A MODEL OF MOTORSENSORY COORDINATION IN ENACTIVE PERCEPTION

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Abstract:
The general idea of perception is the recognition and interpretation of sensory stimuli based on memory and neurological processes that underlie this ability. In this paper I will review and contrast two major approaches to understanding perception: the AI inspired view of perception as passive computational processing of environmental sensory input and the thesis of the embodied enactive perception that considers perception to be proactive motorsensory interaction with environment. Building on the ideas of the enactive perception, I attempt to explicate visual perception as a model of motorsensory coordination. By specifying the falsifiability conditions of the model I seek to demonstrate the empirical nature of the thesis of enactive perception. Reviewed experiments conducted on motorsensory robotic platforms strongly suggest that perception is intimately related to the cognitive agent's ability to initiate and control motor action. Similarly, experiments with human Tactile Vision Substitution Systems provide an empirical demonstration of the necessity to engage in epistemic actions before acquiring ability to perform goal-oriented pragmatic actions. I will argue that the dynamic engagement of a cognitive agent in these two processes constitutes the agent's ability to perceive objects in the environment.

Introduction

Reviewed experiments conducted on robotic platforms strongly suggest that perception is intimately related to the cognitive agent's ability to initiate and control motor action. Similarly, experiments with Tactile Vision Substitution Systems (TVSS) provide an empirical demonstration of the necessity to engage in epistemic actions before acquiring the ability to perform goal-oriented pragmatic actions. I will argue that the dynamic engagement of a cognitive agent in these two processes constitutes the agent's ability to perceive objects in the environment. The purpose of the model of enactive perception as motorsensory coordination that I outline is to provide a useful structure for empirical analysis of complex epistemic and pragmatic activities in terms of the multiple contents and vehicles of the sensory modalities involved in any particular act of perception.

Embodied Perception as an Alternative to Passive Computation

Embodied perception is the proposal that perceptual systems conceptualize the real three-dimensional world as patterns of possible bodily interactions. It challenges the AI inspired view of perceptual systems as passive stimuli-processing devices running pattern recognition software on modules of hardware. An example of the traditional approach is the Representational Framework for Vision (Marr, 1982). It outlines a system that consists of distinct layers of computational processing that build up complex images in the brain by applying certain computational algorithms to retinal inputs. Marr's theory of visual perception is based on the following assumptions:

- Human vision is a perceptual module with well defined computational boundaries separating it from other perceptual systems and from the higher level thinking systems until processing is complete. That is, the vision module deals strictly with constructing representations of the visual stimuli and makes them available for further processing in higher level cognition;
- The visual perception is in essence representational, which means it is a formal system that can be exhaustively described by mathematical equations;
- The processing of visual signals is conceived of as a sequence of discrete stages, which apply progressively more complex algorithms to yield progressively more complex representations.

According to Marr, a human visual system is a distinct module in the brain that works by constructing a full 3D model of the environment in our heads. From the distribution of light intensities in the retina, cortical edge detectors construct a raw primal sketch in early visual areas such as V1. Further, through recursive algorithms the full primal sketch is constructed by finding complex sets of edges that form contours and boundaries. Later processing adds such features like surface texture, reflectance, and color. Finally, upon completion of all the steps one has a full-blown and detailed 3D view of the surrounding environment.

Instead of assuming that vision consists in the creation of complete internal representations of the outside world whose activation somehow generates visual experience, the enactive approach to perception put forth by O'Regan and Noe (2001) proposes treating vision as inherently exploratory activity. This approach is based on the idea that vision is a mode of environmental exploration that is implemented with a knowledge of certain visual-motor contingencies. Thus, according to

O'Regan and Noe, visual perception is determined by two important aspects:

- There is a set of lawful relations of dependence between visual stimulation and the motor actions of an organism[1];
- Objects, when explored visually, present themselves to us as provoking visual sensorimotor contingencies, corresponding to visual attributes such as color, shape, texture, size, hidden and visible parts.

Therefore, vision is a mode of skillful encounter with the environment that requires implicit knowledge of the sensorimotor contingencies and the ability to make use of that knowledge for the purpose of guiding action, informing thought, and language use. Furthermore, important features of the active visual perception include:

- Cognitive agents acquire the ability to exercise mastery of vision-related rules of the sensorimotor contingencies;
- Knowledge of the sensorimotor contingencies is a practical, not propositional form of knowledge;
- Sensorimotor mastery is context-specific; that is, among all previously memorized action recipes that allow one to make lawful changes in the sensory stimulation, only some are applicable at any given moment.

Thus, the set of action recipes applicable now as you are looking at this text and the action recipes currently being exercised constitute the fact of your visual perception of this text. It is important to note that the enactive approach to perception does not claim that there are no representations in vision, but rather that their role in theories of perception needs to be reconsidered. According to Noe (2004), it is a mistake to suppose that vision is just a process that employs the computational task-level characterization of retinal input to generate a complete internal model of the world.

Another view that emphasizes the enactive aspect of perception is Clark's (1997) Model of the Opportunistic Mind. It outlines an alternative

1 The difference between visual stimulation and perception can be illustrated by vision restoration cases reported by Sacks (1995). One of his patients, Virgil, upon having his bandages taken off reported light, color and movement all mixed up in a meaningless blur. This would be an instance of visual stimulation vs. Virgil's later acquired ability of visual perception as a result of active interaction with the environment.

methodology to the traditional cognitive scientific view of perception as passive computation. He argues that the practice of casting each problem in terms of an abstract input-output mapping and seeking an optimal solution can mislead us in several crucial ways:

- The replacement of real physical quantities with symbolic terms can obscure opportunistic strategies that involve exploiting the real world as an aid to problem solving;
- Conceptualizing the problem in terms of an input-output mapping views cognition as inherently passive computation;
- Search for optimal computational solutions may further mislead us by obscuring the role of the cognitive agent's history in constraining the space of biologically plausible solutions.

So, instead of the old abstract problem solving, Clark offers a new methodology for studying the embodied active cognition, whose key features are:

- Physical quantities with the real-world and real-time focus as inputs and actions as outputs;
- Decentralized solutions where coordinated intelligent action does not necessarily require central planning;
- Extended view of cognition and computation—computational processing is spread out in space and time, often outside the physical body and can incorporate features of the environment.

The basic idea of enactive perception and cognition has found its adherents among many researchers in different fields of scientific inquiry: from Merleau-Ponty's (1945) "vision is palpation with the look" to Brooks' (1991) rejection of the idea of representation as "the wrong unit of abstraction;" from Gibson's (1979) notion of action-oriented affordances to Varela's et. al (1991) focus on repeated sensorimotor interactions between an agent and the world as the basic locus of scientific and explanatory interest. Clark neatly summarizes versions of the idea of enactive perception and cognition in his thesis of radical embodied cognition: "Structured, symbolic, representational, and computational views of cognition are mistaken. Embodied cognition is best studied by means of noncomputational and nonrepresentational ideas and explanatory schemes…" (Clark 1997, 148).

Tactile Vision Substitution Systems: Acquisition of Quasi-Visual Perception with Epistemic Actions

Since the 1960's Paul Bach-y-Rita (1972) has been conducting research devoted to TVSS (Tactile Vision Sensory Substitution). The systems used by Bach-y-Rita in his research consisted of a video camera, portable computer and a matrix of 400 activators: 20 rows and 20 columns of vibrating solenoids. The image captured by the camera is transformed into basic patterns by the computer, and those patterns are represented on the matrix placed on the subject's chest, back, or forehead.

The notion of sensory substitution in a general case denotes the ability of the human central nervous system to acquire the ability to perceive one's environment and successfully interact with it by integrating devices of this sort into the general field of consciousness. In essence, people who acquire such abilities learn a completely new mode of perception. Blind or blindfolded subjects equipped with the TVSS are almost immediately able to perceive simple patterns such as horizontal and vertical lines, detect the direction of movement of mobile targets and orient themselves. While the subject initially feels only successions of stimulations on the skin, after a brief learning process the subject ends up neglecting these tactile sensations, and is aware only of the stable objects at a distance in front of him. In other words, the capacity to recognize basic shapes is accompanied by a mental projection of the objects which are perceived as existing in external space and having certain properties relative to the subject.

The externalization and intentionality phenomena were later confirmed by a number of experimental observations. For example, when the zoom of the camera is manipulated unbeknownst to the subject, causing a sudden expansion of the representation of the tactile image, "the subject would take evasive action characteristic for people who perceive dangerously approaching objects: they move backwards and raise their arms to shield themselves" (Bach-y-Rita, 1972). Furthermore, visually blind persons discover perceptive concepts that are quite new for them, such as parallax, shadows, and the interposition of objects as well as reproduction of certain classical optical illusions.

The main point of interest for philosophers in this and similar kinds of research is the fact that the subject's self-initiated and controlled epistemic actions always play a central role in the acquisition of perception that later enables pragmatic actions[2]. Indeed, when TVSS research subjects did not have complete motor control of their cameras (movements up and down, from left to right, zoom forward and back, focusing, etc.) their performance was never better than chance, even after dozens of trials. In other words, perception did not occur when these two conditions were present: (a) the subjects were not able to have full control in manipulating their camera, and (b) if they were not given immediate proprioceptive feedback on their performance in pattern recognition.

Epistemic Actions of Enactive Perception vs. Pragmatic Actions of Behaviorism

The TVSS experiments can be used as a suitable example to ward off a charge of behaviorism that was brought against the thesis of enactive perception by Block (2001). Behaviorism in its general form is the idea that two systems are mentally the same if they have identical input-output capacities and dispositions. Thus, from a behaviorist point of view, a vision restoration subject upon opening her eyes for the first time should be disposed or able to produce the pragmatic behavior of sitting down (among many others) when exposed to a chair. But, as vision restoration cases observed by Sacks (1995) have demonstrated, until subjects engaged in epistemic actions and acquired the sensorimotor contingencies of a chair, pragmatic action was impossible. Thus, for environmental inputs to acquire their causal power of informing pragmatic action, certain sets of motor-system-caused invariant changes of the environmental stimuli have to be established. From our everyday experience we know that when faced with confusing inputs and unable to exercise pragmatic actions, we revert to epistemic actions.

Thus, epistemic actions, which are at the core of the concept of enactive perception, essentially enable pragmatic actions, and not recognizing this connection is equivalent to leaving the proverbial cart without the horse. Hurley (1998) argues a similar point by saying that behaviorism makes a mistake by ignoring feedback from output to input. In other words, perception and action are related by the dynamic patterns of the reciprocal output-informing-input-informing-output loops.

2 Kirsh & Maglio (1994) define epistemic actions as external physical actions that an agent performs to change her own computational relation to the environment with the purpose of making mental computations easier, faster or more accurate. Pragmatic actions are those that create physical states which physically advance one towards certain goal(s).

Furthermore, behaviorists have stressed that the cognitive responses of a creature are always under the control of some environmental stimulus property (Skinner, 1957), thus effectively excluding a cognitive agent from the explanatory scheme. In contrast, enactive perception puts an individual in the focus of the investigation by emphasizing the role of the individual's epistemic motor actions in perception and cognition.

Based on the importance of the epistemic motor actions in the acquisition of perception, I suggest that the direction of causation in enactive perception (output-informing-input) should be reflected in the language discussing it. Thus, instead of the word 'sensorimotor' often used to describe epistemic activity that underwrites enactive perception, I suggest using the word 'motorsensory,' because it correctly captures the origin, causal direction, and sequence of epistemic actions: changes in one's proprioceptive states cause changes in one's exteroceptors and not vice versa.

Model of Enactive Visual Perception as Motorsensory Coordination Realized in a Special Kind of Neural Mapping

If the account of visual perception by O'Regan, Noe, Hurley and others is correct, it appears that acquisition of enactive visual perception necessarily involves a rather close correlation of instances of movement, initiated by the cognitive agent's motor system, with the resulting changes in one's visual field. Such a correlation, can from a neuroscientific point of view be structurally and functionally achieved by some kind of neural mapping between the regions of the brain that realize representations of proprioception (motor cortex and cerebellum) and the parts of the brain that realize visual representations (areas V1, V2, V3, MT, etc.).

In terms of content-vehicle analysis, one's engagement in epistemic actions produces correlated contents in one's proprioception and visual exteroception. Those correlated contents give rise to the correlation of their corresponding neural vehicles, and this correlation is stored in memory via Hebbian-type learning as the output-input mastery. The effect of such acquired correlation is that after repeated epistemic interaction, the agent's exposure to certain visual exteroceptive contents will activate related proprioceptive vehicles, thus making proprioceptive contents poised between the motor control structures and passive visual representations of the external reality for possible engagement in pragmatic actions (input-output mastery).

The outlined model gives us a structure for the analysis of complex epistemic and pragmatic activities in terms of the correlations of the multiple contents and mappings of the multiple vehicles of the modalities involved in any particular act of perception. I suggest that the application of the model of visual perception in terms of the proprioception-exteroception mapping should be extended to perception in other sensory modalities[3]. Thus, the thesis of enactive visual perception can be absorbed into a more general thesis of enactive perception stating that proprioception provides a unifying active platform onto which passive representations in all the sensory modalities are mapped. Furthermore, if perception in all the sensory modalities is proved to necessitate this kind of exteroception-proprioception mapping, one could insist that this particular neural organization is somehow implicated in the unity of human consciousness.

Specifying the Conditions for Falsification of the Thesis of Enactive Perception

The Tactile Vision Substitution and other similar systems[4] can serve as a good testing platform for the thesis of embodied perception. However, before one can proceed with possible experimental designs, one needs to make sure that this thesis can be empirically tested in principle. That is, one must show that the thesis of enactive perception can be falsified. In other words, perception needs to be defined in such a way that it is logically independent of the motorsensory coordination and vice versa.

The model outlined in the previous section effectively restates the thesis of enactive perception in terms of motorsensory coordination and is going to be instrumental in the explication of the empirical nature of the thesis. Thus, the thesis of enactive perception stated in terms of a model of motorsensory coordination spelled out in propositional calculus looks like the following:

(1) ⊠ (x) (Px ⊠ Mx)

Px = x has perception

Mx = x has motorsensory coordination

For any x, x has property P (perception) only if x has property M (motorsensory coordination). Therefore, for the enactive perception thesis to be empirically testable the conjunction of the following two statements has to be true[5]:

(2a) ⊠ (x) (Mx · ¬ Px)

There exists such an x, which has property M (motorsensory coordination), but does not have property P (perception).

(2b) (x) (Px · ¬Mx)

There exists such an x, which has property P (perception), but does not have property M (motorsensory coordination).

In other words, we need to find at least one case in which a subject will have motorsensory coordination but no perception and, vice versa, a subject who will have perception but not motorsensory coordination. By identifying such cases one would make the motorsensory mapping logically independent of perception and perception logically independent of the motorsensory mapping.

Change blindness experiments are going to provide us with the instances corresponding to sentence 2a. Change blindness is a well-documented and studied form of perceptual invisibility: it could be very difficult to see a change in a scene, however, since once the change is attended to it becomes obvious. The change blindness effect can be directly experienced, for example, by visiting Ronald Rensink's University of British Columbia Visual Cognition Lab at http://www.psych.ubc.ca/~viscoglab/demos.htm. For our purposes one can modify the change blindness experiment and imagine that it involves an actual live scene instead of a picture and encourage a subject's motorsensory exploration of the scene after the change has taken place. The philosophical point of the change blindness effect is that in spite of the fact that the motorsensory mapping takes place as the subject visually examines the scene from different angles, she still does not have perception of the change.

A paramecium is a single cell organism that relies strictly on proprioception to navigate its environment. Its body's surface is lined with multiple hairs, which the paramecium uses for propulsion as well as identification and navigation around obstacles it encounters. Thus, when the paramecium bumps into an obstacle, the hairs reverse the direction of their vibrations, executing a maneuver to back up from the

3 See Keeley (2001) for an account of what constitutes a sensory modality.

4 See http://www.seeingwithsound.com/sensub.htm for a good overview of sensory substitution devices by Meijer.

5 Technically, 2b is sufficient to falsify the thesis, however 2a is important for my subsequent argument that proprioception is sufficient for perception.

obstacle. Having reversed a sufficient distance, the paramecium executes a turn away and continues to swim forward. Thus, by relying on the proprioceptive stimuli arising within its own body, the paramecium successfully navigates its environment, that is, acquires perception of it.

To make the point more relevant to humans, one can imagine a person trying to navigate a maze with regular sensory organs of vision, audition, olfaction, gustation and touch temporarily disabled. With only proprioception at her disposal and the ability to report on her progress (for our benefit) this person will be able to achieve perception of her environment by executing motor routines similar to those of paramecium: put one foot in front of the other until you no longer can, if you can't move your feet try turning right or left, or back out, then turn either way and start moving your feet forward again. By following this rather simple proprioceptive navigation routine a person will be able to successfully map out the maze and navigate it with ease. This thought experiment clearly demonstrates that perception is possible without the motorsensory mapping.

It appears that by executing sets of simple motor commands and, literally, probing its way around, any creature with proprioception can acquire an (admittedly rather crude) perception of its environment. In other words, proprioception on its own is necessary and sufficient for perception. Viewed from this perspective, visual perception can also be conceived of as a certain kind of "bumping" into things via encountering the reflections of light from environmental features. Thus construed, all sensory perception ultimately appears to be a multifaceted proprioceptive encounter with surroundings, albeit mediated by a variety of environmental phenomena like electromagnetic radiation, acoustic vibrations, distribution of chemicals in the air, etc.

Model of Perception as Enactive Motorsensory Coordination in Artificial Simulations

Having established the empirical nature of the thesis of enactive perception, it is illuminative to take a look at a couple of attempts to build perceptual robotic systems that implicitly or explicitly employ the motorsensory coordination model. The MIT's Humanoid Robotics Group at the MIT Artificial Intelligence Laboratory has developed several robotic platforms that provide a fertile ground for modeling and investigation of different features of the human mind, including experiments on enactive perception.

The Cog project from the outset was designed as an approximation of the motor and sensory dynamics of a human body. Cog's video cameras provide passive visual representations while joint positions and torque sensors enable proprioception, thus making it a very good platform for modeling perception as motorsensory coordination. In a series of experiments conducted by Metta and Fitzpatrick (2002), the basic ability of Cog to perceive a cube in front of it was based on its initial epistemic interaction with the cube: probing and tapping to find its boundaries, manipulating the hand to measure the aperture of the cube in attempts to grasp it, etc. While Cog's hand was engaged in such epistemic interaction with the cube its cameras were following the changes of the visual field that Cog's movements provided. Simultaneously, the proprioceptive output was being mapped onto the visual input, thus enabling the robot to acquire perception autonomously by fusing vision and proprioception and later employing this in the pragmatic actions of grabbing and manipulating the cube.

Wermter et al. (2004) have been working on the Mirror-neuron Robot Agent (MIRA) with the goal of developing neural solutions for tasks that need to be solved by a robot that learns by the visually perceived demonstrations and verbal instructions. To enable perception in the MIRA the team of researchers used lateral associator connections between the neural networks that support areas of vision and proprioception of the robot. The weights of connections between representations in the visual net and the proprioception net develop concurrently, so that after repeated epistemic actions the robot acquires a background database of possible interactions with the target object. The epistemic actions of the MIRA robot resemble those of humans and other animals: approaching and backing away from the target object, lateral movements, poking and probing of the object and around it with a hand, etc. Eventually, repeated attempts and further fine-tuning of the visual-proprioceptive mapping result in the successful pragmatic action of grabbing the target object.

Setting the much debated issue of the qualia (Chalmers, 1995) aside, it is quite plausible that the robots in the experiments described above acquired perception of the target objects. Voluntary controlled action turns out to be an essential ingredient of unsupervised training of autonomous agents in the ecological context. While the cognitive agent's body provides a necessary reference frame for epistemic action and eventually grounds informative percepts to guide pragmatic action, it is the enactive motorsensory coordination that serves as the main mechanism that gets the job done.

Conclusion

All cognitive biological systems are embodied, and epistemic action is an essential tool they have for recognizing and differentiating objects in the environment. Repeated engaging in motor actions (approaching, poking, pushing, etc.) toward an object reveals how its visual and other characteristics change when acted upon. Experiments with TVSS systems and robotic platforms demonstrate that, in a discovery mode, the visual (or pseudo-visual) system learns about the consequences of its motor actions and builds important motorsensory correlations. In a goal-directed mode the acquired motorsensory contingencies inform pragmatic actions by enabling the system to select the motor action that can cause a particular visual change. These two processes are inherently intertwined and together constitute a cognitive agent's ability to perceive objects in the environment.

The model of perception as the enactive motorsensory coordination gives us a useful structure for empirical analysis of complex epistemic and pragmatic activities in terms of the multiple contents and vehicles of the sensory modalities involved in any particular act of perception as modalities' correlated mappings onto proprioception. In particular, by providing the means to observe and reproduce the genesis of intentionality, i.e. awareness of something as external (the "appearance" of a phenomenon in a spatial perceptive field), the model makes it possible to conduct experimental studies in the area usually restricted to philosophical speculation. Furthermore, the model may provide a useful insight into the mechanisms underlying the apparent unity of consciousness by approaching the structure and functioning of consciousness in terms of the neural mappings of proprioception onto sensory modalities.

Further development of the thesis of enactive perception will involve the investigation into the nature of proprioception, because before a cognitive agent can engage in the active exploration of the environment she needs to map out the proprioceptive environment of her own body. In other words, a robot or a human needs to have her own proprioceptive map in place before proceeding to learn the motorsensory subject-object interactions. Another direction of interest would be investigation into whether the thesis of enactive perception can incorporate recent neuroscientific discovery by Fadiga et. al (2000) that implicates mirror neurons in the cognitive agent's understanding of the actions of others.

Finally, a larger area of the thesis' application would be the idea of the embodied cognition put forth by Lakoff (1987), Johnson (1987), and Glenberg (1997). The rise of the notion of the embodied cognition reflects an increasing philosophical skepticism concerning the ultimate merit of the intuitive divisions of the mental processes into perception, action, and cognition. In other words, it appears that cognitive development cannot be usefully treated in isolation from issues concerning the cognitive agent's physical embedding in, and interaction with the environment. The embodied cognition involves perception, action, and thought as bound together in a variety of complex and interpenetrating ways. The outlined above enactive motorsensory coordination model can provide a foundation and a useful tool for developing structural and functional models of the embodied cognition.

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FROM LOGICAL TO EPISTEMIC CIRCULARITY: THE CARTESIAN CIRCLE REMAINS

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Introduction

One of the most important and perhaps the most difficult question in epistemology is the problem of the criterion. The Cartesian Circle can be seen as a particular case of this problem. In this paper I look at a well-known attempt by James van Cleve to solve the Cartesian Circle by distinguishing between knowledge falling under some criterion and knowledge of that criterion. I will argue that van Cleve's procedure fails because it is epistemically circular and highlight the problem with epistemically circular arguments. I will conclude that, since epistemically circular arguments do not sufficiently answer skeptical considerations and hence do not provide a solution to the problem of the criterion, the Cartesian Circle remains.

The problem of the criterion is characterized by Roderick Chisholm as the difficulty in answering the following two questions in epistemology:[1]

α. *What do we know?*
β. *What are the criteria of knowledge?*

It appears, prima facie, that we cannot answer α unless we know the answer to β, and conversely, that we cannot answer β unless we know the answer to α.

In 'Foundationalism, Epistemic Principles and the Cartesian Circle,' James van Cleve responds to the problem of the criterion with a solution to the Cartesian Circle which makes use of the distinction between different levels of knowledge: knowledge that falls under a criterion and knowledge of the criterion. Van Cleve suggests that this solution to the Cartesian Circle can be used to solve the problem of the criterion as well. I shall first examine van Cleve's solution in detail, and highlight the problems with his solution thereafter.

1 Chisholm, *The Foundations of Knowing*, 65.