinguish oneself from the rest of the world, to re-identify a particular? And exactly how would these capacities be instantiated: what kind of functional or computational capacities would count as, say, seeing a particular *as a particular*? In other words, both the concept of a "subjective world" and that of a "point of view" are (at least in part) representational notions. And if we have made progress on the former – if we now know a little something about what it is like to be a bat – there is good reason to think that progress on the latter could be made as well.

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## NOTES

As a graduate student, I worked for several years with Daniel Dennett at The Center for Cognitive Studies at Tufts University. Part of my job during that time was to unearth "telling" neurophysiological work; although, once found, Dan and I would often disagree about exactly what philosophical consequences could be drawn. In a volume devoted to Dennett's work, then, it seemed fitting to present one body of research that he and I often discussed – the neuroethology of bats – and to trace out what I take to be (some of) its theoretical consequences. Although this contribution is not directed towards Dennett's work (pedagogically, it takes issue with Nagel's views), many of its conclusions are at odds with Dennett's views about consciousness, the intentionality of mental states and the relation between these two phenomena.

- 1 See Dennett (1991), p. 443. In these examples, Dennett's tactic for the attribution of perceptual states to other creatures is to start with our own experiences and then "adjust downwards" as required by the physiological and behavioral data.
- 2 What then of the experience of subjects other than oneself? Given a subject who is sufficiently similar to you, behaviorally and physiologically, you can imagine how things



- would be *for you*, if you were in that subject's particular situation. You can *adopt* that subject's point of view, in other words, through a kind of empathetic projection. Of course, given an "alien" subject, one with whom you have little in common, there will be scant basis for an ascription of your own familiar phenomenology. Hence the problematic nature of our relation to the bat and to all other alien creatures as well: if we cannot adopt their alien point of view, we will never comprehend their phenomenal worlds. We will probably never know what it is like to be a bat.
- 3 In essence, this would give away the game, for if there is a mystery about how a brain could be conscious *at all*, then it ought to be equally mysterious how one could have this or that kind of conscious event.
  - 4 Two warnings about the data presented here are in order at the outset. First, the research presented is not assumed to be immutable or entirely accurate. Many of the findings cited are from recent sources that may or may not stand the test of time; no doubt other parts of the data have already been shown to be inaccurate or incorrect. This does not matter, however, as the project is not to see if we can ascertain what it is *really* like to be a (moustached) bat but rather to see what can be deduced about a bat's point of view given a body of something like objective scientific "facts." The second proviso concerns the selection of research findings. While what we now know about the neurophysiology and behavior of the bat is but a small part of what could be known, there is already an enormous body of experimental literature. Inevitably, the story that follows incorporates only a small subset of that data, one that has seemed revealing of the bat's world.
  - 5 It is not unusual, for example, for Nagel's query, "what is it like to be a bat?" to be seen as equivalent to the question "what would it be like to *hear* the world as opposed to "*seeing* it?" The emphasis, in this latter question, is on the *modality* of the experience, audition – whether a shift in modality *alone* would make for a difference in phenomenology. If you could hear what you can see, what would that be like? The informational equivalence of the two systems is presupposed.
  - 6 Actually, when Donald Griffin first suggested that bats navigate by echo location, his discovery was greeted with complete disbelief by the US Navy. After all, who could believe that a mere bat could be using a sonar system that was clearly more sophisticated than any the Navy had yet to produce?
  - 7 What I am describing here is the view of vision as "inverse optics," the theory first proposed by David Marr (1982).
  - 8 Although not a strict anomaly. Oil birds (a nocturnal species) and Cave Swiftlets (a diurnal species) are both cave-roosting birds that have rough echo location systems that use a series of relatively low-frequency "clicks." In addition, certain species of dolphins (e.g. the harbour and the Bottlenose dolphins), porpoises, and whales (e.g. sperm and killer whales) are water-dwelling mammals that use sonar navigation.
  - 9 Not very much is known about the visual system of bats, although see Pettigrew (1988) for a short but surprising summary article on this subject. Comparing the spatial resolution of both the visual and sonar systems of several species of bats, Pettigrew finds that the visual system is not always inferior to the sonar system over the spatial range within which hunting takes place. Moreover, he suggests that vision and sonar navigation might have a symbiotic relation in bats – vision stepping in for those spatial representation tasks for which sonar is ill suited and vice versa.
  - 10 This way of thinking about the problem was suggested to me by Camhi (1984). Much of what follows draws upon that work, although I have chosen to emphasize somewhat different properties of the auditory world.
  - 11 Actually, there is "ambient" sound – but underwater. Recently, a passive underwater sonar system has been developed at The Scripps Institute that uses ambient noise or what the Scripps researchers call "daylight sound" – the constant hiss caused by the

- oscillations of myriads of bubbles near the ocean's surface. The system uses a parabolic acoustic mirror 4 feet in diameter to focus the sounds, with a shielded microphone at the center to measure the sound intensity at that spot.
- 12 This is why sound is such a good source of information about the presence (or lack thereof) of objects of certain types: the rhythmic crunch of the underbrush signals the presence of a heavy animal and so on.
  - 13 While the passive underwater system developed by Scripps (see note 11 above) solves the problem of focus by using an acoustic mirror, the mirror is 4 feet in diameter – not a very practical solution for your average organism (imagine carrying around your very own satellite dish!).
  - 14 Given the refractive index of water, more of the sound signal will be reflected at the water's surface than will travel through the water and reflect off the fish. So, it is likely that the information about the prey is discerned primarily through the surface properties of the water – through ripples and waves as the fish break the surface, a view confirmed by Suthers (1965).
  - 15 For an entirely contrary view about the evolutionary pressures involved in the development of echo-location systems, see Norris and Evans (1988). These authors argue that sound has many advantages over light as a medium for spatial navigation/representation.
  - 16 Actually, because the returning FM signal will be Doppler shifted and because it is the harmonics of the fundamental frequency that are used in timing the echo delay, one does not want to wait for the return of the *very same* frequency. More will be said about these complications below.
  - 17 Harmonics are multiples of the fundamental frequency. As used in the bat literature, the first harmonic is the fundamental frequency, the second harmonic is twice the frequency of the fundamental, the third harmonic is three times the frequency and so on.
  - 18 But if distance is the crucial factor, why is it that the fundamental frequency is not emphasized, a sound which would travel further? As I said above, there is a trade-off between range and grain, how far the signal travels versus how small an object will reflect the sound. Why, then, have the fundamental tone around 31 kHz? As we will see later, the fundamental frequency is used as a "cue" by the neural system to mark the time of the outgoing call; because the fundamental tone is produced at so low an intensity, only the bat that produces the tone can hear it, thus eliminating much interference caused by the cries of other bats.
  - 19 In recent work, Simmons et al. claim that the Big Brown bat can perceive an echo-delay change of as little as 10–12 *nanoseconds*, which is equivalent to a change in range of  $2 \times 10^{-6}$  meters. Clearly, if this is so, the bat has much finer texture discrimination than any organism with vision. It is for exactly this reason that I am somewhat suspicious of these results.
  - 20 The summary below is taken largely from the research of Nobuo Suga and his colleagues; for summaries of this work see Suga (1984, 1988, 1990).
  - 21 Much of the evidence that confirms this hypothesis comes from studies of the Horseshoe bat not the Mustached bat; moreover, neurons in the CF/CF area also show synchronous discharge. I have simplified the evidence for pedagogic purposes.
  - 22 More formally, following Strawson (1959), let us assume that there are two necessary conditions for having a representation of objective particulars or a point of view. First, for an organism to have a conception of *objective* particulars, the organism would need the resources to distinguish between itself and states of itself, on one hand, and that which is not itself or states of itself on the other. In its crudest form, this is the ability of an organism to make a distinction between "me" and "not me." (For example, in the bat's case, the bat ought to be able to distinguish between motion that it makes relative to a stationary target, and motion of a target relative to the bat, i.e. the distinction between

- "it's moving" and "I'm moving.") Secondly, a conception of *particulars* – re-identifiable particulars – requires that the organism have the means by which to distinguish reliably, over time, between numerical and qualitative identity, between the same object once again and another just like it. (Here, this might be the ability, say, to keep track of and differentiate *this* Lunar moth, now approaching at the right of the sonar field, from *that* Lunar moth, one that just recently made a narrow escape.)
- 23 One should take this only as a denial of only *large-scale* integration, for integration, on a small scale, must occur given the rapid on-off nature of the sonar "chirps."
- 24 Given how little we know about bats, however, this conclusion must be taken with a grain of salt. There are many outstanding questions one would like to see answered, about the bat's behavior during the hunt, about its other activities that involve knowledge of permanent objects and structures, and about the integration and overlap of sonar information with other sensory modalities. One might wonder, say, whether, in tracking the moth during the hunt, there is any predictive element involved, a calculation of the moth's trajectory, or whether the bat's behavior is simply guided by an on-line indication of where the moth is at present as the story suggested. Does the bat predict where the moth will go and then base its behavior on its predicted trajectory or are the evasive movements of the moth simply too erratic to make feasible anything but a simple servo-mechanism? Similarly, when a pursued moth actually does manage to evade the bat, there is the problem of the bat's ability to get back on track, to relocate the moth and begin another pursuit. If the bat is distracted during the pursuit phase, does it have the ability to return to the scene, to take up where it left off, or does it simply start the search phase all over again and proceed as it would for a new insect? Then again, bats, we know, live in complex caves, have permanent roosts, hunt in preferred places and can locate and identify their young in a crowded communal roost with thousands of other nearly identical offspring. How, then, do bats find their way around maze-like structures or pick out their own young as their own? What sensory systems are involved in these kinds of tasks and what representational structures underlie this behavior? Finally, we would want to know how the information gleaned by the sonar system linked with visual information and other sensory modalities. What kind of information does the visual system provide and how is it integrated (or is it?) with sonar encodings. All of these questions are pertinent to understanding the bat's conceptual ontology. For a variety of relevant articles, see, for example, on the topic of image formation, Simmons (1989); on the topic of inter-model interaction, Pettigrew (1988) and Surlykke (1988); on tracking strategies, see Masters (1988) and Campbell and Suthers (1988); and on sonar navigation strategies in artificial intelligence, see Mataric and Brooks (1990).
- 25 This is where my view most clearly conflicts with Dennett's understanding of "the intentional stance", for my claim is that the neural system of any organism must have certain representational capacities if it is to be legitimately ascribed intentional states.
- 26 The notion of a "subjective world" used here is significantly different from what Dennett had in mind when he posited "notional worlds." (For a good explanation of Dennett's concept see "About Aboutness" in Dennett, 1987.) Dennett posited notional worlds as a way of expressing the propositional content of mental events without using "belief that p" statements and their attendant commitments to propositional content. By imagining what world(s) a creature would be *best suited* to survive in, we are supposed to determine between which properties of the world the organism genuinely discriminates. In this way, we can determine what Dennett termed the "organismic contribution" to the semantic content of its belief state. Above, the notion of a "subjective world" is not designed to play any role in a semantic theory of mental states. Rather, it is a notion that is used to show how an organism *without* intentional mental events makes sensory contact with the world: the kind of information available inside the bat under conditions of normal behavior and environment.

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## 8

## Mind is Artificial

BO DAHLBOM

We come to the full possession of our power of drawing inferences the last of all our faculties, for it is not so much a natural gift as a long and difficult art.

C. S. Pierce, "The Fixation of Belief"

When Daniel Dennett's *Content and Consciousness* was published in 1969, two other books of great importance appeared. Herbert Simon's *The Sciences of the Artificial* was a forceful plea for a radical reorientation of the sciences towards "a science of design" based on an appreciation of the fact that "the world we live in today is much more a man-made, or artificial, world than it is a natural world" and the fact that man himself, or the human mind, is the "most interesting of all artificial systems." W. V. Quine's *Ontological Relativity and Other Essays* expressed a more conservative appreciation of the natural sciences, wanting to "naturalize epistemology," defining it "as a chapter of psychology and hence of natural science" studying "a natural phenomenon, viz., a physical human subject."<sup>1</sup>

Quine's ideas about a naturalized philosophy were perceived as radical by the philosophical community and created quite a commotion. Simon's ideas about cognitive science, as a science of the artificial with a sociological aspect, were much too radical to be perceived at all. The cognitive science coming out of the creative atmosphere of the 1960s was and still remains a natural science. As one of the more forceful proponents of naturalism, Daniel Dennett is original in that he has, over the years, shown a growing appreciation of the artificial.<sup>2</sup> Indeed, the way I like to think of his philosophy, is as being situated in between Quine and Simon, rather closer to Quine but very much aware of the attraction of Simon. In this essay I shall try various strategies to push him further in that direction, and then return at the very end to a discussion of some of Simon's ideas for an artificial science. What I will do, in effect, is outline an artificial, or social, alternative to naturalism, and what would be more natural than to call it "socialism?" That word seems to have no better use at the moment.