Chapter 2
Brain Architecture for an Intelligent Stream of Consciousness

Introduction

This chapter proposes a brain system building up from the known logical properties of neurons, which must fit together according to the principles of electrical system theory. The possibility of *reverse engineering* a human brain is not investigated below, since this sort of thing is generally attempted in a very limited way using lower life forms. The goal here is to explain higher intelligence and stream of consciousness.

It seems certain that cerebral neurons must operate together efficiently. This implies a system structure that would not be evident within the confines of molecular biology and biochemistry. System considerations soon lead to the concept of a distributed memory in which each element of memory is dedicated to a given mental attribute, an edge, shade, or color, for instance. For efficiency there has to be a one-to-one correspondence between short-term and long-term memory (LTM), since otherwise, memorization and recall are difficult to explain.

Basic psychology suggests that subconscious LTM is associative, where the recall depends chiefly on cues. Well known is that ambiguous cues lead to unpredictable recalls, while exact cues lead to exact recalls. Associative memory is a topic studied in computer science, the principles of which are likely to apply to human memory as well. Thus, as in any associative memory system, human memory must have valid cues for a memory search while avoiding mental blocks, and must resolve the problem of confusing multiple returns, by determining how much is permitted into conscious STM, and in what order.

Common sense is sometimes misleading when it comes to mental processes, but even so, the basic features of a mental system do not have to be exceedingly mysterious. For instance, *forgetting* can be viewed as a mental block in which cues fail to achieve a return from memory. Mental blocks are fatal in dangerous situations, so for survivability, it seems likely there must be a cue editor that fights mental blocks. The *cue editor* discussed in this book does this, and permits a

memory search in the background for forgotten information such that forgotten things sometimes appear in one's consciousness minutes or hours later.

Mental confusion might result from multiple returns for a given set of cues, a common situation when an inadequate number of cues are used to call forth memories, and many different images are returned at once. For survival, and fundamental to any system of associative memory, human memory included, is multiple match resolution. First of all, it must prevent basic memory breakdown because of multiple returns on the same neural paths. Secondly, a basic *recall referee* is essential, including a processor that assigns priority to memory returns and then chooses the highest priority image to be gated into conscious STM. A basic recall referee is proposed in this book.

Decisions are important to a successful life form, and are shown to be choices made mainly by the brain, and not the person involved, based on past experiences logged in LTM. However, other types of decisions are only influenced by past memories, but not determined by past memories, such as random decisions. These are important when guessing a solution to a mysterious problem, for instance, as discussed below.

It continues to be a mystery how a person achieves inspired choices, such as common sense, truth judgment, intuition, and artistic appraisal. These seem to differ significantly from decision based logically on past memories, and decisions based on a random variable. In view of this mystery this book leaves open the possibility of subneural computing of some sort, possibly quantum computing, or quantum-like computing without an actual quantum system, since a quantum might be difficult to achieve biologically. Quantum computing, however unlikely it seems to skeptics, is too important to ignore completely, and so is introduced below and expanded in later chapters.

Classification of Neural Signals

There are many types of signals in neurons and synapses; the most important are illustrated in Fig. 2.1.

The *weak synapse* is one that results in a single pulse in the dendrite. Single pulses are needed in a practical system for accurate timing, as explained in subsequent chapters. For example, single pulses are needed in those situations in which *sequential* logic is necessary, for instance, when there are multiple returns from associative memory arriving sequentially that need to be parked in separate holding areas.

In contrast, a *regular synapse* produces a pulse burst of about ten pulses and is often used for *neural logic*. Neural logic here refers to neurons that compute Boolean *combinational* logic, equivalent to a network of AND, OR, and NOT gates. Included under logic are *buffers* and delay lines with a simple connective purpose.
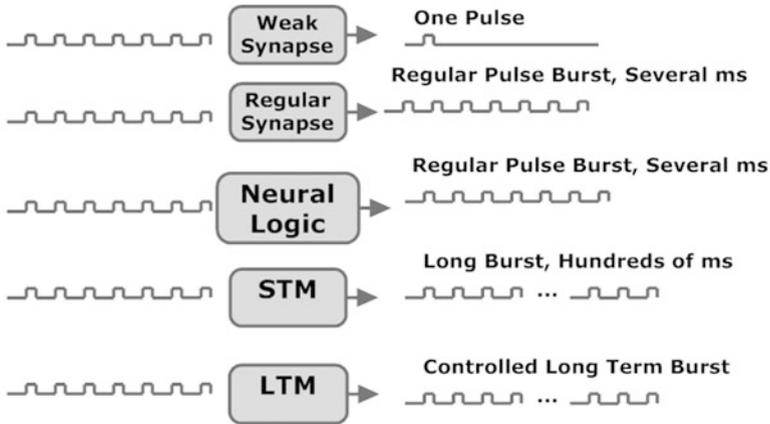
Fig. 2.1 Basic neural signaling (*ms* milliseconds, *STM* short-term memory, *LTM* long-term memory)

Inputs are thought of as pulses propagated along dendrites which have been triggered by receptors. Two major types of neural logic are identified in a later chapter: (1) dendritic logic, of which there may be thousands of gates per neuron, but in a gate of this type, pulses must arrive concurrently, and (2) enabled logic, which is limited to charge accumulation and subsequent triggering at a capacitive body such as a soma. Engineers are familiar with enabled logic in that it pertains to the activation functions used in artificial neural networks.

STM elements have an output burst that can be much longer than ten pulses, depending on ionic conditions within the dendrites, as discussed below. Bursts range in duration from a few milliseconds to several seconds. STM neurons produce regular pulses, that is, between about −70 and +40 mV, with pulse width about 2 ms, so that they are able to signal other neurons.

LTM elements ideally are instantly programmable, and last indefinitely, many decades. They may involve long-term potentiation (LTP) (trapped charge) and recursive neurons (that feed back on themselves); these may be organized to emit regular pulses only when called upon. Mechanisms and purposes of short- and long-term memory elements are going to be discussed in later chapters.

Introduction to Human Memory

The focus in this book is on explicit memory, as perceived in a brain, and not on implicit memory, such as automatic reflexes without direct mental involvement. Human explicit memory may be divided into two types, *conscious STM* and *subconscious LTM*. Signals that activate STM neurons are assumed in this book to flow from the five senses and also from recalls emanating from LTM.

Short-Term Memory Overview

STM lasts a few seconds, and has been termed working memory because if necessary, it could be used for second-to-second living. It stores briefly a significant number of encoded sensations in the form of attributes, or alternately a few complex organized images. STM is somewhat analogous to dynamic memory in a desktop computer, which has to be constantly refreshed.

Intuitively, STM neurons differ in that they may have an internal potassium deficit, or there may be mechanisms to inactivate their internal potassium ions [1]. Consequently a neural pulse in the dendrites can be quite long with an extended positive peak. This pulse is maintained by an assumed lower than normal conductance from the inside to the outside ionic solution so that it cannot quickly discharge. This may be accomplished by an insulator such as myelin. Consequently a long pulse excites the soma to emit an extended burst of pulses easily recognized by connecting neurons. With no extended burst the output is at rest, or false.

Long-Term Memory Overview

When conscious STM experiences images that cycle repeatedly, conditions may be triggered to permit them to be entered automatically into LTM. Images in LTM are not just visual pictures, but include a variety of sensory impressions, songs heard, words read, and impressions in general that have run through STM. What is entered automatically into LTM are particular collections of attributes that make up a mental image.

LTM is somewhat analogous to mass memory in a desktop computer in that it remains hidden until it is called upon. However, LTM in humans differs considerably from LTM in personal computers: Human memory is associative; all images are queried in parallel for matches to given cues. In contrast, computer memory generally depends on knowing a numerical address, and these are looked at serially, one at a time.

LTM and *learning* are two completely different things. Learning may involve synaptic potentiation and growth over a period of time; LTM can be formed immediately, too fast for growth, yet lasts practically forever.

For example, many of us have experienced dramatic or emotional events that occurred quickly, but are firmly remembered. This is a salient feature of LTM; they can be established practically immediately, and they can last indefinitely. LTM, as the term is used in this book, does not require synaptic growth. But it instead uses charge mechanisms that can react immediately. These mechanisms seem to be very different from those of STM neurons.

The exact mechanisms for LTM are still being discussed. How they work is not obvious because neurons do not release many signals compared to solid-state devices, making them difficult to observe in action, especially since they probably

are active for only a brief time, and then only if triggered. Generally speaking, neurons are relatively small and easily upset by probing, so direct in vivo observation is difficult. Note for the record that memory elements are located randomly and duplicated extensively, so given memory episodes are nearly impossible to locate experimentally, meaning particular unwanted memories are difficult to remove surgically.

An interesting theory is that needed attributes are held efficiently by *LTP* [2]. Another interesting theory is that recursive neurons support cycling pulses that use almost no energy, and that are readable with positive signals for needed attributes [3]. A hybrid element using LTP and recursive neurons is proposed in a later chapter, giving instant memorization as well as efficient long-term storage. Elements of LTM as needed for a neural system have to be readily accessible to conscious STM, and it is critically important that they have ability to be queried; so a logical system is suggested.

Introduction to a Memory-Based Brain System

When considering a neural system that results in a stream of consciousness, it may be noted that nature evolves according to certain principles. Entities of nature, including brains, can survive only if, on the average, they are efficient.[1] Concepts such as the *grandmother neuron*, in which all attributes are stored in a single large neuron, have to be discounted because they are incompatible with bringing forth an image into conscious STM in an efficient way.

Transferring images from LTM into STM, and transferring images from STM into LTM must also be efficient. This implies that each attribute located in STM directly corresponds to a similar attribute located in LTM, an architectural feature known as *distributed memory* [4] to be discussed later.

This one-to-one correspondence implies that memory is logically organized into words. Memory words are a logical, not a physical, structure. Since not every image contains every possible attribute, memory words are *sparse*. Sparse means that entries in a word are separated by unused places corresponding to where certain attributes are not present, and that these places hold either unused neurons or neurons that have been turned to some other purpose.

Excitatory synapses serve to initiate neural pulses; inhibitory synapses serve to moderate neural pulses, as does the capacitance of larger bodies such as the soma, all of which results in a pulse-based system of logic. Memorization and other brain capabilities depend on *dendritic logic* which occurs mainly in dendrites where *Boolean operations* are accomplished, as verified in part by simulations of dendrites.

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[1] Maupertuis principle of least action that nature is thrifty in all of its actions.

Another form of logic, known as enabled logic, occurs for larger bodies of capacitance, for instance, somas, as presented in a later chapter. As a result, a complete set of Boolean logic (AND, OR, NOT) is available, a natural result of synaptic activity in combination with active and passive regions in dendrites, soma, and sometimes also axons. Dendritic logic is compared to enabled logic in a later chapter.

Systems are typically expressed in terms of logical, not physical, structures, and brain systems are no exception. Human LTM is *associative*, which hints that location is not a prime consideration; things are recalled not according to where they are, but according to what they are. In contrast, in a desktop computer, each word in memory has a unique *address*, and a physical place. Addresses are used for reading or writing to locations that may be chosen at random, so the choice is random. Hence the term *random access* memory, or RAM. Human memory, in contrast, does not have fixed addresses, so we know a lot less about where memories reside.

Retrieval from subconscious LTM begins with cues. For example, seeing someone's dog can bring forth a memory of your own faithful companion, and might even bring forth details of face, color, size, and so on. Other such examples are visiting your home neighborhood which brings forth memories of stores, houses, rooms, passageways, and so on; seeing a book that you used in college can bring forth memories of what you learned in those days. Cues are essential to memory retrieval.

Cues need to be chosen judiciously from the current contents of conscious STM. If the available cues do not result in a recall, editing is available to adjust the cues for another try. Hopefully there will be a *hit*, which means an exact match to the cues. Memories with attributes that exactly match the applied cues will be read for possible entry into conscious STM. Cues applied to LTM have to be exact, since LTM are called forth only for exact matches. Gratefully, old memories are dormant until receiving an exact set of cues. Serious overload would result if we had to experience all facts, even irrelevant ones, at all times.

Under the distributed model each attribute connects to specific locations in STM and corresponding locations within words of LTM. These locations exist physically, although current technology does not permit a knowledge of exact location. But nevertheless each location in STM has corresponding locations in LTM that are reserved for a particular feature. This is an efficient way to organize STM and LTM because it avoids extra encoding and the passing of data to intermediary storage sites.

A given attribute might be said to have meaning not because it has any special coding, but because of its physical location in a word. For example, the color *red* might be in a certain location, say the 537th cell from the left in a delineation of logical STM; it is also the 537th cell from the left in each of its replications in LTM. Location in memory and the context in which the attribute is used contribute to realizing the meaning of an attribute, as for example, when seeing a fire engine in the context of a street, it is expected to be red.

The one-on-one distributed model implies that neurons are not multiplexed, that is, different attributes are not communicated by the same neuron. Fortunately neurons are quite plentiful and are conveniently dedicated to a given attribute as described.

Human memory is not *erasable* and is not converted into *blank* words in the ordinary sense, nor can words be overwritten as they are in the *RAM* of desktop computers. Once something is committed to memory, it is there indefinitely. In this sense, LTM is akin to *read only memory* (ROM). Under the ROM concept, new brain memories cannot overwrite old memories; instead they must be written into blank words available for that purpose, the subject of a later chapter.

A System for Stream of Consciousness

A system of consciousness can now be sketched: Simulations of neural logic have suggested a brain system based on *bottom-up* construction. *Attributes* are calculated from the senses and are made to enter conscious STM as an image, but alternated with the senses are images in the form of a set of attributes from memory recalls. Attributes currently in conscious STM are a main source of cues, which are not necessarily perfect.

For *conflicting* or *overdetermined* sets of cues, or too many cues, editing is essential. Editing strives to remove conflicting cues to achieve returns. For *underdetermined* cues, when cues are few in number, one expects an excessive number of returns. In this case, returns are edited subliminally, and the one that calculates to be most important is selected for entry into STM, where it becomes a *recall*. Figure 2.2 shows how these two major editors form what may be construed to be a cybernetic[2] system, that is, a system in which attributes selected from a current image are used to determine the next image.

A system for stream of consciousness may be summarized as follows. A set of attributes in STM are taken as cues and serve to find related images in associative LTM. A high-priority recall is selected from the resulting returns, and overwrites the fading contents of STM. The process repeats, giving a moving picture in conscious STM.

Cue Editor

What can happen is either (1) no recall or (2) excessive number of recalls. Everyone has experienced no recall, trying to remember something but being unable to do so. So you go about your business, but unknown to you, a search proceeds subliminally for what you are trying to remember. Cues keep cycling subconsciously, but are insufficient to return an image. However, when you least expect it, possibly at an inconvenient moment, the correct memory will pop into conscious STM with amazing clarity. This is an indication that the brain has worked in the background

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[2] Cybernetics was defined by Norbert Wiener (1894–1964), in his book of that title, as the study of control and communication in the animal and the machine.
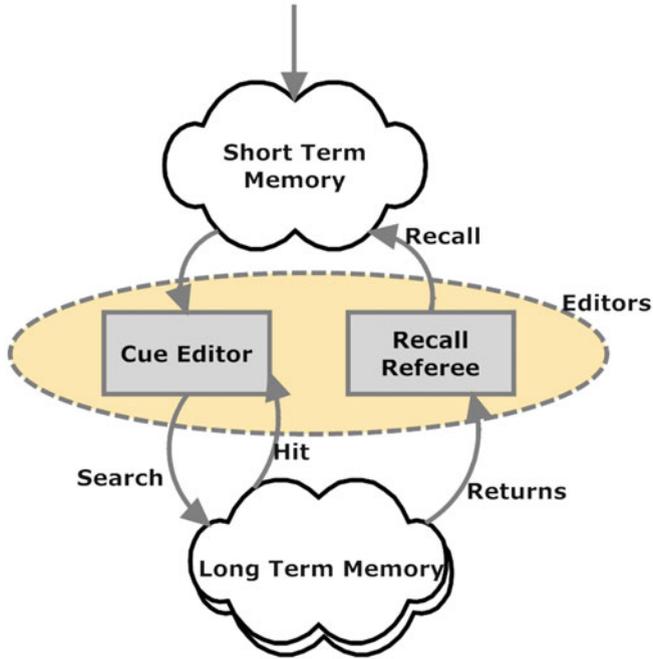
Fig. 2.2 Subliminal editors in relation to short- and long-term memories

without being noticed, adding or subtracting cues from a search until the cues are exactly right, as they must be for a recall.

A *cue editor* helps resolve conflicting cues (which would result in no matches in long-term associative memory). The term *hit* in the above figure means that a return has occurred. But if *hit* is false, it is the task of the cue editor to modify the cues slightly so as to produce a return. As new images from the senses appear in STM, new rounds of cue editing are necessary. The past unfinished editing process moves into the background but keeps working. This is why a person sometimes belatedly recalls a forgotten piece of information. A subsequent chapter goes into circuitry for a cue editor.

A cue editor is not in a position to judge the priority of multiple returns. This is the task of a *recall referee*.

Recall Referee

An underdetermined set of cues generally results in a plethora of returns (think of everything you know that contains the color green, for instance). This overabundance has to be processed to assess the priority of each. If something is critical, it must be passed quickly into STM, because survival may be involved. For instance, safe responses in the event of danger must be promptly directed into conscious STM.

A technical term for what the recall referee must accomplish is *multiple match resolution*. Multiple match resolution avoids neural overload while assessing each return, calculating a priority value for each. Priorities are computed in parallel to speed the process of recall. The highest priority images are gated into conscious STM, giving a stream of consciousness one image at a time.

Returns may occur many per second, so a lot of searching is possible subconsciously. They come forth in rapid succession and are parked in biological registers where calculations are accomplished. The priority computation will contain emotional factors, and survival factors, and others integrated into each word of LTM [5, 6]; these have been well discussed [7]. Priorities are compared. That image with the highest priority is gated into conscious STM to become one's next thought.

Recall editing is accomplished with a novel method of parallel processing using recursive neurons operating as controlled toggles. All this is discussed in subsequent chapters.

The Nature of Decisions

Decisions Based on Past Experience

There is a theory that decisions are made not by *free will* in the sense of personal spur-of-the-moment choices, but by a search process that depends on past experiences and training. Often a ready-made decision is available based on past similar situations held in LTM, as for example when you are asked to donate to a cause that you do not like. A "no" answer is preprogrammed. Decisions, therefore, are affected by past experiences, what you did in similar situations, and whether or not an action supports your basic philosophy.

There is some evidence that free will is an illusion [8, 9]. Electroencephalography concerning the timing of finger movements, published by Benjamin Libit and others, indicates that choices are made in the brain without knowledge by the person involved; decisions were made well before a person realized it. Surprisingly, the brain seems to be in control, making decisions, and eventually informing consciousness. It is not the other way around, in which a "person" makes a conscious decision (without the aid of his or her brain), and then informs the brain.

Decisions with a Random Variable

It may be noted that a brain appears to search itself continuously in the background not only for forgotten facts and situations but also for solutions to problems. A problem could mean a real problem with no easy logical solution, for example, trying to open a complex combinational lock without knowing the combination. Trying all possibilities systematically requires excessive time. It is more practical to

try random combinations and trust to luck (and intuition). The brain may very well solve real problems this way, by random searches for quick solutions.

Random variables come into play in a *cue editor*. Simple circuits can randomly remove cues, search memory, and restore them while randomly removing others to obtain a return. Having good cues is very important. A cue editor is a logical subcircuit that can store a basic set of cues, if they are conflicting, and edit them in a random way, in the background.

As further indication that memory searches occur randomly, dreams, as everyone knows, are brief illogical episodes usually soon forgotten. A person is dimly aware of dreams during light sleep partly because there are no overpowering sensory images to block them out, as there would be during the day. Dreams, according to one theory, are a result of the repeated application of random underdetermined cues and multiple returns, some of which pass through the recall referee into STM because of their emotional content. Repetition of dreams sometimes causes them to be noticed as a person wakes.

Brainstorming may be like this, in which a random attribute is applied to a cue editor that causes unexpected returns. There usually are many returns, but only the most recent, most alarming, or most interesting scenarios are permitted into conscious STM by a recall referee.

Inspired Decisions

Currently there is no way to explain, let alone design machines that have common sense, truth judgment, understanding, artistic appraisal, and other hallmarks of human intelligence [10]. There seems to be a hidden source of computational power. Visionary pioneers have surveyed the possibility of quantum computing within a brain [11]. No doubt there are important quantum mechanical behaviors within ion channels and within synapses and elsewhere, since ions and their electrons are small and subject to quantum theory. One interesting hypothesis suggests quantum computing within the microtubules of neurons, proposed to generate higher consciousness [12, 13]. Others see quantum tunneling of electrons between synapses as creating consciousness [14]. For anything new, there are skeptics [11, 15, 16].

Quantum computations in neurons are an unproven hypothesis. Nevertheless quantum mechanics is a valuable metaphor for certain brain behaviors [11, 12]. Thinking about quantum mechanics is fun, and exercises the brain, which is a healthy activity. A later chapter discusses recent avenues in the search for brain quantum computing.

In contrast to the qubits of quantum theory, it may be possible for recursive neurons to take on qubit properties, such as holding true and false simultaneously with given probabilities in a probability space. Recursive neurons may also serve as controlled toggles for parallel processing, such as needed in a recall referee. Recursive neurons configured to act like qubits are termed *simulated qubits*. They

may be a source of enhanced computational power, particularly if formed at the molecular level within a neuron. Such a discovery might actually be more likely than real qubits, which require an isolated quantum system.

Conclusions

This chapter has presented a model in which the various attributes of a mental image each have their own fixed locations. Also each attribute has one or more backup locations, but physical locations are irrelevant in the logical brain architecture of this book.

Conscious STM is modeled as fed with appropriately processed signals from the five senses, interspersed with successful recalls from subconscious LTM. A person is aware of mental images mainly from the senses, but interspersed are recalls from LTM that are extremely important to survival and intelligent behavior.

A cue editor helps ensure the availability of recalls when cues are inadequate. This book outlines a model in which a cue editor works with selected attributes from a current image in conscious STM. When there is a mental block, the cue editor immediately begins to modify cues in a random way to obtain returns from LTM. A cue editor serves to resolve conflicting (overdetermined) cues, and cues for which there are absolutely no memory matches within associative LTM.

Under this model, ineffective or conflicting cues are not discarded but are stored in a special register composed of recursive neurons. Before searching again, a few cues are randomly removed, and the remaining are used for a new search; and if still there are no matches, then the removed cues are restored. The process of randomizing is repeated again and again until after some point, returns are finally obtained. This system can account for the common experience that forgotten information often pops into one's head with delay, perhaps much later, at an unexpected moment.

Parallel to the neural paths for memory search are neural paths that bring up returns from LTM. A recall referee serves to deal with the common problem of multiple returns from a given set of cues. Multiple returns are expected to occur in a group shortly after cues are applied. Within a recall referee, each return undergoes a quick but exact digital determination of priority. Most returns are rejected as being unimportant, but one will have maximum priority and will be gated directly into conscious STM, where it results in physical actions or additional memory searches.

Methods for priority calculations are presented in later chapters using recursive neurons operating as controlled toggle devices, all operating in parallel. Controlled parallel toggles calculate priority for each multiple return in a prompt manner.

Brain editors as above operate between short- and long-term memories to make decisions and to produce a stream of consciousness, a stream that is infinitely more intelligent than mere dumb acceptance of bad cues and unimportant returns. Subsequent chapters are going to develop a structure with appropriate circuits for short- and long-term memory as well as neural circuits for editing to accomplish the abovementioned system.

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Self-Study Exercises

(If you desire to keep a record of your efforts, please type your answers.)

1. Sketch on graph paper the four major types of bursts found in neurons according to this chapter. (HINT: Single pulses, bursts of about ten pulses for basic communications and logic, extended bursts for up to a few seconds for STM, and indefinitely long bursts, or bursts that can be triggered and stopped if and only if there is an attribute of LTM)
2. List the characteristics of and possible mechanisms for:

   (a) STM (HINT: Lasts no more than a few seconds; could be caused by a shortfall of available internal ions thus resulting in long dendritic pulses; this would trigger long pulse bursts of regular pulses in the soma)

   (b) LTM (HINT: Formed instantly and lasts forever; could be based on quick LTP, or recursive neurons that cause a low-profile pulse to cycle indefinitely, or a hybrid of potentiation and recursion)

3. Explain briefly why the following components are important to humans.

   STM (HINT: For second-to-second living and consciousness)
   LTM (HINT: For knowledge, intelligence, learning from past experiences)
   Cue editor (HINT: For survivability, to guard against memory blocks)
   Recall referee (HINT: For survivability, to avoid confusion and focus only on
      high-priority returns from LTM)

4. Explain what a cue editor does? (HINT: A cue editor keeps track of cues that fail
   to create a return, and changes them a few at a time in an attempt to make them
   work.)

5. Explain what a recall referee does? (HIINT: A recall referee computes a priority
   value for each image returned for a given set of cues, and permits only the
   highest priority image into conscious STM.)

6. What is meant by a memory-based system? (HINT: All possible responses and
   knowledge relate to LTM.)

7. Describe three categories of brain decision making. (HINT: Past experiences,
   random choices, inspired choices)