

The Virtual Reality of the Mind

John F. Sowa

Kyndi, Inc

sowa@bestweb.net

Abstract

In evolutionary terms, imagery developed hundreds of millions of years before symbolic or language-like systems of cognition. Even the most abstract reasoning in science and mathematics requires imagery: diagrams and written symbols supplement short-term memory, and richer imagery is essential for novel analogies and creative insights. A cognitive architecture must relate symbols to the perceptions and purposive actions of an embodied mind that interacts with the world and with other minds in it. This article reviews the evidence for an internal virtual reality as the foundation for the perception, action, and cognition of an embodied mind. Peirce's theory of signs is a unifying framework that relates all branches of cognitive science, including AI implementations. The result is a theory of virtual reality for cognitive architectures (VRCA) that spans the minds from fish to humans and perhaps beyond.

Keywords: Mental imagery, embodied cognition, virtual reality, cerebellum, semiotics, cognitive architecture

1 Symbols and Imagery

For years, the mainstream in AI ignored mental imagery or considered it a side effect of perception that is irrelevant to cognition. Good Old Fashioned AI (GOFAI) is based on symbols organized in language, logic, networks, rules, frames, or chunks. But the emphasis on symbols created more problems than it solved: the Chinese room (Searle 1980), symbol grounding (Harnad 1990), and the way animals relate their bodies to perception of and action upon the world.

After millions of years of leaping and swinging through trees, primates developed three-dimensional cognition with excellent hand-eye coordination. Modern humans have not lost those abilities. Note the feats of Olympic gymnasts or basketball players who can score three points while running through interference by the opposing team. To support that ability, their visual system must process two-dimensional snapshots of a dynamically changing 3-D world, anticipate likely changes, and respond appropriately. Since humans and apes can perform similar kinds of gymnastics, their brains must process the same kind of dynamic 3-D geometry. Either the apes have symbolic systems as advanced as humans, or both humans and apes use similar analog methods.

During the six million years from apes to humans, a modest increase in brain size came with *Homo habilis* about two million years ago. A significant increase came with *Homo erectus* about one mya.

Deakin (1997) claimed that the need to extend and enhance a protolanguage stimulated “the co-evolution of brain and language.” The greatest increase in modern humans is in the huge cerebral cortex, but the cerebellum and brain stem are similar to the apes’. Figure 1 shows the human cortex overlaid with a neurocognitive network by the linguist Sydney Lamb (2016). The areas in pink are highly active in fMRI or PET scans for tasks that involve language semantics; the gray areas are less active for those tasks (Binder et al. 2009).

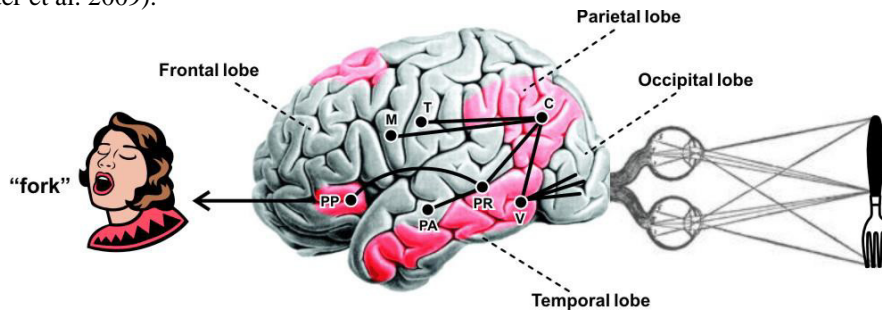


Figure 1. Areas of the left hemisphere that are active in language

The network in Figure 1 shows links from the image of a fork in the primary visual cortex to Broca’s area for pronouncing the word fork. According to Lamb (2010), each labeled node represents a cortical column. Node C is a column for the concept of a fork. He placed it in the parietal lobe, which has links to the primary projection areas for all sensory and motor modalities. For the image of a fork, C has a link to node V, which connects to percept nodes in the occipital lobe. For the tactile sensation of a fork, C links to node T in the sensory area for the hand. For the motor patterns for manipulating a fork, C links to node M in the motor area for the hand. For the word fork, C links to node PR in Wernicke’s area. Then PR links to node PA for recognizing the sound and to node PP in Broca’s area for pronouncing the phonemes.

The primary sensorimotor areas are among the gray areas in Figure 1. For each body part, the sensory area contains a topographic (point-to-point) map from the skin, and the motor areas map to the muscles that control the body parts. The parietal lobes are among the association areas that expanded rapidly in the evolution from primitive mammals to apes and humans. To explain “the nature and development of imagery and verbal symbolic processes,” Allan Paivio (1971) proposed a dual-coding theory (DCT) with a symbolic verbal system that maps to and from nonverbal imagery.

If there are two codes, the next question is whether they are processed by the same methods. In ACT-R (Anderson et al. 2004), production rules are symbolic if-then rules. Images must be mapped to symbols before they can be processed by those rules. In DCT, logogens (symbols) and imagens (percepts or larger images) may be stored and processed by the same mechanisms (Paivio 2007). Marvin Minsky’s Society of Mind (1986) supports an open-ended variety of modules and forms of representation. To connect different modules with different representations, Minsky proposed a system of K-lines (knowledge links), which allow modules at opposite ends of a K-line to use different representations. A module may interpret messages received via K-lines without any information about the internal representations of the sending modules. In his Emotion Engine, Minsky (2006) proposed emotions as the driving forces that motivate the modules and determine the goals to be achieved.

Since these systems address different aspects of cognition, they could be related as components of a larger framework. ACT-R, for example, might be extended to support both codes of DCT. The K-lines of Minsky’s Society of Mind might represent the same nerve fibers as the links in Lamb’s networks. In Figure 1, for example, the concept node C has long links across different lobes. Node T has links from the hand (afferent nerves); node M has links to the hand (efferent nerves); node V links to nodes for visual percepts; and node PP links to nodes that control muscles for producing phonemes. More research is needed to relate the details, but the experimental evidence for each of these systems could be compatible with a larger framework that addresses the role of mental imagery.

Today, the computational methods of virtual reality (VR) are more accurate and effective than symbolic reasoning for analyzing and simulating physical transformations. For every animal, the body with its senses and limbs is the focus, principal actor, and reference standard for its own VR. Consciousness is the content of that VR. Charles Sanders Peirce called it “a moving picture of the action of the mind in thought.”

The nature, the role, and even the existence of mental imagery have been controversial. Pylyshyn (2003) presented serious objections, and Kosslyn et al. (2006) responded to them. Fully embodied cognition would require a dynamic 3-D simulation of the body in relation to the environment. A simulation of 2-D retinal images would be insufficient to counter Pylyshyn’s claims. To support the case for imagery, the next section analyzes the operations in the brain beneath the cortex in animals from fish to humans. The concluding section shows how Peirce’s logic and semiotic can characterize the VR and relate it to perception, action, language, and reasoning about the world.

2 Cerebellum, Basal Ganglia, and Cortex

Until the 1980s, the cerebellum and basal ganglia were considered part of the motor system, with little or no involvement in cognition. But the cerebellum, which takes only 10% of the volume of the brain, has the majority of neurons in the brain. In a historical review, Schmahmann (2010) noted that patients in the 1980s with subcortical lesions showed symptoms that resembled patients with lesions in the cortex itself. He asked “if the basal ganglia are not only motor but cognitive as well, what about the big motor machine at the base of the brain... the cerebellum?”

In analyzing the role of the cerebellum, Doya (2000) observed “Involvement of the basal ganglia and the cerebellum in cognitive functions once was a controversial issue. However, now there are abundant brain imaging data showing their involvement in mental imagery, sensory discrimination, planning, attention, and language... An important role of the cerebral cortex is to provide common representations on which both the basal ganglia and the cerebellum can work together. Unsupervised learning of the cerebral cortex may also be the foundation of building modular organization in which learning modules in the basal ganglia and the cerebellum are flexibly combined.”

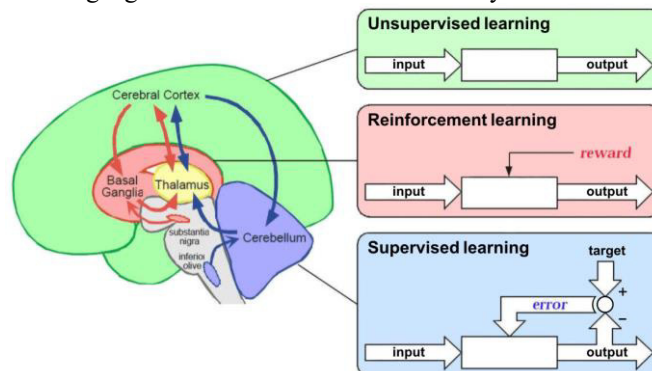


Figure 2. Brain regions for three kinds of learning (Doya 2000)

Figure 2 summarizes Doya’s three-way distinction. The cerebral cortex can reward and supervise learning by the basal ganglia and cerebellum. For reinforcement learning by the basal ganglia, the cortex signals the substantia nigra to produce a reward of dopamine. For supervised learning by the cerebellum, the cortex generates a goal or target. Then the cerebellum subtracts the previous output from the target to generate an error correction that refines future outputs. In a consensus article by 18 coauthors, Caligiore et al. (2016) revised and extended Doya’s diagram. For the cortex, they replaced the label Unsupervised learning with Hebbian learning. For the basal ganglia, they indicated that reinforcement learning generates production rules. They also added more detail to the boxes.

Doya mentioned mental imagery, and the consensus article noted “that the neuronal systems for mental imagery and motor preparation are closely related.” They also note that the cerebellum “is connected with” the language areas shown in pink in Figure 1. But the research that led to Figure 2, by itself, does not resolve the debates about symbolic reasoning vs. mental imagery. A review of brain anatomy from fish to apes provides some perspective:

Fish lack the neocortex, they have a well-developed midbrain, and their cerebellum is the largest component of the brain. For cartilaginous fish such as sharks, the cerebellum may take 42% of the brain (Montgomery et al. 2012). Although fish show little evidence of symbolic reasoning, they navigate in a three-dimensional environment, catch smaller prey, and avoid larger ones. Since they flex their entire bodies as they swim, their brain must relate constantly changing visual images to the changing shape of their body, the tactile feel of the flowing water, and the rapid motions of their predators and prey.

Relative to their size, birds have brains that are comparable to the mammals. But the requirements for aerial acrobatics led them to develop a cerebellum that takes about 25% of the brain volume, compared to the human 10% (Walsh & Milner 2011). Some birds, especially the ravens and parrots, have intelligence that is comparable to the higher mammals.


For almost 200 million years, the early mammals coexisted with the dominant dinosaurs. To evade, outwit, or hide from the huge beasts, most of them remained in their burrows or trees until darkness. Dolphins are distantly related to the hippopotamus, which has a brain that is typical of a large herbivore. But dolphins live in a three-dimensional environment, compete with sharks, which have a highly developed cerebellum, and lack the sharks’ huge olfactory bulb for smelling blood at long distance. Those conditions led the dolphins to develop echolocation for finding their prey in murky water and a language-like code for communicating and coordinating their actions with other dolphins. To support those functions, their brain is comparable to the human size relative to their body weight. But their cerebellum is about 15% of the brain size in comparison to the human 10% (Marino 2000).

Although birds and bats control their wings by different limbs and muscles, the similarities in the sensory inputs led to similarities in their cerebellum. There are two kinds of bats: fruit bats have good eyesight and search for stationary food in daylight; insect-eating bats have poor eyesight and use echolocation to catch insects in the dark. Both kinds of bats have a well-developed cerebellum with similarities to the relative sizes of the lobes in the bird cerebellum. For the insect eaters, the computation required for echolocation also led to an increase in the lobes that correspond to the lobes for echolocation in the cerebellum of the dolphins (Kim et al. 2009). Despite their poor eyesight, echolocation is sufficient for the insect eaters to fly with better speed and accuracy than the fruit bats.

To use a computer analogy, the cerebral cortex corresponds to the central processing unit (CPU), and the cerebellum corresponds to a high-speed, but special-purpose graphic processing unit (GPU). Without a GPU, the CPU can do all the computation by itself, but more slowly. Like the CPU, the human cortex can learn to do many of the functions of the cerebellum, but not as efficiently. Among the very few people who were born without a cerebellum and survived, the best documented is Jonathan Kelleher. All his developmental stages were very late. But after years of speech therapy, physical therapy, and special education, he is now a cheerful, friendly, but awkward adult. He is also able to hold a job and live by himself (Hamilton 2015).

Yet even with years of training, Kelleher still has serious cognitive deficits. Brain scans show that the cerebellum is highly active in language and mathematics as well as physical activity. Without a cerebellum, Kelleher can be trained to do many tasks adequately, but he rarely discovers how to perform novel tasks by himself. The subcortical connections of the cerebellum integrate perception and action with the limbic system. Without them, Kelleher seems to lack the empathy and ability to learn by imitating others. His sister said “He doesn’t really get into this deeper level of conversation that builds strong relationships, things that would be the foundation for a romantic relationship or deep, enduring friendships. It can be a little bit surface-level.” Even so, Kelleher’s surface-level cognition is better than the best symbolic systems available today.

3 Peirce's Semiotic Foundation for Cognition

In the theory of signs or semiotic by Charles Sanders Peirce, perception and action are the foundation. Mental imagery is an extension of perception, and symbols evolve from image-like icons in all sensory modalities. The symbol  is an icon of an old-fashioned telephone. It is now a symbol of things that have no physical resemblance to the original. Its ring tone, which is a symbol of an incoming call, evolved from an auditory icon that sounds like the word ring. But ring tones today seldom sound like the iconic ring. These examples illustrate Peirce's principle that symbols grow.

Although Peirce could not know modern neuroscience, his best friend and colleague was William James, with whom he analyzed and developed theories that are still actively debated today. Peirce and his student Joseph Jastrow (1884) published the first experimental research in psychology that used properly randomized data. With his article on "Logical Machines" in the *American Journal of Psychology*, Peirce (1887) was also a pioneer in artificial intelligence.

In his work on logic, Peirce defined all his notations and rules of inference in purely formal terms, but he also discussed their linguistic and psychological implications. Among his many intriguing insights are the term mental diagram and the claim that his existential graphs "put before us moving pictures of thought... in its essence free from physiological and other accidents" (CP 4.8). But he added, "Please note that I have not called it a perfect picture. I am aware that it is not so: indeed, that is quite obvious. But I hold that it is considerably more nearly perfect than it seems to be at first glance, and quite sufficiently so to be called a portraiture of Thought" (CP 4.11).

Pietarinen (2006) showed that Peirce's mental diagrams and moving pictures are intimately connected to every aspect of his logic and semiotics. The psychologist Johnson-Laird (2002), who had written extensively about mental models, supported Peirce's claims: "Peirce's existential graphs... establish the feasibility of a diagrammatic system of reasoning equivalent to the first-order predicate calculus. They anticipate the theory of mental models in many respects, including their iconic and symbolic components, their eschewal of variables, and their fundamental operations of insertion and deletion." To relate icons to logic without a prior translation to symbols, Sowa (2015) showed how arbitrary diagrams or even pictures could be inserted into existential graphs and processed by exactly the same rules of inference used for symbols. With two additional rules of inference, called observation and imagination, information could be transferred from icons to symbols and back again.

For further discussion of Peirce's contributions and their relevance to of a cognitive architecture based on virtual reality, see articles by Sowa (2006, 2010, 2011, 2014, 2015a, 2015b) and Majumdar and Sowa (2009, 2014).

References

- Anderson, John R., Daniel Bothell, Michael D. Byrne, Scott Douglas, Christian Lebiere, Yulin Qin (2004) An integrated theory of the mind, *Psychological Review* **111:4**, 1036-1060.
- Binder, Jeffrey R., Rutvik H. Desai, William W. Graves, & Lisa L. Conant (2009) Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies, *Cerebral Cortex* **19**, 2767-2796.
- Deacon, Terrence W. (1997) *The Symbolic Species: The Co-evolution of Language and the Brain*, W. W. Norton, New York.
- Doya, Kenji (2000) Complementary roles of basal ganglia and cerebellum in learning and motor control, *Current Opinion in Neurobiology* **10:6**.
- Hamilton, Jon (2015) A man's incomplete brain reveals cerebellum's role in thought and emotion, National Public Radio, <http://www.npr.org/blogs/health/2015/03/16/392789753/a-man-s-incomplete-brain-reveals-cerebellum-s-role-in-thought-and-emotion>
- Harnad, Stevan (1990) The symbol grounding problem, *Physica D* **42**, 335-346.

Johnson-Laird, Philip N. (2002) Peirce, logic diagrams, and the elementary processes of reasoning, *Thinking and Reasoning* **8:2**, 69-95.

Kim, J-Y, H. Marzban, S-H Chung, M. Watanabe, L. M. Eisenman, & R. Hawkes (2009) Purkinje cell compartmentation of the cerebellum of microchiropteran bats, *J. of Comparative Neurology* **517**, 193-209.

Kosslyn, Stephen M., William L. Thompson, & Giorgio Ganis (2006) *The Case for Mental Imagery*, New York: Oxford University Press.

Lamb, Sydney M. (2010) Neurolinguistics, Lecture notes for Linguistics 411, Rice University, <http://www.owlnet.rice.edu/~ling411>

Lamb, Sydney M. (2016) Linguistic structure: A plausible theory, *Language Under Discussion* **4:1**, 1-37.

Majumdar, Arun K., & John F. Sowa (2009) Two paradigms are better than one and multiple paradigms are even better, *Proc. ICCS 2009*, S. Rudolph, F. Dau, and S.O. Kuznetsov, eds., LNAI 5662, Berlin: Springer, pp. 32-47.

Majumdar, Arun K., & John F. Sowa (2014) Quantum cognition, *Web Intelligence and Intelligent Agent Technologies*, vol. 2, IEEE, pp. 1-4.

Marino, L., J. K. Rilling, S. K. Lin, & S. H. Ridgway (2000) Relative volume of the cerebellum in dolphins and comparison with anthropoid primates, *Brain, Behavior, & Evolution* **56**, 204-211.

Minsky, Marvin Lee (1986) *The Society of Mind*, Simon & Schuster, New York.

Minsky, Marvin Lee (2006) *The Emotion Machine: Commonsense Thinking, Artificial Intelligence, and the Future of the Human Mind*, Simon & Schuster, New York.

Montgomery, John C., David Bodznick, & Kara E. Yopak (2012) The cerebellum and cerebellum-like structures of cartilaginous fishes, *Brain, Behavior, and Evolution* **80**, 152-165.

Newell, Allen (1990) *Unified Theories of Cognition*, Harvard University Press, Cambridge, MA.

Paivio, Allan (1971) *Imagery and Verbal Processes*, New York: Holt, Rinehart and Winston.

Paivio, Allan (2007) *Mind and Its Evolution: A Dual Coding Approach*, New York: Psychology Press.

Peirce, Charles Sanders (CP) *Collected Papers of C. S. Peirce*, ed. by C. Hartshorne, P. Weiss, & A. Burks, 8 vols., Harvard University Press, Cambridge, MA, 1931-1958.

Peirce, Charles Sanders (1887) Logical machines, *American J. of Psychology* **1**, 165-170.

Peirce, Charles Sanders, & Joseph Jastrow (1884) On Small Differences in Sensation, *Memoirs of the National Academy of Sciences* **3**, 73-83.

Pietarinen, Ahti-Veikko (2006) *Signs of Logic: Peircean Themes on the Philosophy of Language, Games, and Communication*, Synthese Library, vol. 329, Berlin: Springer.

Pylyshyn, Zenon (2003) *Seeing and Visualizing: It's Not What You Think*, Cambridge, MA: MIT Press.

Schmahmann, Jeremy D. (2010) The role of the cerebellum in cognition and emotion, *Neuropsychology Review* **20:3**, 236-260.

Sowa, John F. (2006) Peirce's contributions to the 21st Century, in H. Schärfe, P. Hitzler, & P. Øhrstrøm, eds., *Conceptual Structures: Inspiration and Application*, LNAI 4068, Berlin: Springer, pp. 54-69.

Sowa, John F. (2011) Peirce's tutorial on existential graphs, *Semiotica* **186:1-4**, 345-394.

Sowa, John F. (2015a) Peirce, Polya, and Euclid: Integrating logic, heuristics, and diagrams, slides presented at the Conference of the American Association for Philosophy, Vancouver, <http://www.jfsowa.com/talks/ppe.pdf>

Sowa, John F. (2015b) Signs and Reality, *Applied Ontology* **10:3-4**, 273-284.

Walsh, Stig, & Angela Milner (2011) Evolution of the avian brain and senses, in G. Dyke & G. Kaiser, eds., *Living Dinosaurs: The Evolutionary History of Modern Birds*, New York: Wiley.