

Rate versus Temporal Coding Models

Introductory article

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Information is represented in the brain by the electrical activity of neurons. A number of current theories attempt to explain this neural code of information and how it is used by the brain to achieve perception, action, thought, and consciousness.

INTRODUCTION

All theories about how the brain functions are based on the idea that information is represented by the electrical activity of neurons. The question of how neurons represent information is therefore fundamental to all branches of neuroscience. What is the neural code of information, and how is it used by the brain to achieve perception, action, thought, and consciousness? In other words, which aspects of a neuron's electrical activity convey information about the environment and our mental states?

It is common practice in many laboratories to display the electrical activity from one or more neurons in an animal while it looks at, hears, and reacts to its environment. This neural activity appears as a sequence of very brief events, known as action potentials or spikes, separated by gaps of variable duration (Figure 1). The intervals between spikes can be as long as a few tenths of a second or shorter than a hundredth of a second. The spikes and the intervals between them convey the neuron's message. If we wish to decipher the neural code, we need to know how to read these messages.

Certain facts are well established. The only message that one neuron can give another neuron in another part of the brain about what it has computed must be represented in the sequence of spikes that are transmitted along its axon. The time-scale for neural computations involved in perception, thought, and action is too short to allow gene expression, protein synthesis, and chemical

cascades to play a part in carrying information. Spikes are the only items in the alphabet, but unlike letters, there is only one kind. The spikes are all-or-nothing events – size does not matter. The question is how to read this sequence of spikes emitted by neurons as a function of time.

In its broadest sense, temporal coding refers to three types of problem. First and most obvious, neurons must code information that changes as a function of time. Stimuli come and go and change their intensity; behavior – and the thought behind it – is dynamic. Insofar as spikes code information, they must code information that changes as a function of time. Second, there is a possibility that the time structure of neural activity could be used to represent information. That is, spike times and intervals could expand the alphabet that the brain uses to encode stimuli, sequences of actions, and ideas. Third, neurons must ultimately code time itself: how much has elapsed, when an expected event is likely to occur, and so on. This article

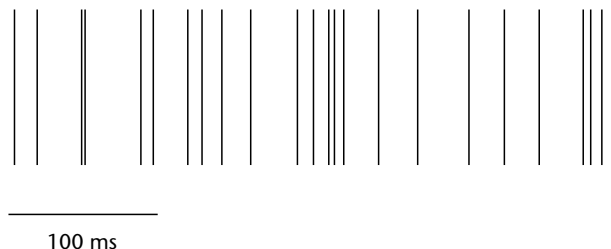


Figure 1. Neural spike trains. Neurons encode information using electrical impulses known as action potentials or spikes. A sequence of impulses is called a spike train. Information processing in the brain occurs through the interactions of neurons that communicate with one another by transmitting spikes. A sequence of spikes like this one was emitted by a neuron in the visual cortex in response to a moving light. Notice the irregular intervals between the spikes. This is a common feature of spike trains in the cerebral cortex.

examines the first two forms of temporal coding; the coding of time itself is only just beginning to be studied at the neural level.

A MENU OF TEMPORAL CODES

It makes sense to confine speculation about the neural code to neurons whose role in perception and behavior are known to at least some degree. Although the properties of neurons in much of the brain remain mysterious, the function of many neurons has been elucidated in some detail, especially in the primary sensory and motor areas of the brain. Thus far, this knowledge has rested on the fact that neurons emit more spikes in less time when a restricted set of conditions holds – such as when light of a particular orientation is present in a tiny region of the visual field and moving in a particular direction. Put simply, the neurons that we know the most about signal information by changing the rate at which they emit spikes.

The spike ‘rate code’ is thus well established as the vanguard neural code, and we will consider its role in temporal coding in a moment. However, there may be other ways to encode information in spike trains in addition to spike rate. In principle, these alternatives could expand the alphabet that the brain uses to encode information. Table 1 looks at the evidence for four putative neural codes: the time-varying rate code, which uses spike rate to code time-varying signals in the environment or in the state of a calculation; the spike bar code and the rate waveform code, which use time itself to evoke information about objects; and the synchrony code, which uses a pattern of spikes across many neurons to encode information. Each of these codes would promote a different scheme for encoding information in trains of spikes. We will consider each of them in turn, keeping in mind that they are not mutually exclusive ideas.

It should be stated at the outset that many ideas about temporal coding are just that: ideas. This is an active area of research that is being updated

continually on the basis of new information obtained at all levels of inquiry, from the channels responsible for electrical activity in parts of the neuron, up to recordings from intact brains in behaving animals. Therefore, in addition to describing the ideas behind the putative temporal codes, this article will try to evaluate the evidence in support of each code.

The evidence for a temporal code can be divided broadly into four categories (see Table 1). First, the code can be detected reliably from neurons upon repeated exposure to the coded stimulus or upon repeated actions or circumstances. Second, the neural signal – its presence, absence, intensity or quality – is associated with variation in an animal’s perception or behavior. If a neural signal putatively codes the color red, the animal should be less likely to ‘report’ (via its behavioral response) that it has seen red when the neural signal is absent or degraded. Third, when the signal is introduced to the brain artificially through electrical microstimulation, it causes an animal to act or perceive in accordance with the information thus encoded. Fourth, the properties of neurons – synapses, passive and active electrical properties – must be capable of preserving the coding scheme. If a proposed code were to require that action potentials occur within 1 ms of each other, we could reject the code on the basis of the fact that neurons have refractory periods of at least 1 ms before they can fire a second action potential.

Note that the first three items require experiments on the intact brain, although the first does not require the animal actually to do anything. The last item is informed by experiments that address how neurons work, namely, the reliability of their synapses and the way in which electric current is gathered by the dendrites and converted to action potentials at the initial segment of the axon.

With these guidelines in mind, let us turn to the four putative temporal codes and evaluate them based on the four categories of evidence.

Table 1. Evidence for four candidate temporal codes

<i>Type of evidence</i>	<i>Code</i>			
	<i>Rate</i>	<i>Spike bar</i>	<i>Waveform</i>	<i>Synchrony</i>
Reproducibility of response	✓	✓	✓	✓
Correlation of response with behavior	✓	✓		
Brain stimulation mimics inferred message	✓	✓	✓ ^a	
Biophysical plausibility	✓	✓	✓	✓

^aEvidence comes from one experiment in peripheral nerve responsible for taste.

Time-varying Rate Code

Neurons throughout the brain, spinal cord, and peripheral nervous system alter their rate of spike discharge to represent a change in intensity. Examples include pressure at a spot of skin, contrast in a spot on the visual field, the salience of a moving visual display, the proximity of an intended eye movement to a place in the visual field, and the force exerted by a muscle. The time-varying rate code is thus the best-known example of a temporal code. It is clearly the dominant principle of activation in the peripheral nervous system: the more spikes, the greater the intensity of the stimulus or the greater the force of the muscle contraction.

The rate code applies in the cortex as well, but there is a catch. Because the spikes emitted by a neuron occur at irregular intervals, the spike rate cannot be discerned from the interval between two spikes. From the point of view of a neuron that is receiving the message about rate, it would need to wait for several spikes to get a sense of their average rate. However, simple perceptual tests show that the brain is capable of processing information about changes in sensory stimuli that occur very quickly, as fast as one or two spike intervals. Evidence from neuroanatomy and neural recording

experiments suggests that the cortex solves this problem by representing rate using several neurons. Because the receiving neuron obtains many samples of the same message, all with different erratically spaced spikes, it can estimate the spike rate by averaging across neurons in a short period (Figure 2).

The time-varying ensemble spike rate is a simple temporal code that allows the brain to keep track of dynamic changes in the sensory environment. In principle, it can be used to represent the intermediate stages of neural computations that underlie changes in mental states, idea formation, decision-making, and emotions.

Of the four categories of evidence described above, all support a role for spike rate in the coding of information.

1. Changes in spike rate are reliably reproduced in laboratory conditions when the same stimuli (or behavior) can be presented repetitively.
2. Variability in the spike rate predicts sensitivity to weak stimuli; for example, when monkeys make difficult judgments about sensory stimuli, their rate of errors can be predicted by the variability in the spike rate of appropriate neurons in the sensory cortex. In parts of the association cortex, it is possible to know which way an animal will decide about an ambiguous stimulus by measuring the spike rate.

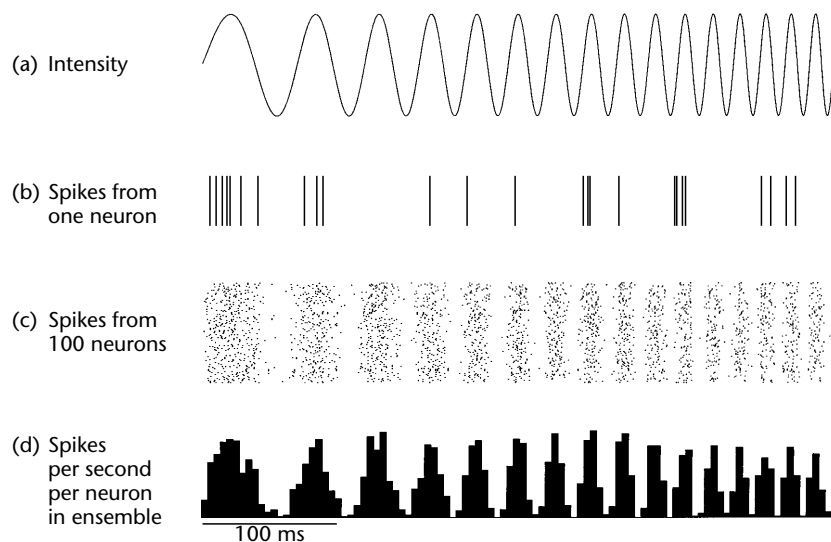


Figure 2. Time-varying rate code. How do neurons encode information that changes as a function of time? (a) A time-varying signal is shown at the top of the figure. This could represent a changing light intensity, or a quantity used in a calculation for directing attention, say, to a bouncing ball. In this example, the signal intensity changes slowly at first (left) but eventually the changes occur more rapidly. (b) A single neuron emits spikes more often when the intensity is high, but the intervals between spikes preclude encoding the rapid changes in signal intensity. (c) If there are many neurons that emit spikes in this fashion, then their average (d) provides a reasonable approximation to the signal. This ensemble coding takes advantage of the presence of many neurons that encode the same information by changing their rate of spike discharge.

3. Electrically stimulating small groups of neurons (300–1000) to higher rates causes movements and, in a few cases, apparent changes in perception. In one remarkable example from the visual cortex, investigators measured the spike rate from individual neurons in association with visual stimuli. On the basis of changes in spike rate, they deduced the message represented by that neuron and its neighbors. This deduction is really a hypothesis about the neural code. In one of the few direct tests of this hypothesis, the investigators stimulated the neurons by passing small amounts of alternating current through the electrode. This stimulation caused animals to report perception of the stimulus, consistent with the message the investigators had inferred from the spike rate.
4. There is ample evidence from biophysics that neurons increase their rate of spike discharge when they receive more excitatory input. Exactly how neurons achieve a stable rate of firing in response to synaptic input is an active area of research. The source of variability in the spike discharge, hence the reliability of the rate code, is also an active area of investigation. As mentioned earlier, the variable spike discharge seems to be a property of cortical neurons, which for unknown reasons are much more variable in their response than are neurons in subcortical structures.

In short, there is ample evidence that the brain uses a time-varying rate code to mark the intensity of a stimulus, action or variable in a computation. The actual identity of a stimulus (e.g. its color,

location, direction of movement), the particular action, or the fact that a variable is subtracted or added is coded by the neuron's location in the brain, namely its connections to other neurons and presumably its position in space in the cortex. According to this view of temporal coding, the rich set of symbols that the brain uses to encode information derives mainly from wiring in the patterns of neurons that can be activated under a variety of conditions (through development and learning). The rate code is just a way to represent the degree of this activation – the amount of evidence for a proposition that is represented by the identity of the neuron or neural ensemble. This idea is sometimes referred to as a labeled-line or place code.

In contrast, we now turn to two putative neural codes that use the pattern of spikes as a function of time to encode different features of the environment. By using time to code something else, they have the potential to achieve a much higher degree of complexity than the rate code.

Spike Bar Code

The intervals between spikes in cortex tend to be quite variable, but depending on one's point of view, this variability can be seen as a nuisance (as above) or as a potential code. Figure 3 illustrates

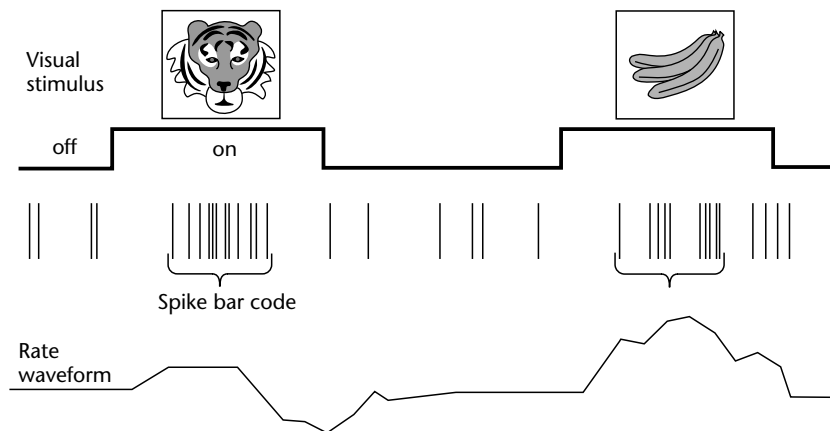


Figure 3. Spike bar code and rate waveform code. Spike activity from an idealized neuron occurs in association with the appearance of two visual stimuli. Brackets identify patterns of spikes that could provide distinct labels for 'tiger' and 'banana' akin to a bar code used to identify merchandise in retail stores. This idea and other related spike interval codes are improbable because specific spike patterns do not occur with any systematic regularity in the cortex. The jagged trace below the spikes represents the ensemble spike rate that might be obtained by averaging the activity from many neurons increasing and decreasing their rate of discharge in a manner similar to the spike train shown. According to this scheme, the exact pattern of spikes from each neuron would not carry information; rather, each neuron contributes to the average spike rate (as in Figure 2). The spike rate waveform has a different shape in association with the tiger and banana. It has been suggested that this rate waveform could encode stimuli. Note that both the spike bar code and the rate waveform codes would allow the same neuron to encode a variety of messages and that both use time to encode stimuli that are not changing.

a rather extreme idea for a temporal code, which this author terms a 'spike bar code'. The example shows a neuron that emits a different pattern of spikes when different pictures are presented to vision. The particular pattern of intervals separating the spikes could in principle symbolize a complex object. There are many possible patterns of spikes that a neuron could emit in a 300 ms window of time – roughly the amount of time between successive scanning eye movements. Therefore, the bar code could provide a rich alphabet for coding information.

The spike bar code illustrates an intriguing idea, but at present there is little evidence to support its use in the brain (see Table 1).

1. There is no example of a neuron in the cortex that emits the same pattern of spikes in association with a particular stimulus or behavior. There are occasional reports of patterns of spikes that seem to occur more often than expected by chance in some parts of the cortex, but not in association with a particular stimulus or action, and the claim that the patterns do not occur by chance has been contested.
2. Without clear evidence of specific patterns, it is impossible to test whether they predict errors in perception or variability in behavior.
3. To the minimal extent that anyone has tried to mimic patterns of activity in the brain, the effort has not yielded anything of interest.
4. The main evidence in favor of such a code is that it is not ruled out by what we know about how neurons generate action potentials.

In particular, neurons seem to be capable of emitting action potentials with a precision of below 1 ms in response to the same amount of current. The argument then goes like this: if the intervals between spikes can be controlled so precisely, then the brain must be using these intervals for coding. Of course, we do not really know that the intervals between spikes can be controlled precisely; we know only that the source of imprecision is not the part of the neuron that converts the current it collects to an action potential.

Besides the lack of experimental evidence for the spike bar code, there are two additional problems. First, the signal would need to be deciphered by neurons at the receiving end. It is hard to imagine a mechanism that would allow a neuron to respond selectively to a spike pattern that extends by more than a few tens of milliseconds or a few spikes. Second, it takes time to decode such a message. At a minimum, it would take the length of the message itself (about 300 ms for the messages depicted in Figure 2). It is hard to reconcile such a scheme with the rapidity of sensory processing.

Rate Waveform Code

The rate waveform code is related to the bar code in that it also uses the temporal changes in spike production to encode information. In this case, it is not the precise pattern of spikes and intervals but rather the rate of spike production that codes information. In the example in Figure 3, a benign stimulus (the banana) causes the spike rate to rise and then return to baseline, whereas in response to a threatening stimulus (the tiger) the rate rises and then falls below baseline before returning to baseline (i.e. it has a positive and negative phase). The spikes themselves occur more or less randomly, but with greater or lesser frequency in accordance with these rate waveforms. As noted earlier, this implies that many neurons undergo similar rate fluctuations.

There is better evidence for the rate waveform code than for the bar code.

1. In the visual cortex, some stimuli give rise to transient increases in spike rate followed by a rapid return to baseline, whereas others lead to more sustained responses. Usually, different neurons respond in these modes, but there are examples of the same neuron responding to one kind of stimulus with sustained activity and to another more transiently. The best example of a temporal code of this sort is found in the taste system, where different tastes (e.g. sweet and bitter) cause the same neuron to undergo different patterns of rate change.
2. The second type of evidence is lacking, however. If different waveforms connote different messages, then one would like to witness a correlation between the variation in response waveform and an animal's perception. Experiments of this type have not been tried or have been unsuccessful.
3. The third type of evidence, manipulation of the code, has been tried in the taste system of rats. When the brainstem nucleus that receives taste information is stimulated, rats respond as if they had tasted bitter or sweet, depending on the pattern of firing rate change induced by the stimulation. Experiments of this type have not been tried in the cortex. The closest example is a negative finding: changing the temporal pattern of activity in the somatosensory cortex does not interfere with a monkey's ability to discriminate flutter vibration frequency.
4. Because neurons can modulate their firing rate, there are no obvious theoretical obstacles to the coding of information with a rate waveform.

Although we do not yet know how a rate waveform would be decoded, it is in principle no more difficult a problem than decoding any time-varying function, as occurs in visual neurons that respond to stimuli moving in a particular direction and speed.

Synchrony Code

The last item on the menu is the synchrony code. This is a popular example of a code that would exploit temporal and spatial relationships between spikes to encode information (spatial in this context refers to places in the brain). The idea is that simultaneous spikes from two or more neurons might encode information. A natural candidate for the kind of information to be encoded is the relation between parts of objects or elements of movement. That is, synchronous spikes could represent combinations of features that are themselves encoded by single neurons or ensembles of neurons with similar properties.

Like the spike bar code, the synchrony code exploits the irregular intervals between spikes. As illustrated in Figure 4, another implication of irregularly spaced spikes is that the odds of any two neurons emitting a spike at the same moment (say, within 3 ms of each other) is a relatively rare chance event. It has been suggested that under particular circumstances, neurons can produce synchronous spikes in excess of the rate expected by chance. These synchronous spikes could constitute a special code. In vision, for example, it has been proposed that synchronous spikes are used to bind together separate features of objects into coherent wholes (Figure 4) and even to promote the representation of vision to conscious awareness.

Despite the enthusiasm for this code, there is little evidence to support it.

1. There are many examples of pairs of neurons that emit synchronous spikes reliably. Typically, these are neurons that lie near each other in the brain and receive common synaptic input. There are also reports of neurons that encode different visual features but tend to respond synchronously when the two features are bound to a common object.
2. The few attempts to correlate synchronous spikes with behavior have failed to provide supporting evidence for a synchrony code. For example, synchronous spikes occur just as often whether a pair of features represented by the neurons is bound to a single object in the foreground or is split, with one feature in the background.
3. Experiments in which synchrony has been mimicked by means of stimulation have been performed in the motor system, but there is no report of any experiments in which sensory neurons have been stimulated in and out of synchrony. This might be technically difficult because stimulation always tends to synchronize the neurons near the stimulating electrode. On the other hand, some investigators have tried to disrupt synchrony by imposing asynchronous flicker to different component features of an object. This

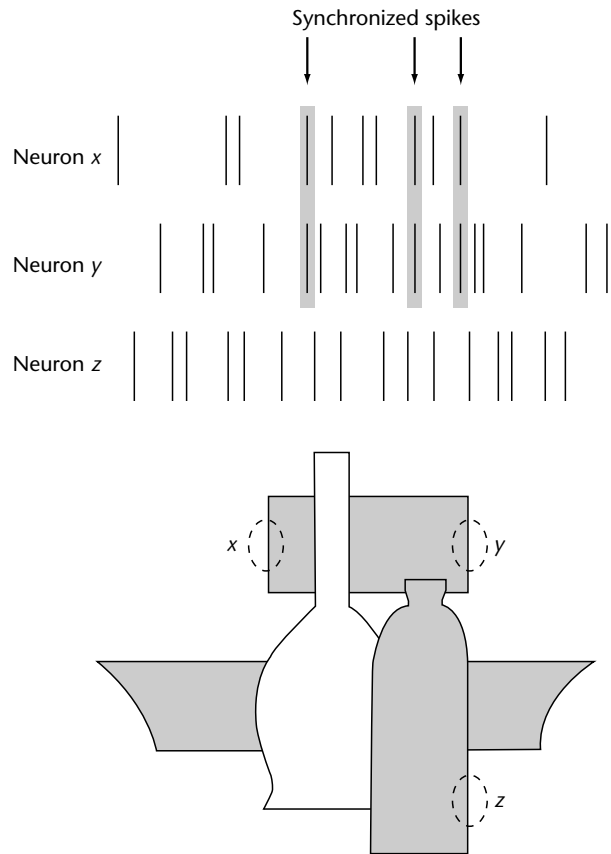


Figure 4. Synchrony code. Idealized responses from three neurons to a visual scene consisting of bottles and shapes. The three neurons respond to vertical contours marked by the dashed ellipses. The ellipses are not part of the scene. The spikes from each of the neurons exhibit variable intervals. On three occasions, spikes from neurons *x* and *y* occur within 3 ms of each other (arrows and gray highlight). Using this criterion, there are no synchronous spikes between neuron *z* and the other neurons. It has been proposed that synchronous spikes could encode information about the scene. For example, the synchronous spikes could indicate that the contours at the locations represented by *x* and *y* are part of the same object, whereas the contours represented by neurons *y* and *z* are not part of the same object. Despite much enthusiasm for this idea, the experimental evidence is weak.

seems to have no effect on perception and thus casts doubt on the idea that synchronous discharge encodes anything special.

4. Much of what we know about synaptic physiology would indicate that synchronous spikes are more effective than asynchronous spikes at inducing a response from a postsynaptic neuron. However, cortical neurons receive many hundreds of excitatory inputs for every spike they emit. It is far from clear how synchronous spikes that convey information are to be distinguished from the rest of these spikes.

CONCLUSION

The topic of temporal coding is fundamental to basic and clinical neuroscience. The ability to read the neural code will help neuroscientists understand how the brain represents information and uses it in novel computations that underlie thought and behavior. Understanding the neural code may one day provide the ability to use brain recordings to control prosthetic devices in people who suffer from spinal cord and nerve injury.

The evidence at hand favors the use of spike rate to encode the intensity of values whose meaning is given by the identity of the neuron or group of neurons emitting spikes. This ensemble rate code is a temporal code because it provides a means to represent intensity (or magnitude) as a function of time. The alternative codes use time to encode meaning. These putative codes could expand the brain's ability to represent information in the same way that the Morse code allows two symbols (dot and dash) to encode all the letters of the alphabet (or the computer binary character code, which allows two numbers, 1 and 0, to encode all typographic symbols). There is some evidence for spike timing codes in the peripheral nervous system and in brainstem structures that are specialized for processing sound, but the idea is largely unsupported in the cerebral cortex.

Further Reading

Bair W (1999) Spike timing in the mammalian visual system. *Current Opinion in Neurobiology* **9**: 447–453.

Britten KH, Shadlen MN, Newsome WT and Movshon JA (1992) The analysis of visual motion: a comparison of neuronal and psychophysical performance. *Journal of Neuroscience* **12**: 4745–4765.

DeCharms RC and Zador A (2000) Neural representation and the cortical code. *Annual Review of Neuroscience* **23**: 613–647.

Di Lorenzo PM and Hecht GS (1993) Perceptual consequences of electrical stimulation in the gustatory system. *Behavioral Neuroscience* **107**: 130–138.

Lamme VAF and Spekreijse H (1998) Neuronal synchrony does not represent texture segregation. *Nature* **396**: 362–366.

Leon MI and Shadlen MN (1998) Exploring the neurophysiology of decisions. *Neuron* **21**: 669–672.

McClurkin JW, Optican LM, Richmond BJ and Gawne TJ (1991) Concurrent processing and complexity of temporally encoded neuronal messages in visual perception. *Science* **25**: 675–677.

Ogawa H, Yamashita S and Sato M (1974) Variation in gustatory nerve fiber discharge pattern with change in stimulus concentration and quality. *Journal of Neurophysiology* **37**: 443–457.

Parker AJ and Newsome WT (1998) Sense and the single neuron: probing the physiology of perception. *Annual Review of Neuroscience* **21**: 227–277.

Rieke F, Warland D, de Ruyter van Steveninck RR and Bialek W (1997) *Spikes: Exploring the Neural Code*. Cambridge, MA: MIT Press.

Romo R, Hernandez A, Zainos A and Salinas E (1998) Somatosensory discrimination based on cortical microstimulation. *Nature* **392**: 387–390.

Romo R, Hernandez A, Zainos A, Brody CD and Lemus L (2000) Sensing without touching: psychophysical performance based on cortical microstimulation. *Neuron* **26**: 273–278.

Salzman CD, Murasugi CM, Britten KH and Newsome WT (1992) Microstimulation in visual area MT: effects on direction discrimination performance. *Journal of Neuroscience* **12**: 2331–2355.

Shadlen MN and Movshon JA (1999) Synchrony unbound: a critical evaluation of the temporal binding hypothesis. *Neuron* **24**: 67–77.

Shadlen MN and Newsome WT (1994) Noise, neural codes and cortical organization. *Current Opinion in Neurobiology* **4**: 569–579.

Shadlen MN and Newsome WT (1998) The variable discharge of cortical neurons: implications for connectivity, computation and information coding. *Journal of Neuroscience* **18**: 3870–3896.

Singer W (1999) Neuronal synchrony: a versatile code for the definition of relations? *Neuron* **24**: 49–65.

Softky WR and Koch C (1993) The highly irregular firing of cortical cells is inconsistent with temporal integration of random EPSPs. *Journal of Neuroscience* **13**: 334–350.