DERMATOLOGY PRACTICAL & CONCEPTUAL
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On the nature of thought processes and their relationship to the accumulation of knowledge, Part XV – Limits to cognition: epistemic, random, or both?

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Citation: Anderson C. On the nature of thought processes and their relationship to the accumulation of knowledge, Part XV – Limits to cognition: epistemic, random, or both? Dermatol Pract Conc. 2012;2(1):13. http://dx.doi.org/10.5826/dpc.0201a13.

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Introduction

The purpose of this essay is to explore the nature of limits to cognition. Are the limits epistemic, are they irreducible, or both? For the purposes of this essay, "epistemic" refers to issues related to our thought processes and "irreducible" refers to randomness.

Many of the essays in this series have addressed limits to cognition, focusing primarily on limits epistemic. In this essay I want to introduce the possibility that at least some of the limits we face are inherent in the universe as a result of the complexity of the universe and not merely the result of limits of our brains, individually and/or collectively.

First we will consider some aspects of our understanding of the concept of limits. Then we will review a little about how our brains evolved. We will then discuss epistemic limits. We will then review evidence that our brains are actually "hard-wired" to think probabilistically and review some precepts from complexity theory.

How do we understand the concept of limits?

As we learned in the previous essay on language, words are ambiguous and meaning becomes more restricted in context. The word "limits" is no exception and can also refer to many ideas. *Encarta World English Dictionary* defines "limit" as "the farthest point, degree, or boundary, especially one that cannot or should not be passed or exceeded; the boundary or edge of an area, or something that marks a boundary or edge; a feature or circumstance that restricts what can be done."

Another point about language is that emotion is often attached to the meaning of a word. For example, in the essay in this series on "Evidence" [1], it was pointed out that, although most of us assume, when we hear the word "evidence," that the bit of evidence must be true and unassailable, we apply that attribute – true unassailable – to the word, but in actuality, "evidence" is merely a term that can be applied to anything we want to persuade others to believe.

I believe that one attribute that we have a strong tendency to apply to the word "limit" is that of "not enough." We hear often about "limited resources." According to economists, an unlimited resource is one for which everyone could have as much as s/he wants if the item is free. Parenthetically, an important concept here is "wants," as opposed to "needs." Clearly economists consider many everyday items to be "limited resources," since many people will say something like "I'll take ten – no I'll take a hundred – let's make it a thousand, why don't we."

But "limit," *per* se, does not necessarily imply that there "is not enough to go around." For example, mathematically, "limit" means a value that will not be exceeded by a mathematical formula. For example, if we divide 1 by 2 and then divide that answer by 2 again and continue n times where n is a positive integer that approaches infinity, the answer approaches zero. But the answer never actually **is** zero and a mathematician can perform the operation an unlimited number of times because of the concept of "infinity." Any person can have as many as s/he wants of the numbers in that infinite series; but the ultimate answer does have a limit – zero.

I bring this last point up because, when we look more closely into cognitive limits, I do not want us to think automatically that there is some sort of limit to the number of "facts" that can ever exist – that some day someone will say, "Gee, everything that is to be known in the Universe is known." I think there is ample evidence that that day will **not** dawn. What **does** occur is that each time we think about some idea, we must define the problem, thus drawing a set of limits within which to consider that idea. But the number of ideas out there is infinite – without limit.

So what exactly is limited?

As Jacob Bronowski has pointed out in *The Origins of Knowledge and Imagination* [2] and as Lawrence Slobokin has pointed out in *Simplicity and Complexity in Games of the Intellect* [3], it is necessary to "limit," that is to say, draw a set of boundaries, or describe a "frame of reference" from which to consider our problem. Without rules, we cannot draw any valid conclusions at all.

We are reminded by Godel that, in any consistent system, there are true things that we cannot prove and that, in an inconsistent system, we can "prove" anything. Every time we frame a problem, we do so in order to make that system consistent so that any conclusions we **can** draw will be valid. What we are **not** limited in is our ability to reframe a problem; we can reframe a problem in innumerable ways. Then we are free to make new connections and gain new knowledge (as per Bronowski).

For decades, neuroscientists shared the problem "frame" of determinism. But when that frame was finally exited and the new frame, described by Glimcher and discussed later in this essay, of game theory or neuroeconomics, it became possible to draw new conclusions about mechanisms of human thought.

We must be mindful of the problem, discussed in earlier essays in this series, of "authority." We **must** learn from authority, but we must not be **bound** by authority. As Feyerabend has pointed out in *Against Method* [4] much can be gained and learned by considering new data in the context of multiple **possible** theories in order to avoid being bound by a charismatic or dogmatic authority.

Glimcher [5] has referred us to the work of David Marr, who has insisted that the best way to work through neurophysiologic problems is to consider the **goal** of a behavior.

Epistemic limits

In this series of essays we have discussed that our ability to think is limited in a number of ways. For one thing, we can only consider a certain number of items at any one time – those items we can "juggle" in Working Memory. For another thing, we must define each problem before we can think about it – we draw boundaries that define the problem, excluding necessarily items that we deem "irrelevant" to the problem at hand. Also, we define certain rules that pertain to the problem, and must hold to those rules while considering the problem, since those rules constitute part of the boundary of the problem. As Jacob Bronowski has pointed out in *The Origins of Knowledge and Imagination*, it simply is not possible to consider the entire universe as "the problem"; we must carve out a small part of it at any one time.

We think if we can frame a problem just right – that is, if we ask the right question in the right way, all will become clear and all puzzlement will dissolve into a universal truth – like the Buddha's Enlightenment. But this feeling of "surety" is merely a trick of the brain.

David Gamez, in *What We Can Never Know* [6], posits that many of our attempts to explain and make sense of the world are in essence Hermeneutic circles. *Encarta World English Dictionary* defines "hermeneutic" as "serving to interpret or explain something." "Hermeneutics," then, is the "science and methodology of interpreting texts [or bodies of thought, or theories]." A key point brought out by Gamez is that the interpreter or explainer cannot interpret or explain without him/herself being part of the world or theory being described. All stable hermeneutic circles, as Gamez calls them, are necessarily self-reflexive and must be able to explain how the person could create the theory in the first place. This sets us up for paradox that might arise from using self-reference unwisely, as discussed in more detail in the essay in this series on Language.

Additionally, a concept that is pretty much accepted is that none of us really "knows" what our world is like. Everything we sense is interpreted by our brain, and our brain has no mechanism for experiencing the world directly. The theory is usually referred to as the "brain-in-a-vat" theory. The theory asserts that our reality is merely a "virtual reality" constructed by our brain.

Gamez describes a "dream" about being in a blue room. Writes Gamez, "I close my eyes and cross the room to the table. On the table lies a large piece of meat. With my left arm I reach out and feel the meat. It is warm, textured, rubbery and slightly sticky with blood. I pick the meat up. It is heavy and pulls my arm towards the ground. With my eyes still closed I reach out with my right arm. I can feel nothing there: the piece of meat has vanished and so has the table. My right hand moves about freely in empty space where the table and meat were present only a moment before. I allow my right arm to fall by my side and reach out again with my left arm. Now the meat and table have returned. Once again I palpate textured flesh between my fingers; once again I encounter an area in the world that resists my grasp. I open my eyes. A piece of meat oozes gently onto the white table in front of me. I look at my left hand. It is pink and opaque; it obscures the objects behind it. Within the visual form of my left hand I experience the sensations of my left hand. These are initially very diffuse, but by concentrating I can focus on the feeling in each finger. When I wiggle the fingers of my left hand I see a pink form wiggling in space in front of me. Now I gaze at might right hand. My right hand is transparent; it does not obscure the objects behind it. I experience my right hand within a diffuse hand-shaped zone in front of me. By concentrating, I can feel the sensations in each finger. When I wiggle the fingers of my right hand I do not see anything happening in the world in front of me, but I can still feel my fingers wiggling. My left arm is visible between my shoulder and my left hand. My right arm becomes invisible about ten centimeters from my shoulder. The visible part of my right arm emerges from my shoulder and terminates in a stump. The transparent part of my right arm extends from the stump to my transparent hand."

Gamez's "dream" is that of one's experience with a phantom limb following amputation. Gamez goes on to point out that amputees often experience a vivid phantom. The brain "expects" certain events and fills them in. The brain itself is intact and all the "hardware" of the sensory and motor cortex assigned to the now absent limb is still present and operating. In the essay in this series on Patterns, we looked at the work of Erich Harth, who discussed how the brain can "augment" certain "perceived" features, but that our experience with our actual senses usually allows us to determine "reality" from the construct. Harth points out that we rarely hallucinate when we are awake, alert, and observant. Jeffrey Schwartz, in *The Mind and the Brain* [7], discusses that the brain exhibits "neuroplasticity." Pathways that are used often, such as practicing a musical instrument or sport, are reinforced, adding new neurons to the pathway, while pathways not used atrophy, such as after a stroke.

I think there may be no way around understanding our world as a sort of "virtual reality." The question, I think, is whether we should allow ourselves to become paralyzed by this very realistic view of our existence.

As Gigerenzer has pointed out in *Adaptive Thinking* [8] and some of his other works, we humans have co-evolved with the world and, whatever "reality" is out there as viewed from the nonexistent "ultimate frame of reference," we perceive the wave-lengths of light we need to perceive to survive and can solve problems well enough to survive in the world as it "exists." What matters then is, given our starting point (our "virtual reality"), where can we go from here? And an important part of the plan is to ensure that we define whatever frame of reference we are using at the time in a consistent way and that we strive to ensure inter- and intra-observer agreement.

Background – evolution

Gary Marcus, in *Kluge: The Haphazard Evolution of the Human Mind* [9], points out that evolution works with what is available at the time and "experiments" through mutation, seeing what ends up fitter than others, the fitter thus producing more progeny and continuing the process through time. Parenthetically, "kluge" is a "clumsy or inelegant – yet surprisingly effective – solution to a problem." Marcus avers that biology is loaded with kluges. He mentions that the human spine is not the most efficient way to support load in an upright two-legged creature; yes, our hands are free, which aids survival, but we are prone to develop back pain. We evolved from quadripeds, so we are stuck with having one column to support our upper bodies instead of the more efficient (from an engineering point of view) four equal cross-braced columns. He continues with another anatomical kluge – the human eye. The retina "is installed backward … leaving us with a pair of blind spots."

Says Marcus, "Nature is prone to making kluges because it doesn't 'care' whether its products are perfect or inelegant. If something works, it spreads. If it doesn't work, it dies out. Genes that lead to successful outcomes tend to propagate; genes that produce creatures that can't cut it tend to fade away; all else is metaphor. Adequacy, not beauty, is the name of the game."

Marcus mentions instances of the sublime in evolution. "The human retina can detect a single photon in a darkened room…spider silk is stronger than steel and more elastic than rubber… hemoglobin is exquisitely adapted to the task of transporting oxygen …" He points out that "sometimes elegance and kluginess coexist, side by side. Highly efficient neurons…are connected to their neighbors by puzzlingly inefficient synaptic gaps, which transform efficient electrical activity into less efficient diffusing chemicals, and these in turn waste heat and lose information." He mentions, using the analogy of hill-climbing mentioned in the essay in this series on Reasoning, that the vertebrate eye is elegant in its capacity to focus and adjust to varying amounts of light and "operates with more sophistication than most digital cameras," but it is hobbled by the construction of the retina with its blind spot. "On the highest peak of evolution, our eyes would work much as they do now, but the retina would face forward (as it does in the octopus), eliminating those blind spots. The human eye is about as good as it could be, given the backward retina, but it could be better – a perfect illustration of how nature occasionally winds up notably short of the highest possible summit."

Marcus also mentions that there exists a sort of "'evolutionary inertia' since new genes must work in concert with old genes and because evolution is driven by the immediate... natural selection tends to favor genes that have immediate advantages, discarding options that might function better in the long term." Marcus quotes Francois Jacob, who noted that evolution is like a tinkerer "who...often without knowing what he is going to produce...uses whatever he finds around him, old cardboards, pieces of strings, fragments of wood or metal, to make some kind of workable object...[the result is] a patchwork of odd sets pieced together with and where opportunity arose." Of Jacob's words, quips Marcus, "If necessity is the mother of invention, tinkering is the geeky grandfather of the kluge."

Marcus opines that kluges give us both insight into our evolutionary history and clues to how we can improve ourselves.

Marcus states of human memory, "Memory is, I believe, the mother of all kluges, the single factor most responsible for human idiosyncrasy. Our memory is both spectacular and a constant source of disappointment … Our memory is prone to distortion, conflation, and simple failure."

He compares human memory to that of the computer, finding our human memory to be "fragile," yet that of the computer "robust." He points out that computer programmers have constructed a computer's memory to be "postal-code"; each bit of information is assigned a specific location in the databank. Our memory is "contextual." Says Marcus "…we pull things out of our memory by using context, or *clues*, that hints at what we are looking for. It's as if we say to ourselves, every time we need a particular fact, 'Um, hello, brain, sorry to bother you, but I need a memory that's about the War of 1812. Got anything for me?' Often our brain obliges, quickly and accurately yielding precisely the information we want…even though [we] might not have the foggiest idea *where* in [our] brain that information was stored." He points out that contextual memory has a very long evolutionary history, existing not only in vertebrates, but also in arachnids and mollusks.

An advantage to contextual memory is that it prioritizes by bringing to mind common and recent items. Recall from the essay in this series on Error and Expectation that James Reason explained his model in which we recall items by "frequency gambling" and "similarity matching," with a small compartment adjacent to working memory that holds recent items for rapid retrieval. Marcus also points out that context-dependent memories can search in parallel and do not have the need to "keep track of [their own] internal hardware (like computers do), thereby making up for slowness of neurons compared to computer memory chips. Marcus adds that search engines even mimic the human brain by choosing cues to eliminate some possibilities instead of marching steadfastly through each location in the hard drive and listing all possible "matches."

Marcus admits that no one knows for sure how the human brain recalls items into current thought; he opines that the process is autonomous. In the first essay in this series we noted that Karl Lashley had observed that one is never conscious of the process of thinking; one is only conscious of the product that one has thought.

A Knowledge Products audio-course I once listened to about complexity points out that complex systems must have a way of getting rid of waste as a means of adapting to change. Perhaps, therefore, it is a **good** thing that we do not remember everything. Useful things are likely to occur commonly and we are likely to remember items that will be utilized. As Marcus points out, we have evolved to have context-dependent memory, thus it must have served us fairly well to date. Besides, we have constructed computers and developed libraries to hold "memories" for us and to document our history.

Because our memories are inexact at times, and because we do not know everything, our brains do not have access in a timely manner to all answers; therefore, we must have some sort of game plan for solving problems under the condition of uncertainty.

Probability Theory was developed, beginning in the mid 1600s. But is that theory just a "frame of reference" constructed by humans to deal with uncertainty? Or could a method for dealing with "probability" actually be built into our brains? We have discussed in earlier essays in this series, including Evidence, the work of Gerd Gigerenzer, who has concluded that "logic" is not the natural thought pattern of humans. Humans have, rather, developed "fast and frugal heuristics" to deal with most day-to-day problems. However, it turns out that, although we do not naturally think "logically" according to the formal rules of logic developed by mathematicians over the ages, our brains do have a mechanism for considering and dealing with probability. It is clear to us, from an evolutionary standpoint, and by this I mean including nonhuman animals, that an individual organism cannot have complete knowledge and must be able to function successfully under the condition of uncertainty.

Glimcher's work

Paul Glimcher, in *Decisions, Uncertainty, and the Brain* [5], outlines the history of man's quest to understand how the brain "thinks," describing developments beginning from the Renaissance and bringing us through the time of publication of his book in 2003.

Glimcher posits that limitations to thought are unavoidable because randomness is an inherent property of the universe. He opines that from the earliest study of the mechanisms of human thought, the underlying, often not explicitly stated, concept was that of determinism.

Furthermore, he suggests that the very method of study actually **requires** that the world be deterministic. He points out that during the period of history known as the Enlightenment, it was recognized that there were limitations to existing knowledge. In order to eliminate the gaps in knowledge, a method of describing the world and for testing the accuracy of descriptions was developed, which we know as the "scientific method." The scientific method was rooted in the most logically rigorous system of thought available at the time – analytic geometry, developed by Rene Descartes. The whole premise underlying the scientific method is that the world is deterministic and that it is possible to develop models/descriptions of the physical world that are predictive – that correct models will predict the future. Analytic geometry is a determinate mathematical system; thus, states Glimcher, "…[there was] a significant bias in the way that scientists thought about the world. Believing that the future state of the world could be predicted with analytic geometry not only implied that the world was deterministic, it also rested on the assumption that the world *must* be deterministic." So, from the time of the Enlightenment, we have been caught up in a paradox related to self-reference.

Slowly, over time, various scientists and mathematicians have chipped away at the assumption to end all assumptions – that the world is deterministic. Probability theory was developed. Godel's theorem proved that in a consistent, closed system (and all systems we define to study are closed) items that were true in that system could not be proved in the system as defined. Game theory was developed.

Furthermore, as Jacob Bronowski has pointed out in *Origins of Knowledge and Imagination*, as new connections are made when thinking about the world, new knowledge is gained. Scientists began to approach the problem of learning about how thought processes actually work by looking at the problem from different perspectives.

When neuroscientists began their studies, opines Glimcher, they adopted the assumption of determinism. Charles Sherrington in the early 1900s studied the flex arc of the bicep contraction in decerebrate cats, in whom the spinal cord had been completely transected from the brain cephalad to the reflex studied. He demonstrated in his model the deep tendon stretch reflex with which we physicians are all familiar. However, Glimcher points out that "reflexes are a theory and not a fact." He does not argue that the reflex demonstrated by Sherrington does not exist, rather he disputes that "reflexes" are the way problems are solved by humans as they go about their daily lives. Glimcher points out that people have argued that it has been proved beyond reasonable doubt that the "stretch response [that we actually demonstrate] and the stretch reflex [the theory to explain the stretch response] are physiologically equivalent." However, Glimcher avers, "Over the last hundred years many intelligent and respected physiologists have suggested that the reflex is not an adequate model for explaining *any* determinate behavior. Many of the physiologists have argued that there simply are no such things as reflexes in the real world." A problem arises when one begins to consider just exactly what the reflex is. If one holds an arm at different angles relative to gravity, the arm moves differently when stimulated to respond by the supposed reflex, depending on the angle at which it is held. One would have to propose that a number of separate reflexes exist, one for each possible angle relative to gravity. Glimcher hypothesizes that portions of the brain integrate bits of information before initiating an appropriate response.

Many experiments, of which Sherrington's is one, have been designed and carried out starting with the "hardware" and trying to see what that hardware could do. Glimcher refers us to the work of David Marr, a computer scientist working in the field of cognitive neuroscience, who suggested that a better approach might be to consider the

goal of a behavior. The **goal** of any behavior is, of course, to improve the fitness of the organism exhibiting said behavior. Glimcher describes some of the experiments performed.

Economics, especially classical economics, assumes that humans, but also other organisms, choose to **maximize** their "take." However, taking into account the constraints of evolution – that the organism is fittest that has the best apparatus at the time for dealing with the environment as it is at the time and that, referring to the hill-climbing analogy described in the essay in this series on Patterns, many "peaks" climbed may be local peaks and not the highest peak – "no actual neural system could ever achieve any computational goal with 100 percent efficiency." Additionally, as we will see, it behooves an organism to "test" the system periodically to ensure that a new paradigm is, or is not, preferable to the current favored choice.

As an example, foraging theorists have tried to figure out how animals decide what to eat. Animals may encounter, but decide not to eat, a prey item (be that item an animal in the case of carnivores, or plants in the case of herbivores). It is hypothesized that the forager might consider the size of the potential food item, the time required to obtain it, and the scarcity of that type of prey. Once an animal has begun to eat an item, it must decide when to stop eating it. Theorists hypothesize that there must be a theory of predation. "Optimal predation is the process of achieving a maximum rate of energy intake with a minimal expenditure of effort in a random and unpredictable world." Attempts have been made to determine the most efficient predation strategy for any animal, using mathematical tools to formalize such strategies.

Glimcher describes an experiment performed by Krebs and colleagues in the mid 1970s, testing the foraging efficiency of titmice (a type of bird). Titmice like to eat mealworms. The test system was such that a hungry titmouse was placed in a one cubic meter cage, beneath which a conveyor belt was running, carrying mealworms. There was a hole cut in the bottom of the cage and the titmouse would sit on a perch conveniently placed so that the titmouse could see anything passing by on the conveyor belt. The investigators made "standardized" mealworms by cutting up mealworms. "Large" mealworms consisted of eight body segments from the mid portion of a mealworm and "small" mealworms consisted of four segments. Five foraging situations were devised to test the titmice. In condition A, large and small mealworms were placed independently on the conveyor belt, but each appeared once every 40 seconds such that large and small meal worms were encountered at a rate of about once every 1.5 minutes. In condition B, the worms were encountered with equal frequency, as in A, but the rate doubled to one encounter every 20 seconds. In conditions C, D, and E, the large worms appeared every 6.5 seconds, but the small prey rate was varied to between once every 3.5 seconds to once every 20 seconds. An underlying hypothesis held by the investigators was that the large mealworms held for the titmice twice the value of the small mealworms.

The scientists considered it likely that birds that handled small prey the fastest, would always take all prey because the highest rate of energy intake would be achieved by taking all prey, large and small – the birds were fast enough to not miss any worms going by on the conveyor belt. Slower birds, on the other hand were predicted to take only large prey once the large prey was available more often than every 7-8 seconds. It was thought that the slow birds would ignore the small mealworms in conditions C, D, and E.

When the experiment was run, the fast birds were unselective, as predicted. Also, the slow birds did show a preference for the large worms once they were available every 6.5 seconds, and this included the condition in which the small worms were available more often.

Another hypothesis Krebs wanted to test was the so-called "zero-one" rule. This rule stated that, if the prey is worth eating, it is worth eating all the time, and if the prey is not worth eating, it would never be eaten. In conditions C, D, and E, it was observed that the slow birds, although selective, took the large worms only about 85% of the time; they took the smaller worms occasionally. Krebs hypothesized that the birds would occasionally take small worms to update for themselves an internal estimate of the relative profitability of the two prey types, the rationale being that the birds recognize that situations change in "the real world," and it is prudent to "keep up with the times" so to speak. Alternatively, it may be, considering the process of evolution as described by Marcus, the birds may be unable to behave "optimally."

Glimcher describes his own work using the visual system of rhesus monkeys. Visual information is received by right and left retinas, which process the information somewhat and send the information via the optic nerve to the neurons of the Lateral Geniculate Nucleus (LGN). The structure of the LGN is such that each location in the nucleus is specialized to monitor a specific position in the visual world. The geniculate maps then project to specific areas of the visual cortex, these areas also being topographically organized. Within each topographic area, some neurons respond to vertical information, some to tilted information, some to colors, and so on. The retinotopic map projects to area V1 in the visual cortex, and sends information to other areas such as V2, V3, V4 and MT; there are more than 30 mapped areas that each contribute to our perception visually of the world.

Glimcher studied visual saccades in monkeys. Visual saccades (the quick component of eye movements) are controlled by a number of neural circuits that control the six muscles within the orbit that move the eye so that gaze can be stabilized and aligned to compensate for the animal's self-motion and the like. Information to control saccadic movement goes through centers in the brain, the Superior Colliculus (SC) and Frontal Eye Field (FEF); the SC and FEF are also constructed in topographic fashion.

The actual studies consisted of rewarding monkeys with Berry Berry Fruit Juice whenever they learned specific visual saccade tasks. Electrodes were placed in specific neurons in the monkeys' brains to see when these neurons were active relative to the portion of the task they were performing. The monkeys would stare at an oscilloscope screen and look for the appearance of a stimulus/point. The tasks would vary. Sometimes the monkey was supposed to stare at stimulus, but move his/her focus to a second point on the screen when it appeared. Sometimes the monkey was to ignore the appearance of the second point (continuing to stare at the first point). Sometimes the monkey was to move his/her gaze to point two after point one disappeared from the screen. Sometimes the monkey would have to remember where the extinguished point was and return his/her gaze there after a delay of a second or two. And so forth. In each study, the monkey had to figure out what s/he was supposed to do by finding out whether his/her behavior was rewarded by juice.

Each study was constructed as a series of, say, a hundred or so trials while the monkey learned what s/he was supposed to do, followed by multiple iterations of a slight alteration of the first trial and so forth.

An important part of the brain Glimcher and others studied is the Lateral Intraparietal Area (LIP), which seemed to be related to holding attention or having an intention to perform another action. Glimcher devised a complex experiment (says Glimcher, "Amazing though it may seem, the monkeys readily learned this task"). "Each cued saccade trial began with the illumination of a central yellow light at which the monkey had to look. After a brief delay, the secondary and tertiary targets were illuminated, one at the best location and one at the null location. After a further delay, the central yellow light changed color. On a randomly selected 50% of trials it turned green. On the other trials it turned red. The monkey had been taught in advance that on trials in which the central fixation stimulus turned red, the left light served as the secondary target (the saccadic goal) and the right light served as the tertiary target (a completely irrelevant distractor). On trials in which the fixation stimulus turned green, the converse was true; the right light served as the target and the left light was irrelevant. The monkey was, however, not allowed to look at the secondary target until we turned off the central fixation stimulus. If, after that point, the monkey looked at the correct target, she received the juice reward."

Glimcher had thought to prove conclusively that either the LIP carries sensory-attentional signals, or the LIP carries motor intention plans. The hypothesis was that "if the LIP were motor-intentional, the neurons should respond strongly when the stimulus within the response field was a target, but **not at all** when it was an irrelevant distractor." The results showed that the LIP neurons discriminated between the two conditions, but the neurons were not silent – only less active – when the stimulus was the distractor.

After additional studies, at least as complex for the monkeys to learn, Glimcher concluded that the LIP neurons in fact more likely track both prior and posterior probabilities throughout the trials. Further studies showed, "In our free-choice task, both monkeys and posterior parietal neurons behaved as if they had knowledge of gains associated with different actions. These findings support the hypothesis that variables that have been identified by economists, psychologists and ecologists as important in decision-making are represented in the nervous system."

Glimcher then moves to the subject of game theory. "Game" in "game theory" refers to all interactions between intelligent competitors. Von Neumann and Morgenstern developed the concept, trying to develop a mathematical system that would describe how an actor in a "game" would make choices to obtain the best possible outcome for himself "given that his opponent or opponents were also attempting to obtain the best possible outcome for themselves." John Nash developed the mathematical formulas that describe the "Nash Equilibrium" point, for which either choice has the same value to the chooser.

Glimcher concludes, reviewing the work of Maynard Smith on the concept of Evolutionary Stable Strategies (ESS), what is important is that at the level of individual acts behavior must be unpredictable, but for the whole population, behavior must be "lawful and predictable at a probabilistic level." As an example, Glimcher describes the work of Harper who studied foraging of ducks. There was a population of 33 ducks on a lake at Cambridge University. Harper devised an experiment whereby two people, Harper and an assistant, would throw 2-gram or 4-gram bread balls from positions about 20 meters apart at the edge of the lake. The person throwing the 2-gram balls would throw one bread ball every 5 seconds. The other person would throw the 4-gram balls either every 5 seconds (one experiment) or 10 seconds (second experiment). The experiment was considered from the standpoint that one duck was playing against the rest of the flock so that the mathematics to determine the prediction would be simplified. The hypothesis was that the duck-of-interest would join the line to maximize his intake of bread. For the experiment where the two sizes are thrown at the same interval, twice as much actual bread is in the 4-gram area, so that it is more likely that a duck would join that line. If all 33 ducks rush to the 4-gram line, however, only 2/3 of the possible bread is being eaten, so some ducks should notice this and go to the other line. When the time interval between the 4-gram bread balls was doubled, equal amounts of bread are available from each line and the prediction is that there would be an equal number of ducks in each line. When Harper actually performed the experiment, he found that the ducks figured out the situation in about 60 seconds, before even half of the ducks had actually received a bread ball.

Glimcher advises us that, although game theory can provide an accurate way to predict equilibrium situations, "...the great limitation of contemporary game theory is that it fails to provide tools for describing the dynamic process by which equilibriums are reached."

Glimcher describes the "Inspection" game of "Work or Shirk." In one iteration of the game, humans play against a computer. A worker is expected by his boss to work every day to earn his wage. The boss, however, does not work at the same location and either trusts the worker to be working or goes to inspect to see if the worker actually shows up. If the boss finds out the worker did not show up, the worker does not get paid. The variables of the game include **E** (the effort the worker expends at work), **W** (the wage the boss pays the worker), **P** (the value to the boss of the product produced by the worker), and **I** (the cost to the boss of inspecting). If the worker works and the boss inspects, the worker earns {**W - E**}; the boss earns {**P - W - I**}. If the worker works and the boss does not inspect, the worker earns the same as before, but the boss earns more by not having to pay for the inspection {**P - W**}. If the worker does not work and the boss inspects, the worker earns nothing {no wage, but no effort expended} and the boss has only the cost of the inspection {**- I;** no product, but no wage paid}. If the worker does not work and the boss does not inspect, the worker gets his wage {**W**; no effort expended} and the boss pays only the wage {**- W**; no product received and no cost of inspection}. The actual mathematical numbers vary according to how the numerical values of **E, W, P** and **I** are set, but it comes down to the formulae as the outcome for the equilibrium of **I/W** as the probability of the worker shirking and **E/W** for the probability of the boss inspecting. This was the actual outcome in the contest between the human (worker) and the computer (boss).

Glimcher carried out this experiment with his monkeys since he wanted to know if the Lateral Intraparietal (LIP) area was at work. He reasoned that if the monkeys were somehow computing and behaving so as to maintain the Nash equilibrium, "… across all of the different conditions we studied there should never have been a change in LIP firing rates if the LIP firing rates encode relative expected utility." And that is just what Glimcher found. Throughout various values of **E, W** (more or less milliliters of juice for the monkeys), **P**, and **I**, the firing rate of the LIP neurons "was pretty stable throughout the day, even though the animal's behavior varied significantly from one block of trials to the next." Glimcher concluded that "these computations [performed by the LIP neurons] seemed be the same regardless of whether the monkey was in a deterministic task [such as the experiment with the complex saccadic task described earlier] … or an irreducibly uncertain task [such as work/shirk] … Neurons in LIP *did* seem to see all of behaviour as a single continuum governed by a single set of goal directed rules and computations."

Precepts from complexity theory

In his Teaching Company course, *Understanding Complexity* [10], Scott Page makes important points about complex systems. First, biologic systems are adaptive. That is to say, as mentioned earlier in reference to game theory, when elements of a system interact, those elements influence each other and change their behavior in response to what the other element does. Second, in any complex system, no single element controls the system, but **any** element can influence any or all other elements.

Page refers to adaptability in systems as "nonstationarity." Returning to the "hill-climbing" analogy referred to earlier, in a stationary system, a landscape might be referred to as "rugged." Some hills are higher than others, but the height of them does not change – they remain stationary. Page introduces the concept of "dancing" landscapes. In dancing landscapes, the hills actually change heights. Those hills are **not** stationary. The heights of the hills in a dancing landscape adapt according to influences.

Conclusion

I think it is clear from the discussion above that there are epistemic limits to cognition. I think it is equally clear that there are limits to cognition that are due to randomness – randomness generated in the complex adaptive system in which we live.

From the work of Glimcher, Marcus, and Page we can see that intelligence, including human intelligence, has evolved in an adaptive/dancing landscape and that we have developed a hard-wired capability to assess issues of probability and to deal with uncertainty, coping as we must with intelligent adapting beings.

As Glimcher pointed out, until fairly recently humans have assumed the existence of determinism, relegating all feelings of uncertainty to the realm epistemic. Determinism, however, assumes stationarity. I think there is ample evidence, via complexity theory, that our world exhibits features of nonstationarity.

Our task, then, is to embrace the concept of nonstationarity and to reconsider as much as possible what we think we have already learned from this new perspective.

Harth, as discussed in more detail in the essay in this series on Patterns [11], has described that when we look for something, our brains are likely to "see" the item, enhancing some features of what we are looking at to meet our expectations. He also points out that we use our senses to evaluate the object and to "rein in" our imaginations, informing our brain that what we really see is not the "coin in the sand at the beach" we are looking for, but merely a piece of shell. We rarely hallucinate.

Our senses serve as a sort of "tether" to reality. When we learn to evaluate patients in medical school and residency and to use various instruments to extend our native human abilities and to interpret histologic sections during our pathology training, we rely on our mentors to say "yes, that is the rash of dermatitis herpetiformis" or "no that is not invasive cancer because..." Each of us needs some sort of tether to reality, just as we need our senses to keep our brains from hallucinating.

I think our next task is to improve the way we as individuals interact so that we, collectively, can define new frames of reference from which we can gain new knowledge. We must learn about and understand how our brains work as well as how complex systems work and use this knowledge to further our understanding of the world. While we will never escape the epistemic limit to cognition imposed by the "brain-as-virtual-reality-only" or "brain-in-a-vat" point of view, I do not think this should limit our progress very much. After all, we have co-evolved with our environment to sense the items we can sense and we are surviving.

Summary

Evidence exists that there are limits to cognition. Some limits are the result of our embodiment whereby our brains have no direct experience with the world; all experience is via the senses and all input is processed in some way by the brain before we become conscious of a thought. Other limits are due to the nature of the world itself; the world being a complex adaptive system.

However, although limits exist, there are still an infinite number of thoughts and hypotheses about the world we can entertain by viewing each body of data from multiple points of view and by helping each other to discern a collective reality, about which can draw conclusions, and from which, we can progress as a species, understanding more fully how we exist and evolve in the complex adaptive system in which we live.

References

1. Anderson C. On the nature of thought processes and their relationship to the accumulation of knowledge, Part XIII: The nature of evidence. Dermatopathology: Practical and Conceptual. 2009;15(4):20. http://www.derm101.com/content/57644.
2. Bronowski J. *The Origins of Knowledge and Imagination*. New Haven: Yale University Press, 1978.
3. Slobodkin L. *Simplicity & Complexity in Games of the Intellect*. Cambridge, Massachusetts: Harvard University Press, 1992.
4. Feyerabend P. *Against Method*. 4th ed. London: Verso, 2010.
5. Glimcher P. *Decisions, Uncertainty, and the Brain*. Cambridge, Massachusetts: MIT Press, 2003.
6. Gamez D. *What We Can Never Know*. London: Continuum, 2007.
7. Schwartz J. *The Mind and the Brain*. New York: Regan Books, 2002.
8. Gigerenzer G. *Adaptive Thinking*. New York: Oxford University Press, 2000.
9. Kluge G. *The Haphazard Evolution of the Human Mind*. Boston: Mariner Books, 2009.
10. Page S. *Understanding Complexity* [DVD]. Chantilly, VA: The Teaching Company, 2009.
11. Anderson C. On the nature of thought processes and their relationship to the accumulation of knowledge, Part XII: Detecting and Using Patterns. Dermatopathology: Practical and Conceptual. 2009;15(2):16. http://www.derm101.com/content/32781.