The Virtual Reality of the Mind

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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.

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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 difficulties in mapping discrete symbols to a continuous 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).

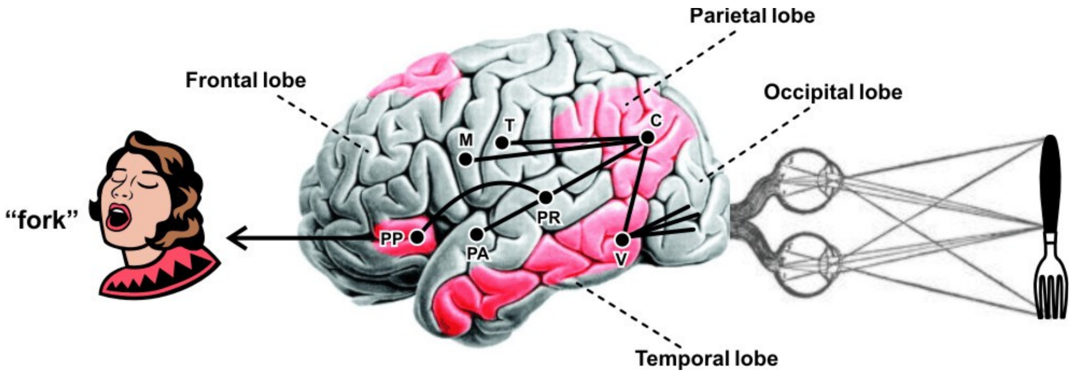

Figure 1. Areas of the left hemisphere that are active in language

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 a 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." Jakob von Uexküll called it the *Innenwelt* (inner world) of humans and other animals. The many writings on phenomenology and embodied cognition may be interpreted as studies of that VR and its relationship to human life and 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."

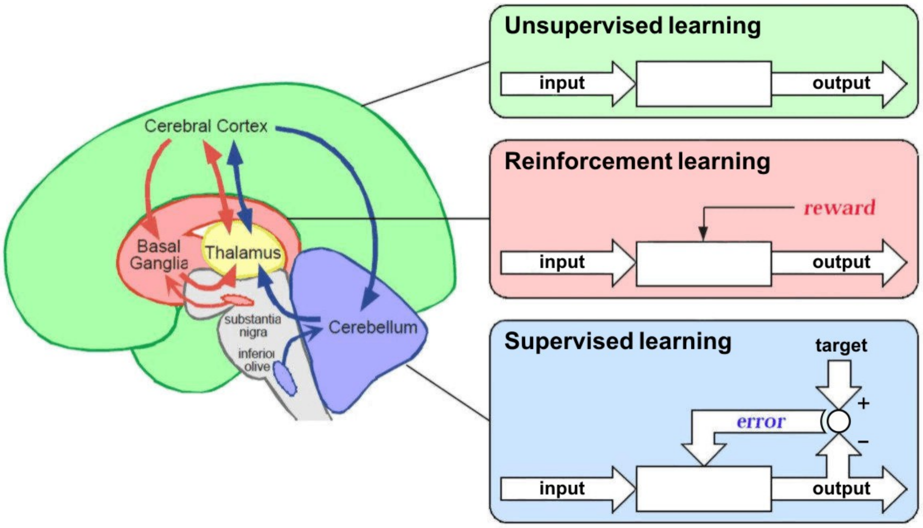

Figure 2. Brain regions for three kinds of learning (Doya 2000)

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) presented Figure 3 as a revised and extended version of Figure 2. In this version, arrows with a pointed end add new patterns; arrows with a circular end inhibit or delete older patterns.

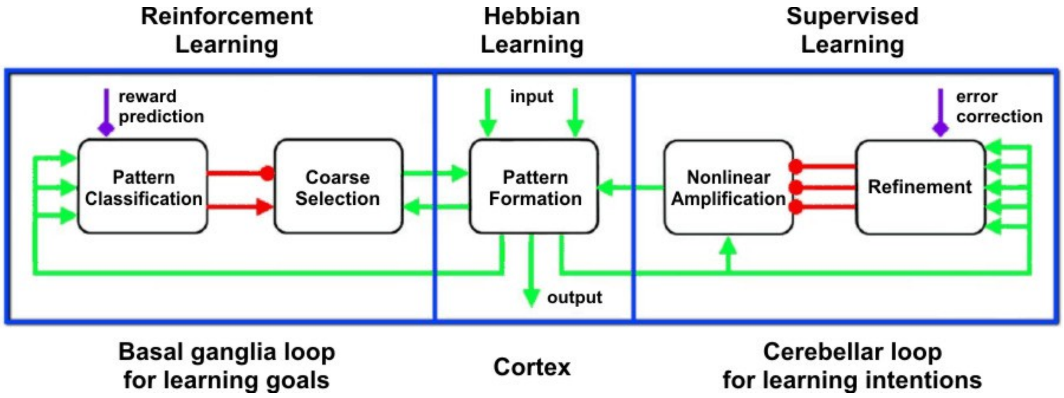

Figure 3. Revised and extended version of Figure 2

For learning by the cortex, Figure 3 has the label *Hebbian learning* instead of unsupervised learning. For the basal ganglia, it indicates that reinforcement learning generates production rules. The box for pattern classification in the basal ganglia loop would correspond to the if-part of a production rule. The box for coarse selection would correspond to the then-part. An arrow with a pointed end would represent a rule of the form "if *p*, then *q*." An arrow with a circular end would represent a rule of the form "if *p*, then not *q*." In logical terms, the word *coarse* in Figure 3 may be interpreted as generalization: the pattern in the then-part of a rule would represent the commonalities or general structure of many related patterns in the cerebral cortex.

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 Figures 2 and 3 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 comparable to the higher mammals. A parrot named Alex was able to learn and use a subset of English at a level comparable to the sign language learned by apes (Pepperberg 1999).

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 Logic and Semiotic

Charles Sanders Peirce was a close friend and colleague of William James for over 50 years. Both of them had a solid foundation in the philosophy and psychology of their time. But Peirce was also a pioneer in logic, and he had published research in mathematics, physics, chemistry, and astronomy. With his student Joseph Jastrow, Peirce (1884) published the first research in experimental psychology that used a properly randomized methodology. Peirce (1887) published an article on "Logical Machines" in volume 1 of the *American Journal of Psychology*. Minsky (1963) included that article in his bibliography of artificial intelligence. In language, his father had taught him Latin and Greek as a child, and he was fluent in French and German. In lexicography, he worked as an associate editor of the *Century Dictionary*, for which he wrote, revised, or edited over 16,000 definitions.

In Peirce's theory of signs or semiotic, 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 letter M, for example, was borrowed from the Phoenician letter *mem*, which was adapted from the Egyptian hieroglyph 𓈖 for water. The symbol ☎ evolved from an image of an old-fashioned telephone. Its ring tone, which is a symbol of an incoming call, evolved from an auditory image that sounded like the word *ring*. But ring tones today seldom sound like the iconic ring. He recognized that continuity is essential for adapting a discrete set of symbols to a continuously variable world:

> Symbols grow. They come into being by development out of other signs, particularly from icons, or from mixed signs partaking of the nature of icons and symbols. We think only in signs. These mental signs are of mixed nature; the symbol parts of them are called concepts. (CP 2.302)

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 may be transferred from icons to symbols and back again. Those rules may be used in both formal and informal reasoning. In fact, all formalisms, including mathematics, logic, and programming notations, are disciplined versions of natural languages. Peirce's rules can be applied to any or all of them (Sowa 2015b).

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, 2015c) and Majumdar and Sowa (2009, 2014).

References

Albus, James S. (2010) A model of computation and representation in the brain, *Information Sciences* **180**, 1519-1554.

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.

Anderson, Sarah E., & Michael J. Spivey (2009) The enactment of language: Decades of interactions between linguistic and motor processes, *Language and Cognition* **1:1**, pp 87-11, doi:10.1515/LANGCOG.2009.005

Andrews, Kristen (2011) Beyond anthropomorphism: attributing psychological properties to animals, *The Oxford Handbook of Animal Ethics*, Oxford: University Press, pp. 469-494.

Arbib, Michael A., ed. (2013) *Language, Music, and the Brain*, Cambridge, MA: MIT Press.

Arbib, Michael A. (2016) Towards a Computational Comparative Neuroprimatology: Framing the language-ready brain, *Physics of Life Reviews*, in Press.

Aristotle, *On Interpretation*, vol. 1 of *Works*, Loeb Library, Cambridge, MA: Harvard University Press.

Barsalou, Lawrence W. (2009) Simulation, situated conceptualization, and prediction, *Philosophical Transactions of the Royal Society B* **364**, 1281-1289.

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.

Borst, Grágoire, Rogier A. Kievit, William L. Thompson, & Stephen M. Kosslyn (2011) Mental rotation is not easily cognitively penetrable, *J. of Cognitive Psychology* **23**, 60-75.

Bybee, Joan (2010) *Language, Usage, and Cognition*, Cambridge: University Press.

Cartmill, Erica, & Dario Maestripieri (2012) Socio-cognitive specializations in nonhuman primates: evidence from gestural communication, in J. Vonk & T. K. Shackelford, eds., *The Oxford Handbook of Comparative Evolutionary Psychology*, New York: Oxford University Press, pp. 166-193.

Casagrande, Vivien A., & Jon H. Kaas (1994) The afferent, intrinsic, and efferent connections of primary visual cortex in primates, in *Cerebral Cortex* **10**, *Primary Visual Cortex of Primates*, A. Peters & K. Rockland, eds., New York: Plenum Press, pp. 201-259.

Deacon, Terrence W. (1997) *The Symbolic Species: The Co-evolution of Language and the Brain*, W. W. Norton, New York.

Deely, John (2004) Semiotics and Jakob von Uexküll's concept of Umwelt, *Sign Systems Studies* **32:1-2**, 11-34.

Descartes, René (1662) *de Homine*, Leiden: Peter Leffen & Frans Moyard.

de Waal, Frans B. M. (2009) *The Age of Empathy: Nature's Lessons for a Kinder Society*, Toronto: McClelland & Stewart.

Doya, Kenji (2000) Complementary roles of basal ganglia and cerebellum in learning and motor control, *Current Opinion in Neurobiology* **10:6**.

Fogassi, Leonardo, & Pier Francesco Ferrari (2012) Cortical motor organization, mirror neurons, and embodied language: an evolutionary perspective, *Biolinguistics* **6:3-4**, 308-337.

Gallese, Vittorio, & George Lakoff (2005) The brain's concepts: The role of the sensory-motor system in conceptual knowledge, *Cognitive Neuropsychology* **22:3-4**, 455-479.

George, Dileep, & Jeff Hawkins (2005) A hierarchical Bayesian model of invariant pattern recognition in the visual cortex, *Proc. Proc. of International Joint Conference on Neural Networks*, pp. 1812-1817.

Grandin, Temple, & Catherine Johnson (2004) *Animals in Translation: Using the Mysteries of Autism to Decode Animal Behavior*, New York: Scribner.

Greenspan, Stanley I., & Stuart G. Shanker (2004) *The First Idea: How Symbols, Language, and Intelligence Evolved from Our Primate Ancestors to Modern Humans*, Cambridge, MA: Da Capo Press.

Hamilton, Jon (2015a) 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

Hamilton, Jon (2015b) Clues to autism, schizophrenia emerge from cerebellum research, National Public Radio, http://www.npr.org/blogs/health/2015/03/16/393351760/clues-to-autism-schizophrenia-emerge-from-cerebellum-research

Hampson, David R., & Gene J. Blatt (2015) Autism spectrum disorders and neuropathology of the cerebellum, *Frontiers in Neuroscience* **9**, article 420.

Hanson, Alicia, William Grisham, Colleen Sheh, Jacopo Annese, & Sam Ridgway (2013) Quantitative examination of the bottlenose dolphin cerebellum, *Anatomical Record* **296**, 1215-1228.

Harnad, Stevan (1990) The symbol grounding problem, *Physica D* **42**, 335-346.

Hawkins, Jeff (2004) *On Intelligence: How a New Understanding of the Brain will Lead to the Creation of Truly Intelligent Machines*, New York: Times Books.

Hebb, Donald O. (1949) *Organization of Behavior*, Wiley & Sons, New York.

Hebb, Donald O. (1968) Concerning imagery, *Psychological Review* **75**, 466-477.

Hindy, Nicholas C., & Nicholas B. Turk-Browne (2016) Action-based learning of multistate objects in the medial temporal lobe, *Cerebral Cortex* **26**, 1853-1865.

ISO/IEC (2007) *Common Logic (CL) — A Framework for a family of Logic-Based Languages*, IS 24707, International Organisation for Standardisation, Geneva.

Johansson, Sverker (2013) The talking Neanderthals: What do fossils, genetics, and archeology say, *Biolinguistics* **7**, 35-74.

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

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

Kosslyn, Stephen M., & G. Wayne Miller (2013) *Top Brain, Bottom Brain: Harnessing the Power of the Four Cognitive Modes*, second edition 2015, New York: Simon and Schuster.

Laird, John E. (2008) Extending the Soar cognitive architecture, in P. Wang, B. Goertzel, and S. Franklin, eds. *Artificial General Intelligence 2008*, Amsterdam: IOS Press, pp. 224-235.

Lakoff, George (2012) Explaining embodied cognition results, *Topics in Cognitive Science* **4**, 773-785.

Lamb, Sydney M. (1999) *Pathways of the Brain: The Neurocognitive Basis of Language*, Amsterdam: John Benjamins.

Lamb, Sydney M. (2004) *Language and Reality*, London: Continuum.

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.

Lee, Daeyeol, Hyojung Seo1, & Whan Jung (2012) Neural basis of reinforcement learning and decision making, *Annual Review of Neurosciece* **35**, 287-308.

Leiner, Henrietta C., Alan L. Leiner, & Robert S. Dow (1986) Does the Cerebellum Contribute to Mental Skills? *Behavioral Neuroscience* **100:4**, 443-454.

Leiner, Henrietta C., & Alan L. Leiner (1997) How fibers subserve computing capabilities: similarities between brains and machines, *International Review of Neurobiology* **41**, 535-553.

MacNeilage, Peter F. (2008) *The Origin of Speech*, Oxford: University Press.

Majumdar, Arun K., John F. Sowa, & John Stewart (2008) Pursuing the goal of language understanding, in P. Eklund LNAI 5113, Springer, Berlin, 2008, pp. 21-42. http://www.jfsowa.com/pubs/pursuing.pdf

Majumdar, Arun K., & John F. Sowa (2009) Two paradigms are better than one and multiple paradigms are even better, in S. Rudolph, F. Dau, and S.O. Kuznetsov, eds., http://www.jfsowa.com/pubs/paradigm.pdf

Margulis, Lynn (1995) Gaia is a tough bitch, in J. Brockman, ed., *The Third Culture*, New York: Simon & Schuster, pp. 129-146.

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

Martin, Christopher Flynn, Rahul Bhui, Peter Bossaerts, Tetsuro Matsuzawa, & Colin Camerer (2014) Chimpanzee choice rates in competitive games match equilibrium game theory predictions, *Scientific Reports* **4**, 5182.

Marr, David (1969) A theory of cerebellar cortex, *J. of Physiology* **202**, 437-470.

Marr, David (1982) *Vision*, San Francisco: Freeman.

Minsky, Marvin (1963) A selected descriptor-indexed bibliography to the literature of artificial intelligence, in E. A. Feigenbaum & J. Feldman, eds., *Computers and Thought*, New York: McGraw-Hill, pp. 453-523.

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.

Nussbaum, Martha C., & Hilary Putnam (1992) Changing Aristotle's mind, in M. C. Nussbaum & A. O. Rorty, eds., *Essays on Aristotle's De Anima*, Oxford: Oxford University Press, pp. 27-56.

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. Paulin, Michael (1997) Neural representations of moving systems, in J. D. Schmahmann, ed., *The Cerebellum and Cognition*, New York: Academic Press, pp. 516-535.

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

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

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

Peirce, Charles Sanders (EP) *The Essential Peirce*, ed. by N. Houser, C. Kloesel, and members of the Peirce Edition Project, 2 vols., Indiana University Press, Bloomington, 1991-1998.

Pepperberg, Irene Maxine (1999) *The Alex Studies: Cognitive and Communicative Abilities of Grey Parrots*, Cambridge, MA: Harvard University Press.

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.

Rosa, Marcello G. P., & Rowan Tweedale (2005) Brain maps, great and small: lessons from comparative studies of primate visual cortical organization, *Phil. Trans. of the Royal Society B* **360**, 665-691.

Samsonovich, Alexei V. (2010) Toward a unified catalog of implemented cognitive architectures, in A. V. Samsonovich et al., eds., *Biologically Inspired Cognitive Architectures 2010*, Amsterdam: IOS Press, pp. 195-244.

Savage-Rumbaugh, Sue, Stuart G. Shanker, & Talbot J. Taylor (1998) *Apes, Language, and the Human Mind*, New York: Oxford University Press.

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

Schoenemann, P. Thomas (2009) Evolution of brain and language, *Language Learning* **59**, Supplement 1, pp. 162-186.

Searle, John R. (1980) Minds, brains, and programs, *Behavioral and Brain Sciences* **3**, 417-424.

Shanker, Stuart G. & Stanley I. Greenspan (2005) The role of affect in language development, *Theoria* **20:3**, 329-343.

Singh, Push (2003) Examining the society of mind, *Computing and Informatics* **22**, 521-543.

Sowa, John F. (1984) *Conceptual Structures: Information Processing in Mind and Machine*, Addison-Wesley, Reading, MA.

Sowa, John F. (2002) Architectures for intelligent systems, *IBM Systems Journal* **41:3**, 331-349. http://www.jfsowa.com/pubs/arch.htm

Sowa, John F. (2003) Laws, facts, and contexts: Foundations for multimodal reasoning, in *Knowledge Contributors*, edited by V. F. Hendricks, K. F. Jørgensen, and S. A. Pedersen, Kluwer Academic Publishers, Dordrecht, pp. 145-184. http://www.jfsowa.com/pubs/laws.htm

Sowa, John F. (2005) The challenge of knowledge soup, in J. Ramadas & S. Chunawala, *Research Trends in Science, Technology, and Mathematics Education*, Homi Bhabha Centre, Mumbai, pp. 55-90. http://www.jfsowa.com/pubs/challenge.pdf

Sowa, John F. (2006) Worlds, Models, and Descriptions, *Studia Logica*, Special Issue *Ways of Worlds II*, **84:2**, 323-360. http://www.jfsowa.com/pubs/worlds.pdf

Sowa, John F. (2009) Conceptual Graphs for Conceptual Structures, in P. Hitzler & H. Schärfe, eds., *Conceptual Structures in Practice*, Chapman & Hall/CRC Press, pp. 102-136. http://www.jfsowa.com/pubs/cg4cs.pdf

Sowa, John F. (2010) The role of logic and ontology in language and reasoning, Chapter 11 of *Theory and Applications of Ontology: Philosophical Perspectives*, edited by R. Poli & J. Seibt, Berlin: Springer, pp. 231-263. http://www.jfsowa.com/pubs/rolelog.pdf

Sowa, John F., & Arun K. Majumdar (2003) Analogical reasoning, in A. de Moor, W. Lex, & B. Ganter, eds., *Conceptual Structures for Knowledge Creation and Communication*, LNAI 2746, Springer-Verlag, Berlin, pp. 16-36. http://www.jfsowa.com/pubs/analog.htm

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. (2010) The role of logic and ontology in language and reasoning, in R. Poli & J. Seibt, eds., *Theory and Applications of Ontology: Philosophical Perspectives*, Berlin: Springer, pp. 231-263.

Sowa, John F. (2013) From existential graphs to conceptual graphs, *International Journal of Conceptual Structures* **1:1**, 39-72. http://www.jfsowa.com/pubs/eg2cg.pdf

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) Natural logic: Foundation for language and reasoning, slides presented at the Smart Data Conference, San Jose, California, 20 August 2015. http://www.jfsowa.com/talks/natlog.pdf

Sowa, John F. (2015c) Signs and Reality, *Applied Ontology* **10:3-4**, 273-284. http://www.jfsowa.com/pubs/signs.pdf

Stocco, Andrea, Christian Lebiere, & John R. Anderson (2009) Dopamine, learning, and production rules: The basal ganglia and the flexible control of information transfer in the brain,

Stout, Dietrich (2016) Tales of a stone age neuroscientist, *Scientific American* **314:4**, 28-35.

Stout, Dietrich, & Nada Khreisheh (2015) Skill Learning and Human Brain Evolution: An Experimental Approach, *Archaeological Journal* **25**, 867-875.

Strausfeld, Nicholas James (2012) *Arthropod Brains: Evolution, Functional Elegance, and Historical Significance*, Cambrdge, MA: Harvard University Press.

Sultan, F, & M. Glickstein (2007) The cerebellum: Comparative and animal studies, *Cerebellum* **6:3**, 168-176.

Thomas, Nigel J. T. (2014) Mental imagery, *The Stanford Encyclopedia of Philosophy*, E. N. Zalta (ed.), <http://plato.stanford.edu/entries/mental-imagery/>

Thompson, Jacqueline M., Hans-Christoph Nuerk, Korbinian Moeller, & Roi Cohen Kadosha (2013) The link between mental rotation ability and basic numerical representations, *Acta Psychologica* **144:2**, 324-331.

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.