Modularization and hierarchical processing appear to be general features of all cortical processing. Using the processing of visual information as an example, a general model of hierarchical processing is proposed to explain how information from specialized visual areas—those processing lines, colors, motion, etc.—can be integrated (and, in many instances, combined with information from other modalities, such as auditory, tactile, and semantic perceptions) to decipher the identity of an object. Because higher-level cortical processes seem to use the same peripheral sensory apparatus to generate mental imagery in conscious awareness and to verify predictions about incoming sensory experiences, feed-forward and feedback pathways in such a model can generate synchronized oscillations at all levels of the hierarchy at the moment of perceptual recognition.

The brain appears to use the same peripheral sensory module in perception and its mental imagery. For instance, damage to the visual cortex often produces deficits in mental visualization and in dreaming that parallel impairment in visual perception in the same cognitive domain.

Mental imagery most likely involves feeding information back to the lower sensory cortices to recenter images and sensations in conscious awareness. This is because conscious awareness, by itself, does not have the machinery to generate those mental images. The conscious mind, therefore, needs to rely on the same peripheral sensory apparatus as those used to perceive objects and events in the external world to recreate those images in conscious awareness.

According to Jeff Hawkins’ memory-prediction framework, the mind is always making predictions about incoming experiences, based on its interpretation of the sensory input. Such predictive information is sent back through feedback pathways in the cortical hierarchy to make sure that sensory input matches the predictions.

Synchronized Oscillations As The Neural Correlate Of Consciousness

The above illustration shows the hierarchical structure of cortical processing in a peripheral sensory modality.

Specialized modules (represented by rectangular boxes) are organized by hierarchical levels stacked together in a pyramidal configuration. A specialized module processes information received from subordinates at lower levels and passes the result to its superiors at the next higher level. Information becomes progressively more concise, and meaningful, as it flows from the bottom toward the top. In the visual system, for instance, information from the retina enters the bottom layer (area V1) of the pyramid, and the processed result emerges at the top (the visual association cortex). The resultant high-level representation then becomes available in conscious awareness (or the imaginary thinking theater of the mind) to integrate and correlate data from other modalities to achieve perceived unity and understanding. In the hierarchy, the feed-forward pathways are frequently accompanied by feedback pathways (illustrated by lines with double arrows). Feedback circuits also exist among many levels (shown by the backward arrows). These feedback circuits are used to provide mental predictions from higher-level representation and to exert top-down influences. Their presence sets up circular loops of feedback and feed-forward circuits in the hierarchy.

Consider a specialized cortical module (represented by a rectangular box in the hierarchy) as a feed-forward neural circuit that processes a specific input signal, based on past learning and remembrance, to produce a corresponding output signal. Now if in mental imagination (or prediction), exactly the same output signal is used to regenerate the same input signal to the module, by some feedback neural circuit, we can then create a reverberating circuitry by connecting the feed-forward path to the feedback path in a loop. In such an arrangement, the circuits would then be set up to oscillate in a fixed pattern, as the input signal is processed by the feedback circuit to produce the output signal, which in turn is used by the feedback circuit to recenter the same input signal to the feed-forward circuit.

Look at the entire hierarchical circuitry as a whole. Sensory information presents at the bottom of the hierarchy. This is processed by the hierarchical circuitry to produce a perceptual result at the top of the pyramid. The conscious mind then uses the result to make predictions that are fed back by the various feedback pathways to modules on the lower levels to make sure the predictions match the input. Notice, at a steady state, when the perceptual result is correct—that is, when the perceptual result corresponds to the mental image in conscious awareness—predictions (feedback signals) will match the input signals to the modules at all levels of the hierarchy, and the entire circuit will oscillate in synchrony. In such a steady state, all the circuit loops in the hierarchy, from the bottom to the top of the pyramid, will oscillate synchronously. This is because in any given loop, the input signal to the feed-forward circuit will produce an output signal that redefines the same input signal by the feedback circuit, in a circular fashion.

The onset of each steady-state reverberation—when our mental predictions about an object match the input signals—may signify the moment when we recognize an object in conscious awareness. At the moment of perceptual recognition, the coalition of neurons in the brain corresponding to an object in a particular situation will have achieved a steady state of synchronized oscillations at all hierarchical levels. Such a coalition may include neurons from modalities such as vision, hearing, short-term memory, language, semantics, and emotion. Therefore, the recognition of an object sets up synchronized oscillations across many modalities relating to the object, which also corresponds to the moment we identify the object consciously. The acquired information is registered in a mental map (short-term memory) in conscious awareness, which may include knowledge about the object’s identity, its relationships to other objects, and its particular properties and attributes.

As our attention shifts externally to other matters, or turns internally in thinking or imagination, different patterns and coalitions of synchronized oscillations will emerge, corresponding to the object and subject matter of our thoughts. Once an object is known, there is no use for us to maintain conscious attention on it, since knowledge about the object is already registered in short-term memory (or, metaphorically, in the imaginary thinking theater of the mind), and therefore has no further role in our use in the thinking process. Consequently, shifting our attention will break up an established pattern of synchronized oscillations, so other new patterns may emerge as our conscious mind moves on to analyze other objects and events.

Other conclusions that may be derived from this hierarchical model of modular processing include:

1. The majority of our memories about object and events in the world are stored in specialized sensory cortices that process information about those objects and events, in a distributed fashion.
2. Consciousness is not found in the activities of a specific neuron or of specific groups of neurons. Similarly, in the brain, objects and events are not represented by specific neurons but by synchronized firing patterns of different coalitions of neurons.
3. It is possible that “mirror neurons” in the premotor areas are not doing any “mirroring” at all, but are merely reflecting what is being imagined and thought of in our mind.
4. Perception is not simply a matter of feeding sensory information about an object into a circuitry and watching its identity emerge from the other end. In human perception, many neural operations at higher cognitive levels are involved. It is a complex, recursive process of generating hypotheses, based on sensory data, conceptual interpretation, emotional information, and past experiences in analogous situations, and making predictions to validate and modify the working mental model by feedback correction to arrive at the most probable solution.

Conclusion:

A hierarchical model of information processing in a peripheral sensory module is proposed to show how feed-forward circuits (used in perception) may be integrated with feedback circuits (used in mental imagination and gestation) to create synchronized oscillations at the moment of conscious perceptual recognition and understanding.
Synchronized Oscillations as the Neural Correlate of Consciousness

Jeff Hawkins in his 2004 book On Intelligence observed that the cellular structures in the brain’s cortical layers all appear fairly uniform. A typical neocortex is about two millimeters thick and has six cellular layers, designated as L1 to L6, that are populated with similar types of neurons on each layer. By embryological design, the cortex is composed of microcolumns, each about the width of a human hair, running perpendicular to the layers. During morphogenesis, neuronal stem cells migrate up the columns to settle and differentiate into specialized neurons at different layers.

Inferring from this observation about the uniformity of the cortical structure, Hawkins went on to propose that different areas of the neocortex must share similar mechanisms of information processing, whether in the visual cortex, the auditory cortex, or the frontal cortex. Their different functions are caused by the different ways they are connected and the different information they have to process, rather than by any intrinsic difference in the neural circuitry.

In his hierarchical model of cortical processing (see Figure A1.1), Hawkins asked us to imagine layers of processing modules stacked one on top of another in a pyramidal configuration to decipher information into ever more concise and meaningful representations. In the visual cortex, for example, the first layer would correspond to the V1 area of the primary visual cortex, where different specialized modules process information from a retinal image to discern an object’s lines, edges, angles, color, motion, light intensity, etc. Once these elementary features of an object are extracted, the information is then passed on to the next higher level for further processing. The process continues until, at the top of the pyramid, the object is identified—a dog, a cat, a boat, or whatever one sees. Notice at each level, a module takes information from those be-
Figure A1.1  The hierarchical structure of cortical processing. In a peripheral cortical modality, specialized modules are organized by hierarchical levels stacked together in a pyramidal configuration. A specialized module processes information received from subordinates at lower levels and passes the result to its superiors at the next higher level. Information becomes progressively more concise, and meaningful, as it flows from the bottom toward the top. In the visual system, for instance, information from the retina enters the bottom layer (area V1) of the pyramid, and the processed result emerges at the top (the visual association cortex). The resultant high-level representation then becomes available in conscious awareness (or the imaginary thinking theater of the mind) to interact and correlate with data from other modalities to achieve perceptual unity and understanding. In the hierarchy, the feed-forward pathways are frequently accompanied by reciprocal feedback pathways (illustrated by lines with double arrowheads). Feedback circuits also exist among many levels (shown by the backward arrows). These feedback circuits are used to provide mental predictions from higher-level representations and to exert top-down influence. Their presence sets up circular loops of feedback and feed-forward circuits in the hierarchy, which create synchronized oscillations at the moment of perceptual recognition. (See text for discussion.)

neath it, processes it based on its learned and remembered knowledge, and then passes on the information in a more condensed and meaningful form to its superior in the next higher level. New knowledge—the module’s past learning—is added as information flows from the input of the module to its output. (The process is analogous to how our intelligence apparatus works, from the spies who gather information in the field, to the analysts who process the data and report the results to the CIA director, who then informs
the president. Everybody operates on a need-to-know basis.) Hierarchical processing is necessary and advantageous in the brain because the organization allows a small assembly of unconscious modules—each having only limited capability—to process a large amount of complex data. As an analogous example, consider how our president, George W. Bush, runs the country. Mr. Bush by himself is only an individual with limited attention and ability. Yet because he is able to delegate his responsibilities to his subordinates, he can focus his mental resources to process higher-level information submitted to him by lower-level officials that is manageable within his ability. By such delegation of responsibility and division of labor down successive ranks of the governmental organization, he is able to run a country as vast and as complex as the United States of America—a task that he would not be able to do by himself without the hierarchical organization, no matter how capable he is or how much help he can muster.

This does not mean, of course, that subordinates do not receive any feedback from their superiors. In the brain, many feedback pathways are found between different levels, from the higher association cortices to the lower primary cortices. And in many instances, there are more backward pathways than forward pathways. This is illustrated in Figure A1.1, where the backward arrows represent feedback from modules at higher levels to modules at lower levels. The shortest feedback loop could be from the output of a module back to its input. The longest feedback loop could be from the top of the pyramid to the base of the pyramid.

Hawkins postulated that these backward pathways serve the important function of matching our mental predictions to real-world observations. According to his “memory-prediction framework,” the mind is always using memory to make predictions about the incoming experiences, based on its interpretation of the sensory inputs. While walking down a street, for instance, we often catch ourselves stumbling when an expected step-down does not materialize at the curb, even when we are not consciously paying attention. When we raise our hand to open the front door to our house, we instantly notice if someone has changed the color or shape of the doorknob. So even if we are not consciously aware of it, our mind is always making predictions about what should happen next in our sensory experiences as we go about our daily routines, and trying to match such predictions with real-world experiences. In a way, the mind is always checking and validating its expectations—
consciously, subconsciously, and unconsciously—to make sure its internal mental model is congruent with outside reality.

Hawkins asserted that such predictive information is sent back through the feedback pathways in the cortical hierarchy to make sure that the sensory inputs match the predictions. Any discrepancy is immediately noticed by those higher in the echelons, and corrective actions are taken to restore congruence. These actions may include changing the prediction, redirecting attention to other aspects of the external world to bring in more information for reassessment, or imparting additional data to the lower processing modules directly to change their outputs.

There is no question that top-down influence can change our sensory perception. In the Rorschach test, the same inkblot image may be perceived as different objects, depending on the subject’s psychological state and preconception bias. Here information from higher cortical areas is fed back to lower sensory areas to bias their processing of the input data toward a particular interpretation: e.g., by focusing on certain aspects of the data while minimizing others, or by providing “fill-in” information to complete the picture (similar to the way the brain fills in the blind spots in our eyes). To a certain extent, our subjective interpretation can determine what we see and what we perceive.

Mental imagination most likely involves feeding information back to the lower sensory cortices to recreate images and sensations in conscious awareness. Earlier in this book I argued that the conscious mind relies on the same peripheral sensory apparatuses to render mental images in conscious awareness as those used to perceive objects and events in the external world. (People with extensive visual cortex damage seem to have deficits in mental visualization and in dreaming that parallel impairment in visual perception in the same cognitive domain. This is especially true with damage to the higher visual association areas in the temporal and parietal cortices.) This is because conscious awareness—think of the Conscious Room, or the imaginary thinking theater of the mind, discussed in this book—by itself, does not have the machinery to generate these sensory images. Our conscious mind, therefore, needs to provide the sensory cortices with information about the objects and events to be generated before they can be recreated and perceived in conscious awareness—alogous to the way we need a VCR machine to play back a videotape so we can watch the images on TV. It is likely that information about high-level
representations is first fed back (from consciousness) to those high in the sensory hierarchy, which then decode it and pass the information along by feedback pathways to successively lower-level modules, decoding it into ever more detailed predictions down the pyramid, to recreate the desired details in our mental imagery.4 (The operation is analogous to the way a conscious command to “run” is automatically decoded and carried out by a hierarchy of unconscious processes. A chain of command implements the action to the very last detail of coordinating the twitching of individual muscle fibers. Similarly, a command to pick up a cup with our eyes closed is automatically decoded and carried out by the appropriate sensory hierarchies to produce the ersatz sensations of performing such an action in imagination.) Experimental evidence seems to suggest that the recreation of mental images occurs mostly in visual cortices higher than area V1. Instead of generating a detailed image on V1, the brain can simply take a shortcut and activate higher-level representations to create only what is necessary for mental visualization; the reason why, perhaps, the mental images created in our imagination (and dreaming) are never as vivid and detailed as the real-world images we see.5 Still, they are often good enough for our purpose of mental manipulation, action guidance, feedback correction, or making predictions.

As we think, our thinking brings about mental images of remembered sensations and experiences—though in a somewhat ersatz form—for our evaluation and prediction. Thinking usually precedes action in everything we do. The moment before we shoot a basketball, for instance, thinking about it automatically generates the mental images of executing the action from our remembered experiences: how we would raise our arms, jump on our feet, and toss the ball into the hoop, and the sensations associated with executing such a sequence of actions. (Close your eyes and imagine yourself raising your hand to pick up a cup and drink from it. Even though you are not actually doing it, your mental rehearsal allows you to visualize the action and experience the associated sensations.) And, when we actually throw the ball, these mental predictions are used to guide and correct our moment-to-moment execution. Similarly when our executive brain gives a command to open the door to our home, the command is automatically translated—subconsciously, unconsciously, via the remembered sensory experiences in the peripheral cortices—into a series of detailed predictions about what to expect as we carry out the action. Any discrepancy between pre-
diction and the actual experience is immediately noticed and attracts conscious attention to investigate. These mental images and sensations in thinking must be recreated from the peripheral sensory apparatuses.

Similarly, mental visualization may be used to assist in visual perception. Several objects of various sizes, rotations and obscurities may be present on a retinal image, which is mapped topographically onto area V1 of the visual cortex. This presents a problem about how to transfer or “gate” the image of a specific object to the appropriate perceptual modules higher in the hierarchy to decipher its identity—given the likelihood that there is only one set of perceptual modules at the higher levels for such an operation (the function is not duplicated), and the simultaneous presence of other objects may confuse its processing. Of course, paying attention to a specific object often causes our eyes to move to it and focus on it, centering the object on the fovea, so a “proto-image” may be produced on V1 for perceptual identification. However, this does not change the size or the aspect of the object we are looking at. Alternatively, we can use our mental imagination to resize the object or change its aspect, adjusting for lighting and all the other extraneous factors, so a more familiar image is reproduced in the lower sensory level for perceptual processing. When we think about our car, for instance, we tend to visualize it in a certain way and in a certain size. And when we try to identify a person we saw just a moment ago who was situated at a distance from us, we tend to blow up his facial features in our mind’s eye for scrutiny, in an effort to identify it. These mental manipulations are made possible by the mind’s ability to use the lower sensory apparatuses to recreate mental images.

Subjectively, when we see an object we do not just see a flat two-dimensional image. In our mind’s eye, we usually perceive a three-dimensional object with the missing information filled in by our unconscious assumptions. Perception therefore is more than a passive analysis of the available sensory data. It is an active interpretative process with the brain continuously injecting its knowledge and assumptions, exerting top-down influences and biases, and making corrections and modifications until a plausible match is found between prediction and data.

Consider the theory about “mirror neurons” proposed by Rizzolatti, Fogassi, and Gallese at the University of Parma in Italy. In the early 1990s, their research group, while recording electrical
activity in the brains of macaques, found that a subset of neurons in the premotor areas responded when an individual monkey performed certain actions and also when it observed others (another monkey or a human) performing the same movements. Interestingly, the same “mirror neurons” also responded when the monkey was watching an experimenter communicating the intention of performing the same movements, without actually seeing the intended movements being performed—in other words, the neurons’ response seemed to reflect comprehension of the experimenter’s goal in initiating the movements. From these observations, they concluded that action understanding is a primary function of the mirror mechanism.7

For our purpose, the implications of their findings may be interpreted in two ways. First, the presence of the mirroring system in the brain seems to support the hypothesis that empathy is largely an automatic and involuntary process. When we observe the actions of others, we necessarily use our own “neural maps” and experiences (action patterns, theory of mind, our likely emotional responses in similar situations, and so on) to understand their behavior and intentions. It is as if we are running a simulated replica (including a person’s physical actions, his belief system, his goals and desires, his emotional biases, and so on) of the person we are observing “online.” When we see a person raise his hand, we immediately imagine what it is like for us to raise our hand and what our intention might be in doing so (imagining if we were him). When we see a person acting distressed in a situation, our emotional system automatically activates a vicarious emotional response (imagining us in his place) to help us understand his mental state. The mirroring mechanism thus enables empathy, which may then lead to sympathy, and allows us to connect with one another.

Second, it is entirely possible that the mirror neurons in the premotor areas are not doing any mirroring at all, but are merely reflecting what is being imagined and thought of in our mind. Remember my earlier conjecture that our consciousness really does not have the machinery to fabricate objects and events (images, actions, and emotions) for its mental manipulation, and it needs to rely on peripheral modules to reproduce those entities for its processing (just as we need a VCR machine to play back a videotape so we can see the images on TV). When we watch a person doing something, we automatically reproduce a mental image of the event in our imaginary theater of the mind for other unconscious modules
to process. And because we are always making predictions of what will happen next, we instinctively guess the intention of the actor based on his behavior. So, as we understand the intention of the person performing the action, his intention is thought of and enacted in our mind, and the premotor “mirror neurons” (as part of a peripheral motor module) are necessarily activated to render such an imaginary enactment on the conscious stage. This may explain why the so-called mirror neurons seem to reflect more an observer’s understanding of an actor’s actions than merely “mirroring” the actions themselves. Mirror neurons, therefore, actually reflect what is being played out and understood in our mental imagination. They are merely part of the machinery of mental thinking. Similarly, when autistic children fail to activate their mirror neurons when they observe the movements of a hand opening and closing, that is because they do not “understand” the meaning of such an action—i.e. they only see objects moving, and they are not able to synchronize such an observation with knowledge stored in other cerebral modules to understand its meaning. Because the action appears like meaningless movements, they do not know what it means, they are not able to make any prediction about it, and they do not know what to do with it.

But how exactly is mental meaning and understanding achieved at the hardware level, the level of neural circuitry? Let’s look at a plausible mechanism that uses synchronized oscillations to integrate knowledge from disparate cerebral domains. Consider a specialized cortical module in Figure A1.1 (represented by a rectangular box in the hierarchy) as a “feed-forward” neural circuit that processes a specific input signal, based on its past learning and remembrance, to produce a corresponding output signal. Now if in mental imagination (or prediction), exactly the same output signal is used to regenerate the same input signal to the module, by some feedback neural circuit, we can then create a reverberating circuitry by connecting the feed-forward path to the feedback path in a loop. In such an arrangement, the circuits would then be set up to oscillate in a fixed pattern, as the input signal is processed by the feed-forward circuit to produce the output signal, which in turn is used by the feedback circuit to regenerate the same input signal to the feed-forward circuit.

Look at the entire hierarchical circuitry in Figure A1.1 as a whole. Sensory information presents at the bottom of the hierarchy. This is processed by the hierarchical circuitry to produce a
perceptual result at the top of the pyramid. The conscious mind then uses the result to make predictions that are fed back by the various feedback pathways to modules on the lower levels to make sure the predictions match their inputs. Notice, in a steady state, when the perceptual result is correct—that is, when the perceptual result corresponds to the mental image in conscious awareness—predictions (feedback signals) will match the input signals to the modules at all levels of the hierarchy, and the entire circuitry will oscillate in synchrony. (In such a steady state, all the circuit loops in the hierarchy, from the bottom to the top of the pyramid, will oscillate synchronously. This is because in any given loop, the input signal to the feed-forward circuit will produce an output signal that regenerates the same input signal by the feedback circuit, in a circular fashion.)

The onset of such a steady-state reverberation—when our mental predictions about an object match the input signals—may signify the moment when we recognize an object in conscious awareness. Earlier in the book I argued that perception consists mostly of guesswork involving the piecing together of disparate clues to arrive at the most probable conclusion. In the imaginary thinking theater of the mind, many processes, conscious and unconscious, work together to divine the identity of an object and the meaning of a situation. When we encounter an ambiguous object, for instance, our visual apparatus analyzes the color, size, shape, and motion of the object to give us a rough first impression of what the object might be, the auditory apparatus provides information about the object’s auditory identity, context information recalled from short-term memory narrows down the likely choices, and the emotional system produces conditioned emotional responses triggered by stimuli embedded in the sensory data. This wealth of information is processed to produce a hypothesis of what the object might be in the imaginary thinking theater of the mind. This tentative mental image—e.g., the object is a whimpering dog rotated 45 degrees to the right, approximately 25 feet away, with its head partially obscured by the shadow of a shrub in the setting sun—then elicits its associated knowledge from memory to make certain predictions from the hypothesis. These predictions are broadcast to the peripheral modalities (visual, auditory, short-term memory, language, emotional, etc.) to make sure they agree with the incoming inputs. Simultaneously, the mind redirects its attention to search for additional information to confirm or refute its hypothesis: such as moving our
eyes to focus on different aspects of the object and visual scene, or recalling associated facts from memory to guide our validation. Top-down and bottom-up processes are used to reconcile differences at all levels to bring about the most compatible explanation. As new information emerges, and the discrepancy between prediction and observation is noted, the internal mental model is modified accordingly to produce the more congruent hypothesis. (I may remember, for instance, that the cry of a seal is similar to the whimpering of a dog, and I am visiting at SeaWorld, so the animal is more likely to be a seal than a dog. Given this thought, and the modified mental image accompanying it, I may then direct my attention to look for features of a seal to confirm my new hypothesis.) Hopefully, in the final steady state, I will have a mental image (hypothesis) that is most consistent with all the inputs from the different peripheral modalities (sensory, memory, semantic, emotion, etc.), and the predictions of the hypothesis match the inputs at all levels of their hierarchies. Subjectively, I will then feel that I have recognized the object and its meaning with good certainty. This moment of perceptual recognition will be marked by synchronized oscillations across all the hierarchical modalities, in effect binding all the disparate features together to a common percept.

In most cases of perception, we do not need to go through all this conscious work, of course. The perception of most familiar objects in life has become subconscious or unconscious routines, taken over mostly by unconscious zombies. When we are driving on the street, for instance, and we catch a blurry object at the corner of our eye, we automatically perceive it to be a vehicle (or we assume we recognize it as a vehicle) even though we have not seen enough detail about the object to properly identify it. In this situation, the context of the situation has narrowed the identity of the object to a few likely choices, and the limited sensory data (the color of the object, its approximate size, its relative speed) cause us to intuitively perceive the object as a car and then recall our schema about cars to interpret it. (Reliance on assumptions is a habit of the human mind that illusionists and magicians have exploited to good advantage in their sleight-of-hand tricks.) It is not until we notice the object has legs that our conscious attention is interrupted to investigate, alerted by the discrepancy between our mental predictions and the actual observations at the lower sensory levels. Therefore, the perception of most familiar objects and events in life is “overlearned,” relying heavily on the use of
schemas and assumptions. Sensing the presence of a familiar object will mindlessly trigger synchronized oscillations in all pertinent modalities and elicit from memory the associated knowledge (schemas) for use in response.

Human perception, therefore, is more complicated than it appears. It is not simply a matter of feeding sensory information about an object into a circuitry and then watching its identity emerge from the other end. Many mental operations at the higher cognitive levels are involved. It is a recursive process of generating hypotheses, based on sensory clues, contextual interpretation, emotional information, and past experiences in analogous situations, and making predictions to validate and modify the working mental model by feedback correction to arrive at the most probable solution.

At the moment of perceptual recognition, therefore, the coalition of neurons in the brain corresponding to an object in a particular situation (e.g., a dog rotated 45 degrees to the right, with its face obscured by the shadow of a shrub, barking, perhaps at strangers) will have achieved a steady state of synchronous oscillations at all hierarchical levels. Such a coalition may include neurons from modalities such as vision, hearing, short-term memory, language, semantics, emotion, etc. If a state of synchronized oscillations is considered a stable steady state, then a state of disorderly asynchrony may be considered an unstable state, still working its way toward a synchronous state of perceptual unity. Even though we know what the desired final state is, we don’t know how the brain gets there, or the mechanism enabling its neural circuitries to achieve synchronized oscillations from an initial asynchronous state.

It is almost as if in such an ensemble of neural circuits there exist many attractors—stable states corresponding to different scenarios, based on our past learning and remembrance—and given any particular set of sensory inputs, the entire circuitry would be driven to migrate, or gravitate toward the closest attractor by some unknown mechanism (with the hypothesis-prediction-correction routine embodied in its operation) to settle at the most plausible explanation of the inputs. And the attainment of such an explanation would be marked by a steady state of synchronized oscillations in a coalition of neurons, corresponding to our recognition and understanding of the input data (in the form of a mental image, or a
thought accompanied by a feeling, perhaps) in the imaginary thinking theater of the mind.

When we first walk into an unfamiliar room, we immediately survey the room to identify the many different objects in the room and to understand the situation in the room. Even though we may become aware of the presence of several objects simultaneously, it is likely that we need to pay attention to each object individually to decipher its identity. Our attention is singular, fixating on one thing at a time—just as we cannot think of two thoughts at once, but our thinking can switch back and forth rapidly among different subjects. (The brain, however, can use “chunking” to group several objects into one item for our attention, just as it can for memory.) In our visual survey, our eyes can execute up to three saccades a second, and our attention jumps quickly from one feature of an object to another, and from one object to the next, until all the objects in the room are identified.

As soon as an object is recognized, it sets up synchronized oscillations across many modalities relating to the object, which also corresponds to the moment we identify the object consciously. This information is registered in a mental map in conscious awareness, which includes knowledge about the object’s identity, its relationships to other objects, its particular properties and attributes, etc., so even when we close our eyes, we can still remember what the room looks like and what is in it.

As our attention shifts externally to other matters, or turns internally in thinking or imagination, different patterns and coalitions of synchronized oscillations will emerge, corresponding to the object and subject matter of our thought. Once an object in the room is known, there is no need for us to maintain conscious attention on it, since knowledge about the object is already registered in short-term memory (or, metaphorically, in the imaginary thinking theater of the mind) ready for our use in the thinking process. Consequently, shifting our attention will break up an established pattern of synchronized oscillations, so other new patterns may emerge as our conscious mind moves on to analyze other objects and events. The process continues until we recognize all the objects in the room and their meanings and record the knowledge in short-term memory.

Thinking always evokes synchronized oscillations in the relevant peripheral modalities, as the brain relies on their neural
circuitries to generate mental imageries and their memories to retrieve knowledge of past learning. Because the conscious mind does not have the machinery to produce the objects or events of its thinking, nor the memory and knowledge necessary to implement its thinking operations—these are stored in the peripheral modules—synchronized oscillations, by way of feedback loops to the higher levels of the peripheral modules, are necessary to sustain the various components of a thought in conscious awareness. When the synchronized oscillations cease to exist, so will the thought they sustain in conscious awareness. (The thoughts already registered in short-term working memory are likely sustained by their own oscillations there.) Similarly, when our attention shifts to think about different things, different coalitions of synchronized oscillations will be set up to sustain those thoughts. Only in deep anesthesia, when conscious thinking stops, do we fail to detect such signature synchrony in the brain.

When perception is first initiated, the elementary features of an unknown object need to be deciphered first before the results can be passed on and used in higher-level analysis. (In visual perception, for instance, the specialized lower-level modules decode a retinal image into more concise and meaningful representations of lines, angles, color, light intensity, motion, etc. before sending this information to the higher association cortices for further analysis.) As a result, initially anyway, perceptual decoding proceeds in a bottom-up fashion in the sensory hierarchy. It follows that synchronized oscillations must be established at the lower levels first (e.g., visual area V1) before they can gradually spread to the top of the hierarchy to render a result, which will then evoke feedback (predictions) to verify and modulate the perceptual analysis in the entire circuitry. As mismatches are detected and feedback information is added, this will cause changes in the oscillation patterns as the entire hierarchical circuitry searches for a steady-state solution that will match conscious predictions to real-world observations.

Similarly, it also stands to reason that lower-level oscillations should be more stable and last longer than higher-level oscillations: so they can continue to supply the entire hierarchy with elementary information about the object, and sustain the mental imagery and input information necessary until a synchronized steady state can be achieved. Specifically area V1 of the visual cortex should continue to maintain a close one-to-one correspondence with in-
coming real-time retinal images—otherwise we would be blind to happenings in the outside world during the process of perception, mental visualization, or daydreaming. This is the reason why, perhaps, higher-level feedback does not seem to have much effect on activities in V1, and V1 does not seem to be necessary for the generation of mental imagery or dreaming. Recent evidence seems to show that only damage at the higher visual association cortices (specifically in the left temporal and right occipital areas) will reliably cause deficits in mental visualization that parallel deficits in visual perception. This suggests that feedback is predominantly to the higher levels of the visual hierarchy, at a distance at least two or more synaptic levels removed from V1.10 This qualification, however, does not controvert the hypothesis that synchronized oscillations across different modalities in the higher association areas—produced and supported by the results of synchronized oscillations at the lower levels—correlate with recognizing and understanding a percept in consciousness.

It is possible that feedback from higher cortical areas does reach V1, but in a somewhat sparse, ersatz, or coarse form. After all, our mental images are never as vivid and detailed as those we see in the external world. And there is no need to reinvent the wheel by reconstructing an image from the ground up, when it is much easier to activate higher-level representations. This also suggests that the feedback signals created from higher mental areas are probably not as detailed and specific as the feed-forward signals from the lower sensory areas. (Think of the ersatz sensation you feel when you close your eyes and imagine yourself throwing a basketball into the hoop. The sensation is never as vivid, detailed, or definitive as the real experience, but it is often good enough to serve as a rough guide or prediction for your action.) Perhaps limited by attention span and short-term memory capacity, the brain only needs to do the minimum that is necessary to create visual images for its mental manipulation. It can always increase the details of its visualization based on the demands of the task.

Francis Crick in his 1995 book, The Astonishing Hypothesis, suggested that, “Consciousness depends crucially on thalamic connections with the cortex. It exists only if certain cortical areas have reverberatory circuits that project strongly enough to produce significant reverberations.”11 The thalamus is an enigmatic structure, the size of a quail egg, that sits on top of the midbrain. It receives axons from every part of the cortex and sends axons back
to those same areas. The thalamus appears to be necessary for consciousness: bilateral damage to the thalami leads to a persistent vegetative state. Of interest in the thalamus is the lateral geniculate nucleus (LGN), which has topographic projections that terminate in V1 of the visual cortex. Other nonspecific cells broadcast axons more diffusely back to different regions of the cortex. Even though the reciprocal projections between the thalamus and the cortex make it an ideal candidate to mediate feedback oscillations, the coarse and nonspecific nature of many of its projections seems to make it more suited for regulating arousal, gating signals, or activating specific areas of the cortex for learning or focused attention.

Notes:


2. See note 8, Chapter 4. Some patients who lost their primary visual cortices to stroke continue to dream in visual images, suggesting that activity in V1 is not necessary for dreaming and mental images can still be generated by higher-level visual areas. Koch, 2004, 109.

3. According to Koch (2004), the seat of the conscious executive function is in the frontal lobes. This is where the outputs of all the peripheral modalities converge to produce imageries and subjective experiences in conscious awareness. This is also where the results of the different modalities interact and are used in mental manipulation to solve problems. Specifically, in visual perception, an occipital-temporal pathway (the “what” pathway) seems to mediate the perception of object form, color, and facial recognition; and another occipital-parietal pathway (the “where” pathway) mediates the perception of spatial imagery, the deficit of which can cause imagery neglect.

4. Goldenberg suggested that visual knowledge is represented at two distinct levels: within perceptual mechanisms and in semantic memory. See G. Goldenberg (1998), “Is there a common substrate for visual recognition and visual imagery?” Neurocase, 4:141–147. For visual imagery, many of the higher-level representations (codes, instructions) are probably stored as semantic memory in the temporal lobes. In surgery of epileptic patients, only stimulation of the temporal lobe produced complex visual forms such as people and scenes from the patient’s memory. Stimulation of the earlier oc-
cipi-tal cortex produced simple visual forms such as blobs or spots, or simple geometrical shapes such as rectangles or diamonds.


6. Notice that we also have the ability to shift our attention to a specific location (or object) in the visual field without moving our eyes, as was verified in experiments.


9. Remember here that the inputs to the neural circuits and the outputs from the neural circuits are not fixed analog electrical signals but pulse trains of action potentials with some inherent noise and randomness. Consequently, the output signal of the feedback circuit will never be identical to the original input signal to the feed-forward circuit. But the neural circuits in our case are not designed to process exact signals, but to map approximate inputs to their closest-matched outputs.


Bibliography:

