

ADAPTIVE CONTROL LOOPS AS AN INTERMEDIATE MIND-BRAIN REDUCTION BASIS

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Abstract

Jaegwon Kim has proposed that the proper way to reduce mental to physical events and properties is to apply the *causal inheritance-as-identity principle*: “*M* is the property of having a property with such-and-such causal potentials, and it turns out that property *P* is exactly the property that fits the causal specification. And this grounds the identification of *M* with *P*”. It is argued that this principle should require further that the connection between properties *M* and *P* be dynamically intelligible (that is, compatible with the evolutionary and developmental features of mind-brains), and nomologically grounded. It is claimed that an adequate ‘causal inheritance-as-identity principle’ requires an intermediate level of reduction between mind and brain, in terms of adaptive control structures. It is further argued that this level provides dynamical intelligibility of the *P-M* connections, and provides nomological explanations for how physical and mental properties must develop jointly.

1 MULTIPLE REALIZATION, CAUSAL INHERITANCE AND PROPERTY IDENTITY

The so-called “mind-body problem” arises from the difficulty of understanding how mental states and events (endowed as they are with intentional and phenomenal properties) are related to brain states and events. Cartesian dualism is a traditional answer to the problem; it has been found wanting on many accounts; in particular dualism has trouble explaining how two different substances can be made to interact causally. Reductionism is the view that the mind is identical with a set of brain processes (Place, 1956). Reductionism holds that there is only one type of causation, physical causation, holding between individual physical events. This view of causation is called “physicalism”: only physical entities are able to pro-

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duce changes in the material and in the mental domains. While physicalism remains the dominant view concerning causation, the metaphysics of reductionism has been rejected by most philosophers. Types of mental states cannot be taken to be identical with types of neural states. Before we come to the main argument for this claim, let us agree first on the type of argument that simply *does not* apply. What is at stake here is not what the terms “mind” (mental state, pain, etc.) or “brain” (cerebral state, firing neurons) *mean*, but whether they can be shown to be identical through empirical research, i.e. theory construction.² Thus the idea *is not* to reject mind-brain identity on the basis of the fact that people fail to know how pain is realized, but are still aware of what pain is. The main objection to reductionism has rather to do with the multirealizability thesis (MT), which was first stated by Putnam (1967).

In a nutshell, here is Putnam's argument. Let us represent mental activity using an analogy with a Turing Machine whose states (including motor dispositions) are probabilistically related, and are able to combine and to influence output. What are the relevant mental states in such a probabilistic Machine? Taking a physically characterized state of this machine, (or a neural state) as providing the basis or the condition of an identity between two tokens of mental states would involve two important mistakes. First, one would tend to misdescribe two states from two different systems as identical, on the superficial evidence of their having the same physical realizer, even though they may belong to different machine tables,³ and have, e.g. different probabilistic connections with other states. Conversely, one would fail to track the functional analogy of two different organisms which happen to have a different realization for the same function. Pain, for example, does not seem to be nomologically associated with a given physical realization, for we have no idea how many possible physical realizers for pain there may be in nature. On this “functionalist” view, what makes a mental state a state of pain consists rather in the “transition probabilities” to avoidance behavior, to a certain set of self-directed emotions, to a disposition to classify certain stimuli as having a common valence, etc. *The multirealizability thesis claims that what makes a functional compo-*

² See U.T. Place (1956), Putnam (1967), p.433.

³ A machine table describes the rules allowing the transitions between a current state (q_i), a symbol currently read, and specific actions: i) erase or write a symbol; ii) then move the head to the left, to the right, or stay in the same place; iii) then go to prescribed state (q_{i1}).

ment the mental type it is, is its role in relating inputs to outputs and its relations to other functional components.

MT, however, is compatible with physicalism (even though it does not entail it as reductionism does). The kind of physicalism that is compatible with MT is “token physicalism”, according to which having a mental state *supervenies on* some physical state or other – a human brain state, or possibly some non-human brain state, or even some circuit state in a computer. More generally, properties that are causally involved in the special sciences, such as psychology, economics, etc., *supervene on* physical properties, but cannot be reduced to them. The laws of physics are not contradicted by the laws of the special sciences, but the latter have their own vocabulary, and their own regularities, which cannot be couched in physical terms. What makes this physicalism “non reductive” is that two properties in the special sciences may be identical while having a different physical realization. In other words, mental states may be functionally identical, but fail to be realized by the same type of brain state.

However, as Kim observed, supervenience baptizes a difficulty rather than solving it. There is a variety of ways in which supervenience itself can be explained. The way in which MT explains supervenience consists in invoking the relation between the mental state and its physical basis as one in which a second-order property *M*, (such as the property of having such and such a functional role) is related to a first-order property *P* that “realizes” *M*. In Kim’s terms: “Having *M* is having a property with causal specification *D*, and in systems like *S*, *P* is the property meeting specification *D*.” (Kim, 1998, p.24). Many authors have taken this “realization” relation to relate two different types of properties, physical or neural, on the one hand, and mental or psychological, on the other. On such a view, mental properties, although they are necessarily physically realized, are not reducible to their realizers. This non-reductive interpretation of the “realization” relation, however, has been questioned. It raises the old worry of causal overdetermination; if there are two different properties, then why should we attribute any causal role to the mental property, once it is admitted that it has a physical realization? To prevent causal pre-emption of the physical over the mental, Kim offers three arguments in favor of a different view of “realization”, in which the two properties are actually identical. First, he observes that, pace Putnam, multirealizability is not an obstacle to

having “local reductions”, i.e. species or structure-specific bridge-laws.⁴ Second, reduction seems to be the best way of explaining why a mental state M correlates with a given brain state. How can mere “bridge-laws”, such as those that correlate mental and physical properties, be themselves accounted for if not in terms of identity? “If M and P are both intrinsic properties and the bridge-law connecting them is contingent, there is no hope of identifying them. I think that we must try to provide positive reasons for saying that things that appear to be distinct are in fact one and the same.” (98). Third, reduction offers an ontological simplification that contrasts with a non-reductive approach (in which entities proliferate). It is only when bridge-laws correlating the mental and the physical are “enhanced into identities” that we obtain the ontological simplification that is needed.

We can conclude with Kim that “functionalization” – a characterization of mental states through their functional roles – is compatible with reductionism, *at least if* we are able to provide a way of enhancing the relations derived from bridge-laws into identities. The method recommended in this endeavor, however, is itself fundamentally flawed, if it only consists in a purely nominal or a priori move. For as we have seen, identity of a mental and a physical state is a consequence of how the real world turns out to be. Kim's own strategy is to include the contingent dependency of the mental on the physical as the ground of the M - P identity in the following way:

(1) *The causal inheritance-as-identity principle (CIIP)*: “ M is the property of having a property with such-and-such causal potentials, and it turns out that property P is exactly the property that fits the causal specification. And this grounds the identification of M with P ” (p.98)⁵.

“Turning out to fit a causal specification” is a contingent property: what realizes M changes from world to world, and the identity $M = P$ is both metaphysically contingent, and nomologically necessary: in all the worlds nomologically similar to ours, M will be identical with P . The identity of M and P as formulated in (1) has the interest of avoiding the kind of objection derived from Kripke's idea that an identity is necessary when M and P rigidly designate their referents. Here, M only refers non-rigidly to the property to be reduced; it is only defined relationally, through the set of its causal potentials at the psychological level.

⁴ On the difficulties of claiming that local reduction does not present a problem for reductionism, see Kistler (1999).

⁵ See also p.111–112.

As a consequence of (1), and given that functionalization (i.e. the pattern of causal dispositions which constitutes M) is not species- or structure-specific, there are as many different realizers for one and the same functionally defined M as there are species (on the assumption that no two species are alike in their physical realizers or neural structures). Actually, neuroscientific research has collected evidence showing that no two individual subjects are alike in their neural structure either, a fact that provides still further reason to embrace (1). Multirealizability therefore obtains, in the sense that at a certain level of description of the pattern of causal relations constituting M , there are several realizers that are identical to M depending on the species, or the individual structure considered.

Although conceptually correct in the nominal sense, the problem for the mind-body theorist is to convert this nominal identity into a real identity; that is, an identity that can be shown to be instantiated in our actual psychological dispositions. We must offer evidence that we are in a world in which (1) is satisfied (let us call this demonstration “the CIIP (Causal Inheritance-as-identity principle) satisfaction condition”). Why should CIIP be argued for, rather than taken for granted? The reason is that we have assumed, right from the start, that two sets of causal descriptions hold at a world. We started with two different, heterogeneous⁶ ways of characterizing causation, one at the psychological, the other at the physical (including neural) level, and discussed the possibility of having the first realized via the second. If, however, it is contingent that there is one property P such that it “fits the causal specification”, as (1) requires, then we must show how it can be the case that it does, that is: what the physical properties are that are involved in mental causation, and through which processes they come to have this surprising “fit” with psychological functions. Otherwise, (1) simply holds in a set of worlds in which mental states turn out to be identical to physical states, but we don't know whether it holds in our world. In other words, “the property of having a property with such-and-such causal potentials” again *describes* a solution to the mind-body problem, rather than providing one.

In summary, CIIP needs to be shown to work in a given world, by explaining how, given the nomological regularities in that world, information and physical structure are related in a way that instantiates CIIP in it.

⁶ When the reduced theory contains terms or concepts that do not appear in the reducing theory the reduction is said to be “heterogeneous”. (Nagel, 1961) By extension, the causal regularities that hold at each level can be called “heterogeneous” too.

Otherwise, causal inheritance as property identity is postulated *ad hoc* rather than justified.

2 THE SPECIFICS OF MENTAL CAUSATION

How can we offer a more specific explanation of how *M* and *P* are in fact one and the same causal property? Two features need to be present for such an explanation to be adequate. First, to be explanatory, the connection between mental and physical properties, or rather between the functional characterization of a mental property and the physical causal network that realizes it, must be *nomologically necessary* (in the sense of being not only compatible with, but necessitated by the laws of physics given the biological constraints that apply to psychological properties).⁷ One obstacle here is that the metaphysical debate about mental causation does not rely on a scientific understanding of what a psychological function, and a psychological property, are in their essences. It relies, rather, on folk psychology, and merely assumes that common parlance on the mental captures the psychological properties that are causally relevant in perceiving, learning and acting. Note, in addition that there is no agreed scientific definition of what a psychological property is, nor of a psychological function.⁸ Most theorists agree that psychology involves representations.⁹ What representations are, however, how they are acquired, and how they combine, are still controversial, open issues.

A second required feature of the connection is that it should *be dynamically intelligible*. The picture of the mind shared by most philosophers engaged in metaphysics is under the joint influence of the computer metaphor, (mental states are Turing machine “table states”) and the linguistic characterization of mental contents. This view is a convenient simplification, which was initially the source of important insights about intentionality and mental content. Indeed mapping a set of structurally specified states to what they are about is helpful when our job is to understand interpretation and communication. When metaphysical questions are being raised, however, the exercise is no longer to identify shared contents, but to actu-

⁷ This requirement is articulated by Kim: “We may know that *B* determines *A* (or *A* supervenes on *B*) without having any idea why this is so. Can we explain why something has *M* in terms of its having *P*?” (Kim, 1998, p.18).

⁸ For a proposal concerning a definition for mental function, see Proust (2009).

⁹ With the notable exception of Gibson and his followers.

ally characterize the causal processes through which mental properties represent world properties, i.e. acquire the function of carrying information about them. Here, the ‘static’ view of the mind is clearly inadequate, for unstable patterns of activation can also have causal efficacy, a fact that is much more easily accounted for in terms of attractors in connectionist networks than in terms of symbolically articulated mental states.¹⁰ A causally adequate account of psychological properties should thus explain, not only what their global relations are with inputs, outputs, and other states, as stipulated by the functional definition (where “mental states” are roughly characterized, through their recurrent input-output interactions), but why they are *developing, dynamic* entities: why can they be (or not be) acquired, how easily? How resiliently? With how much inertia? How do some subsets of them determine the dynamics of others? Obviously, these important characterizations are only partially available given the present state of science. But adequacy conditions, if they are shown to be relevant, are meant to drive research, rather than follow it. Research on the dynamics of the mental, however inchoative, already exists on three types of time scale, which as we will see, are the most relevant to understanding what psychological properties “actually” are.

The first is the *phylogenetic level*. On a Darwinian view of Evolution, organisms are selected, by and large, as a result of their capacity to adjust flexibly to a changing environment. The study of the plasticity of minds over evolutionary time is thus a goldmine for those attempting to understand mental causation and to identify psychological properties in terms of this evolution.¹¹ Mental causation develops, at this dynamic scale, under the influence of two main evolutionary types of selection; one is the

¹⁰ See Cleeremans & Jimenez, 1999, p.151: “Such patterns are no less representational than stable ones: the entire activation space at each layer of a connectionist network is thus both representational and causally efficacious”. Unstable states however are present at all the dynamic levels that jointly constitute mental causation.

¹¹ Here are two prominent examples of how such a study can be conducted. Behavioral Ecology – the study of the ecological and evolutionary basis for animal behavior – takes phylogenetic constraints and adaptive significance to be the structuring causes of any organism’s behavior. Similarly, Evolutionary Psychology hypothesizes that human behavior is generated by psychological adaptations; the latter were selected (on the basis of prior adaptations) to solve recurrent problems in human ancestral environments. (See, inter alia, Gintis et al., 2007, p.613. These two types of research can offer fruitful ways of framing the metaphysical question we are interested in, concerning the nature of mental causation. For a general discussion, see Sterelny (2000, 2003) and Proust (2006, 2009).

phenotype, the other is the group. Cooperation is associated with within-group beneficial behaviors and the suppression of internal competition, which in turn influences evolutionary dynamics. The dynamics of primate mental evolution should then be studied both at the genetic and at the cultural level, taking into account both the physical and the (group-level) institutional environments.

The second is the *ontogenetic level*. Scientists now fully appreciate that genes are expressed as a result of their interactions with physical and social environments. The connection of genes to cognitive competences is currently hotly debated. While evolutionary psychologists tend to favor the view that genes directly drive the development of highly specialized cognitive modules, neuroconstructivists argue that genes regulate low-level processes, such as motor coordination and detection of contingencies, rather than macro-adaptations such as linguistic competence or theory of mind (more on this below).

The third time scale is that of the dynamics of *individual learning*. Granting that a given organism has inherited a set of genes as well as an ecological niche which will structure its development, the way it uses its mental capacities will dynamically retro-act on them. Exercising a function (whether perception, memory, empathy or action planning) does not leave a mind unchanged. As evidenced in brain imagery and in experimental psychology, cognitive exercise on a task modifies both the individual's neural connectivity and his/her "behavioral output" in a way that is tightly constrained by temporal and dynamical factors. This evolution-sensitive aspect of individual psychological organization and brain "realization" is again an indication for the mental being dynamically coupled with a temporally developing environment.

Let us note that a complex interactive pattern among the three types of selection is at play at any given time. Learning indeed is primarily made possible by specific developmental patterns and pre-adaptations, which seem to be present in all animate organisms, in the most primitive and enduring forms of habituation and sensitization.¹² Which specific contents are learned, however, does not depend on evolution and development alone; it depends on the changing organism's environment – which itself retroacts, as we saw, on the genes' influence on development. Similarly, learning partly drives development; learning how to focus on individual contents is a precondition for most acquisition relevant to developing capacities, such

¹² See Hawkins & Kandel (1984).

as linguistic, motor or social capacities. Individuals with a similar genetic endowment and similar ontogenetic development may still present considerable differences in the ways they use their cognitive capacities if their environment provides them with different tasks and motivations. We need therefore to make room for a distinctive causal level for individual learning, in order to account for the fact that even genetically similar individuals have differently shaped mental dispositions.

3 FROM STANDARD FUNCTIONALISM TO DYNAMIC FUNCTIONALIZATION

The notion of mental causation that is used in standard functionalism ignores the previous distinction between the dynamic levels at which causation operates. The mind is taken to be essentially constituted by a recurring, single-layer causal structure, characterized from a snapshot viewpoint. When a mental state is identified with its causal network comprising inputs, outputs, and other states, the dynamics through which it acquires these various dispositions is deemed irrelevant. This snapshot view, however, fails to keep track of the phylogenetic, developmental, and learning constraints that causally explain how the mind forms and uses representations as it does; it ignores the fact that a mind is a flexible set of dispositions, and that flexibility in structure (neural plasticity) and in use (learning ability) constitute, in combination, fundamental conditions for mind-brain identity.

Cognitive scientists might object that, where the philosopher Jaegwon Kim merely contrasts a higher-order with a lower-order type of causation, at which the physical realizers perform the actual causal work, the psychologist of vision David Marr offers a more complex theory of the functional organization of the mind, which allows one to account for the different dynamic layers contrasted above.¹³ According to Marr, a functional device needs first to be characterized at the most abstract level of what it does, and why it does it. For example, an adding machine is performing addition, characterizable by a set of formal properties. This he calls the “computational theory”, which provides the rationale that accounts for the device being present. The *computational, or program, level* describes in the most general terms what the cognitive task is, and why this particular device is adaptive, i.e. fulfills its constraints. Thus the computa-

¹³ See Marr (1982), p.22 sqq.

tional theory offers a response to the evolutionary query above. The second “*algorithmic*” level spells out the specific representations that the process uses, as well as the algorithm that transforms inputs into outputs. This level cashes out the higher-level characterization in terms of causal-representational processes, which may well differ from one individual to the next (either because they belong to different species, or because they have had different developmental stories, or different learning processes). The third level, as in Kim's model, “*implements*” the representations and their algorithmic relations in specific hardware structures, whether neurons or silicon chips. This third level, again, offers the theorist a chance to take into account the various constraints explaining why a particular individual uses idiosyncratic realizers for his/her representational and computational needs (for example, why an adult will use her fingers to add).

While acknowledging that there seems to be a theoretical duality between starting with mental states to reconstruct the dynamics that generated them, and starting with dynamic facts to reconstruct mental states, the dynamicist might insist, in response, that such a duality has merely conceptual rather than methodological relevance. For only a dynamical functionalization will have the two features that a proper connection between *M* and *P* events requires, namely nomological necessity and dynamical intelligibility. Each mind-brain can only be explained, in the ways required, if its structure as well as its functional organization are accounted for in terms of its evolution, its ontogenesis and its learning environment. If these dynamic properties are actually what shape minds, then state stability is a curious exception. Most probably, one state can only be considered to be the same state as another (prior in time in the same individual, or in another individual of the same species) if one adopts, for the sake of interpretation, a simplificatory method by which a mental state is characterized non-structurally. One might for example consider that an organism does “the same task” insofar as the same linguistic description can be offered for it, a standard way of speaking in experimental psychology. But if what is at stake is the mind-body problem, we cannot help ourselves to these linguistic descriptions of cognitive contents, because they do not respect Kim's restriction on causal inheritance as structure-bound.

If these observations are on the right track, then the proper way of functionalizing mental facts should be to look at them as constituted by the various co-evolving systems that determine, at each moment, the patterns of sensitivity and reactivity of a particular organism. Let us use the term “D-functionalism” for an approach to the mind in which the causal connec-

tivity of interest is not that among individual mental states, but among individual developing cognitive dynamics. D-functionalization requires looking at how the mind-brain develops; the idea behind it is that an approach to mental events through D-functional organization is the only one able to satisfy our two explanatory constraints, which in turn suggests that neural dynamics is the relevant level at which nomological explanations can be offered for why a system does what it does, or does not do what other systems do. Looking at mental states as static, recurrently activated nodes in a causal network, in contrast, would fail to offer these kinds of explanations; it would, that is, block insight into prior dynamical conditions and further evolutions.

4 D-FUNCTIONALISM: LEARNING AND BRAIN CHANGE

D-functionalism, in contrast with standard functionalism, aims to account for how a given neural substrate gains a specific functional role – for how it comes to be recruited in the performance of such and such a mental task. In order to understand the relationship between the mind and its “realization”, we must figure out which types of process this notion of “realization” (which in standard functionalism is a purely conceptual one) refers to in our world, for a given cognitive organism, and how it is in fact instantiated. One way of fulfilling this aim is to explain how brain growth relates to learning. Two types of responses have been offered to these questions. For *neural selectionism*, also called “brain Darwinism”, brain development drives learning under genetic influence¹⁴. A neuronal competition occurs, and selection among the fittest is operated in interaction with environmental demands: neurons that are more often used outlive the others. For *neural constructivism*, learning is what stimulates and guides brain growth, by inducing changes in the brain structures involved in learning.¹⁵

Within both schools of neural growth theorists, there is a large consensus *against* standard functionalism, and the way it frames the relationship between the functional and the physical levels. Not that they embrace eliminativism: the brain is a “representational device” (*representation* here being taken to mean that neural events and properties are correlated with

¹⁴ Representatives of this view include Edelman (1987) and Changeux & Dehaene (1989).

¹⁵ Representatives of this view include Karmiloff-Smith (1992), Thelen & Smith (1994), Quartz & Sejnowski (1997), Christensen & Hooker (2000).

world events and properties, about which they carry information).¹⁶ Brain development, however, is seen as the indispensable process which generates the constitutive link between cell growth, on the one hand, and informational uptake and monitoring, on the other. Research on learning, for example, shows that specific representations do not develop in a linear way. Representational development in ontogeny is, rather, characterized by “U shaped” patterns, in which children begin by performing well, then undergo a period of failure, by overgeneralizing their earlier knowledge, until they finally come up with a new stable, more robust, and extensive ability. As the neuroconstructivist Annette Karmiloff-Smith has documented,¹⁷ later representational stages are not mere refinements of earlier stages, but involve large-scale reorganizations. This suggests that the brain is *nonstationary* – its statistical properties vary with time, which means in turn that the structures underlying acquisition change over time. Distal feedback from neural activity helps regulate these reorganizations. In other words, the neural vehicle of a given set of representations is dynamically shaped by the very processes through which mental representations are constructed. Here, then, is a major contrast with standard functionalism: *mental functions and representations cannot be identified independently of how their neural vehicles develop*. Let us explain why in more detail.

Marr’s trichotomy is not rejected, but it is reinterpreted by selectionist theories in a connectionist spirit, as levels of organization *within the nervous system*. At the most basic level is the single cell, with its functional differentiation between axon, dendrite and synapse. At that level, the function of the neuron can already be deemed ‘cognitive’: it is to transform input into output, in virtue of specific patterns of electrical and chemical properties that carry information. A single neuron is already performing a computational task (at Marr’s “program level”); it is following an algorithmic process, and does so according to specific physical properties (molecular properties of the synapse and the membrane). There is, therefore, no “ontological” autonomy of any one task-level, as standard functionalists claim, but a relation of “*co-dependence*” among levels. The characteristics of the synapse and the membrane determine, in part, which computations can be performed, as well as which kind of goal they can serve. Reciprocally, serving a goal modulates both the computational and the physical levels, and helps stabilize the physical properties of the cell. A second ana-

¹⁶ Is it important to observe here that concepts can be represented non-linguistically, as partitions in a multi-dimensional vector space. See Churchland & Sejnowski, (1992).

¹⁷ See Karmiloff-Smith, (1992).

tomical layer encompasses “circuits”, i.e. neuronal assemblies of thousands of cells organized in well-defined structures, i.e. presenting task-dependent synchronous firings. A third layer is constituted by “metacircuits”, i.e. relations of neuronal assemblies. Finally the traditional mental faculties are taken to roughly correspond to various groupings of these metacircuits.

In contrast to standard functionalism, the question of how such an organization emerges can now be raised and answered. The response offered by selectionists is that a recurrent two-phase process is responsible for brain organization and learning. An initial exuberant, genetically driven, growth of neural structure, leading to an overproduction of synapses, is followed by a selective pruning back of connections. There are successive waves of this sort of growth and selection from birth to puberty, each wave presenting in succession “transient redundancy and selective stabilization”. A metaphor used by Changeux is that the system is informed (in the sense of being organized) by the ‘instructions’ delivered by the environment.”¹⁸ Indeed neural growth consists in stabilizing those dynamic patterns that have high predictive value, while suppressing those that have low value, as a function of *the environment in which development is taking place*. Bouts of learning can accordingly be analyzed through some version of Herbert Simon’s “generate and test” procedure. Neural proliferation produces variety; neural pruning selects those variants that have been more often activated through feedback from the environment. The observed mind-brain organization results, on this view, from a generalized and hierarchical stabilizing effect of “generate and test” procedures with re-entrant feedback loops within larger populations of neurons.

The Neural Constructivists’ response to how organization emerges offers a more prominent role to development than Neural Darwinists allow. On their view, dendrite growth (and diversity) is exclusively controlled by the environment, rather than dually by genetic and exogenous influences. Furthermore, they speculate that individual dendritic segments could be the brain’s “basic computational units”.¹⁹ The central contrast with the selectionists is that they take an immature cortex to be initially equipotent. The actual functional organization of the mature brain – and, for example, the brain structure of perceptual areas – is supposed to depend entirely on the external constraints that the brain needs to internalize: “It is the differing pattern of afferent activity, reflective of different sensory modalities, that

¹⁸ Changeux (1985), p.249.

¹⁹ Quartz & Sejnowski (1997), p.549.

confers area-specific properties onto the cortex – not predispositions that are somehow embedded in the recipient cortical structure”.²⁰ While neural suppression plays (on their view) a minor role in brain development, the structuring force consists rather in neural connections being created under the influence of incoming stimuli. The mechanisms that are hypothesized to generate brain tissue growth and, more specifically, dendritic arborization, seem to involve local releases of neurotrophins, i.e. feedback signals that are delivered post-synaptically and are thus activity-dependent signals.²¹ As a consequence of these constructive, bottom-up mechanisms, the cortex is “enslaved”, that is, fully controlled, by the periphery. Representational capacities thus consist primarily in types of “enslavability”: they involve the production of flexible, adapted responses to varying environmental constraints as well as to changing body size. Hierarchical representations result from cascades of environmental influences working from cells to assemblies onto circuits, thus building representations of increasing complexity.²²

In summary, the two neurocognitive theories under review agree on the dynamics of development and its cascading effects on brain structure and function. They disagree, however, on the relations of brain and environment. Selectionists see the brain as imposing structure, through its own innate “biasing” agenda, on an unstructured world. Neural constructivists reciprocally see the world as enslaving the brain by imposing on it spatio-temporal patterns of reactivity and sets of representations.

²⁰ Quartz & Sejnowski (1997), p.552. Constructivists defend, against selectionists, the view that the so-called Darwinian algorithms (cheater detection, snake detection, etc.) which are claimed to constitute modern minds, are actually the outcome of domain-general learning mechanisms, which have turned out to be more often used for specific inputs: *domain-relevant* mechanisms are thus progressively turned into *domain-specific* mechanisms, as a result of their particular developmental history (Karmiloff-Smith, 1992).

²¹ For a clear analysis of these mechanisms in the visual cortex, see Katz & Shatz, 1996.

²² Quartz & Sejnowski (1997) p.550. Several interesting principles are used to explain the mature brain’s functional organization; one is the so-called “geometric principle” through which information is collected in a topological way, spatially or conceptually related representations being realized in neighboring physical structures; the other is the “clustering” principle, through which related inputs onto dendritic segments result in a pattern of termination that mirrors the informational structure of the input. (ibid, p.549)

5 MIND-BRAINS AS SELF-REGULATING AND SELF-ORGANIZING CONTROL ARCHITECTURES

Let us take stock. In Section 1, we presented Kim's interesting proposal: functionalization offers the conditions for mental states to be seen as inheriting the causal properties of brain states, and, from this, as being identical to the latter. Section 2 raised two problems with this reductionist project: two additional requirements should be fulfilled for the proposed account to go through. One is that the functional characterization should be nomologically necessary under some description. The other is that it should be dynamically intelligible. Sections 3 and 4 focus on the latter problem. Section 3 examines how functionalization needs to be modified to be made dynamic, resulting in what is called here "D-functionalization". Section 4 reviews two classes of theories which aim to explore the dynamics generated by the gene-environment-phenotype interaction, and come up, in this process, with a specific view on D-functionalization.

Thus, as we saw, there are two conditions that need to be fulfilled for a reductionist account to be adequate. Being a *dynamic* account is one, being a *nomological* account is another. While they address the first worry, our two theories are silent on the second. Not only because the exact mechanisms for the interaction between genes and information from the environment are not yet known; but also because, were these mechanisms known, they would still fail to be directly derived from physical laws. Our task in this section is to try to determine what the proper reduction basis of the mental would be, one that would fulfill the nomological condition as well as the dynamic one.

The two versions of how neurons develop might each capture one part of the picture: regressive and constructive mechanisms might in fact concurrently be engaged in development, as evidence piles up for each type of process.²³ What we are interested in at present, is not so much adjudicating between them (which obviously would go beyond a philosopher's competence), as looking for the underlying ontology which both views are implicitly appealing to. Our strategy here will involve two steps. In the present section, we defend the view that mind-brains are, as far as their causal structure goes, dynamically shaped by their having a specific kind of control structure, which we will try to specify. In the next and final

²³ Katz & Shatz, 1996, p. 1137, Hurford et al. (1997), p. 567, Dehaene-Lambertz & Dehaene (1997).

section, we will claim that mathematical models of dynamic control offer nomological constraints on mind-brain development.

The causal structure of the mind-brain is an adaptive control structure.

Four ontologically relevant claims are made in both theories of neural growth, which, to anticipate a little, point to the fact that causal efficacy is gained by mental states in virtue of their being embedded in physically realized adaptive control structures. On the basis of these claims, a preliminary rough characterization of the ontology of mental states may be achieved.

1. The brain develops over time and reorganizes itself as a consequence of being an adaptive control system.
2. Regulation and reorganization take place as a consequence of environmental feedback.
3. Environmental feedback drives representational success both through informational capture and attainment or failure of the current goal.
4. There are many different levels of regulation and reorganization, which are generatively entrenched and interdependent. For example, the way in which propagation of activation occurs at the neural cell level imposes limits on how fast one can compute or retrieve a memory.

5.1. The mind-brain is, in its essence, an adaptive control system.

Self-organization is the ability of a system to acquire and modify its structure on the basis of its own behavior in an uncertain, changing environment, by extracting signals that statistically correlate with preferred outputs. Self-regulation is a capacity that is necessary, but not sufficient for self-organization. In self-regulated systems, a controller manipulates the inputs in order to obtain some desired effect as an output. For this to be possible, an arbitrary number of loops mediate the causal interaction of the device with its environment (given the role of feedback, it is called a “closed-loop control system”). In top-down flow, a command is selected and sent to an effector; in bottom-up flow, reafferences (i.e. feedback generated by the selected command) are compared to stored values. Usually, a

feedback loop uses negative feedback: the sensed value is subtracted from the desired value to create the error signal, which is conveyed to the controller. Such comparators help the system decide whether the command was successfully carried out or should be revised.

Describing a mind in terms of control imposes no arbitrary reshuffling of mental functions, but rather allows us to make inner-outer interactions more explicit. From a dynamic control viewpoint, perceptual organs have as a major function that of filling in the data to be used by comparators, by providing feedback, i.e. patterns and intensities to be stored or extracted; in other words, they help select cues that are relevant to monitoring the efficiency of a given command.²⁴ Comparators, in turn, guide current and subsequent control decisions.

While control can sometimes rely on predetermined parameters (think of thermostats, and thermoregulation), mental activity usually does more than adjust itself to pre-established parameters; it can also autonomously create or change its regulation parameters on the basis of the feedback received (from the environment, and from the interactions between its states). As recognized by Neural Darwinists and Neural Constructivists alike, brain plasticity and mental plasticity depend on the evolution of devices subserving close-loop construction over phylogenetic time. The fact that a mind-brain is an adaptive control system, however, should not be taken as a mere brute empirical fact about how our minds develop. It may rather be seen as a result of nomological constraints being exerted on coupled dynamical systems (see section 6).

5.2. Regulation and reorganization are conducted as a consequence of environmental feedback.

A classical worry about control and regulation is that these concepts seem to involve a teleological, i.e. a design interpretation. The selection of commands as well as natural phenomena such as the propagation of light, follow a principle of extremum, (for example the principle of least action) which was long taken to be an expression of divine Providence. As Providentialists, including Leibniz, Maupertuis and Euler, were eager to claim, a variational constraint can and should only be explained by an agent's inten-

²⁴ For a similar view of the mind, see Grush (2004) & Hurley (2008), The grain of truth in enactive theories of perception (Noe, 2004) is that perception is functionally engaged in the control and monitoring of action. On the present view, it has evolved to extract cues for potential action goals and compare new cue patterns with stored ones.

tion. This speculation was made redundant, however, when it was found that variational constraints depend on certain invariant characteristics of the underlying mechanical system and its dynamics. A proper theory of extremum “principles” should rather explain the propagation of light through space on the basis of the symmetry properties of the underlying physical system,²⁵ and an agent's intention through the variational constraints on the control system that constitutes this agent.

In the particular case of the mind-brain, development, regulation and reorganization are based on the retroaction of the environment on brain activity. In Changeux & Dehaene's theory, the brain develops by pruning the dendrites that are not involved in stable connections; the activity of the postsynaptic cell retroacts on the stability of the synapse, through various molecular mechanisms that cannot be discussed here.²⁶ In Quartz & Sejnowski's theory, as we have seen, feedback signals – delivered postsynaptically – are hypothesized to generate brain tissue growth through the release of neurotrophins. On their view, the cortex is “enslaved”, that is, fully controlled, by the periphery.

The ontological consequences of such a constructivist view have been articulated as the “Extended Mind” hypothesis (Clark & Chalmers, 1998). The crucial idea is the following: Being a dynamic system coupled with a specific environment in which it continuously evolves, a mind cannot be taken as being contained in the skull, namely: as being independent from the structuring, contentful contribution of the environment which drives its evolution. The present article follows a similar route to understanding mind-brain relations. On the extended mind view, the environment is constantly reshaping the brain as well as the mind; both reflect its affordances and its constraints; both dynamically adapt to the speed of environmental change and its amount of diversity. If mental content and brain organization are acquired in the very process through which an organism as a whole is coupled with its environment, then mental dynamics (learning) is determined both by neural growth and by environmental dynamics.

²⁵ This is a direct consequence of Emily Noether's theorem.

²⁶ See Changeux & Dehaene, (1989), pp.79–80.

5.3. *Environmental feedback drives representational success both through informational capture and current goal achievement or failure.*

What then is the role that accrues to information in generating mental representations from feedback? In simpler forms of regulators, such as thermostats or Watts' flyball governors, the physical organization of a mechanical device allows unwanted perturbations to be neutralized, and brings the system back to a desired state as a function of the environmental condition. Information plays no role in any particular activation of the mechanism; it plays a role, however, by constituting an adequacy condition on the design itself: a thermostat will only fulfill its role if the thermosensitive device reliably tracks room temperature. Granting, however, that the causal structure of the physical interactions is designed so as to map the values to be compared, information plays no further role in these simple control systems; they are called "slave control systems" because the range of their "responses", given a particular input, is strictly and inflexibly determined by the machine design; these systems cannot learn and cannot change their goals.

In Adaptive control systems, in contrast, control parameters need to be constantly updated, expanded or replaced. Informational capture now seems to have a causal role in making such dynamic coupling possible. Is flexible control a sufficient reason to include information among the causal factors that drive such systems? A common intuition is that information, namely the converse relation of a causal relation, is involved in the stabilization of given commands. For example, if my receptors spot a red traffic light, (as a consequence of the causal effect of that light on my perceptual receptors), the information so collected, "red light", will cause me to apply the brakes: the red light means that there is an injunction to stop the car. This red light was itself selected as a signal for this particular injunction because it can be easily detected by the majority of drivers, who have a strong personal interest in following some coordination rule or other. The same causal process, *mutatis mutandis*, explains sexual coloration as having coordinative value in mating. In both cases, a selection process occurs, in virtue of which the signal is used in a certain way. But did the fact that the signal carries conventional information actively contribute to shaping the agent's behavior? Or is the agent responding, rather, in virtue of the causal properties of the vehicle carrying that information?

Here is an eliminativist view of adaptive control: it is a set of procedures that have been selected because they were more efficient than their

competitors, just as neural Darwinism would predict, and some Neural constructivists as well. It need not involve any kind of informational resources. Adaptive control is a sophisticated selectionist machine, that blindly reproduces what has worked, under pressure exerted by the environment. Just as conditioning can be exhibited in animals without representational abilities, such as *aplysia*, adaptive control can occur without the need to attach meaning to the sequences of neuron firings that are being selected for their beneficial effects.

Eliminativism concerning the role of information in adaptive control, however, results from intuitions concerning the selection of basic types of behavior, such as walking, or adjusting posture to gravity.²⁷ When it comes to processes that objectively require the integration of information from various sources, information seems to have a necessary role to play: a control vehicle will be selected now not only because it has been successful in the past in bringing about some result, but in virtue of its being able to have certain representational properties, i.e. because of the information that it carries. A vehicle now has a double function: that of directly implementing a command, and that of representing that command, or representing a class of other commands similar from a certain control viewpoint.

This double usage of vehicles, both as executers of commands, and as representations of commands, is actually borne out by an important formal finding. Classic control theory theorizes that, in order to reach optimal efficiency, control systems must have internal models available, able to dynamically represent the dynamic facts in the domain they control. How is this dynamic representation best achieved? According to Roger Conant and W. Ross Ashby, the most accurate and flexible way of controlling a system consists in taking the system itself as a representational medium. In an optimal control system, therefore, the regulator's actions are “merely the system's actions as seen through a specific mapping”.²⁸ This means, in other words, that a system that needs to control, say, an army, should be able to represent the space of action for that army, using its own agentic capacity as a model for army movements. Similarly, a system, such as the brain, that also needs to control itself, should be able to simulate itself in the possible behaviors that need to be controlled. Planning to do something is best achieved by using the vehicles engaged in execution to represent themselves, i.e. by using them “off-line”, in a simulatory way.

²⁷ See, for example, Thelen & Smith, (1994).

²⁸ See Conant & Ashby, (1970).

5.4. There are many different levels of control, which tend to be hierarchically organized and interdependent.

Granting that the brain dynamically develops on the basis of its preceding acquisitions, both theories allow for the fact that there are multiple levels of regulation and self-organization. This notion of level has been defined by Kim as an organization of elements that has a distinctive causal power (for example, microphysics and macrophysics refer to different levels of organization). Kim's notion of order, on the other hand, refers to the distinction between a causally efficacious property, and its abstract functional description (for example acetylsalicylic acid is a first-order substance that satisfies the second-order description of being an analgesic).²⁹

In contrast with Kim's mereological definition, the notion of "level" relevant to adaptive control reflects the notion of a progressive evolution and development of the mind-brain, with earlier forms of control being re-used and expanded in more recently evolved forms. This architectural constraint, called "generative entrenchment",³¹ may be fatal if the environment has changed so as to make the first forms of control obsolete; but in most cases, it turns out to be an economical and efficient way of building on prior acquisitions. Various levels of control thus typically include a subordination of prior mechanisms to more recent ones, for tasks of growing difficulty. What a Control "level" means is that, at that level, constraints of a given type are used in selecting a given command, which are not present in lower levels, but which will be inherited at the higher levels. The relevant constraints for the notion of a control level are usually of a temporal nature: the farther in time the constraints involved are, the higher the level considered. For example, Etienne Koechlin has shown, using fMRI, that the control of action is mediated by spatially distinct regions along the rostro-caudal axis of the Prefrontal cortex, with immediate sensory control as the lowest level (supported by premotor cortex), episodic control being the highest, and contextual control being an intermediate structure. In a cascade of this sort, information is asymmetrically inherited in the sense that a higher level combines more constraints into a command than a lower level; cascade also involves enslavement, in the sense that lower forms of control are automatically used by higher forms.³⁰

²⁹ Kim (1998), pp.80 sqq.

³¹ On this concept, see Wimsatt (1986) & Griffiths (1996).

³⁰ Does adaptive control entail a form of downward causation? Craver and Bechtel (2007) argue that the relevant downward relationship is not causal, but constitutive.

6 THE NOMOLOGICAL CONSTRAINTS ON MIND-BRAIN EVOLUTION AND DEVELOPMENT

What we have described in the preceding section can be more economically presented in mathematical terms, as two clauses which define adaptive control:

- (1) $dx/dt = f(x(t), u(t))$
- (2) $u(t) \in U(x(t))$

The first clause describes an input-output system, where x stands for a state variable, and u a regulation variable. It states that the velocity of state x at time t is a function of the state at this time and of the control available at this time, which itself depends upon the state at time t (as defined in 2). Clause (2) states that the control activated at time t must belong to the class of controls available at that state (be included in the space of regulation).

A general theory of how these differential equations can have solutions (in what is called “differential inclusions”, i.e. differential equations with a set-value on the right-hand side) offers us a descriptively adequate, and highly predictive view of how adaptive control systems can or cannot adjust to an environment. Describing the dynamic laws that apply to such systems is the goal of a mathematical theory called “Viability theory” (Frankowska et al., 1990, Aubin, 2001, 2003, henceforth: VT).³¹ Viability theory sets itself the task of describing how dynamic systems evolve as a consequence of a non-deterministic control device’s having to meet spe-

Kistler (in press) acknowledges the possibility of downward causation through a non-causal, and non-constitutive, interpretation of system-level constraints. Dretske’s concept of a “structuring cause” seems to offer a third possibility, which is explored here. Lack of space prevents discussing this important question.

³¹ Let us briefly justify the introduction of a mathematical theory into our “intermediate reduction” account. A mathematical theory can receive various interpretations. VT has been used to model various phenomena in the areas of economics and biology, where dynamic coupling of sets of events must be described. This does not prevent this same mathematical theory from being relevant to the domain of mind-brain relations. As we have seen in earlier sections, the relations of mind-brains to their environments instantiates dynamic coupling. Indeed, the brain internalizes world constraints through self-regulation and self-organization. If this assumption is granted, we are justified in assuming that Viability Theory, which describes the possible dynamics through which such coupling occurs, adequately characterizes our target domain.

cific constraints (both endogenous and environmental). Given one such system, and the constraints of a task in a given environment, are there one or more viable evolutionary paths for that system? The aim of the theory might also be used to describe a central function of a mind: “to discover the feedbacks that associate a viable control to any state”. When some of the evolutionary routes are not viable, (because they fail to satisfy the constraints in a finite time), VT aims at determining the *viability core*, i.e. the set of initial conditions from which at least one evolutionary path can start such that either

- a) it remains in the constrained set for ever;
- or
- b) it reaches the target in a finite time (without violating the constraints).

The set of initial states that satisfies condition *b* only is called the “viable capture-basin” of the target.

The present hypothesis can now be articulated as the following set of claims. As claimed in section 1, a reduction of mental to physical states or properties cannot be directly obtained, for lack of bridge-laws accounting for how a neural structure or neural activation accounts for the existence of a psychological function or mental content. It is possible, however, to express such a reduction using an intermediate level of reduction, where functionalization and “implementation” coincide. At that level, we can explain how both mental and neural events occur, how mental and neural properties are acquired, as parts of dynamic control structures, which explain their respective growth and development as physical and as mental events and properties.

This theory can further be used to articulate an alternative to Kim’s proposal, discussed in section 1. Remember Kim’s *Causal inheritance-as-identity principle (CIIP)*, stating “*M* is the property of having a property with such-and-such causal potentials, and *it turns out* that property *P* is exactly the property that fits the causal specification. And this grounds the identification of *M* with *P*”. The problem we had with this formulation was that “turning out” was a contingent property that we had no reason to think was holding in our actual (or some other, possible) world. Now consider the alternative formulation which I will defend in this section:

“*M* is the property of having a property with such-and-such causal-dynamic potentials. A neural property with an identical causal-dynamic

potential exists, which exactly fits the causal specification, in virtue of the regulation laws and the feedback laws which apply to neural-environmental interactions; these two sets of laws jointly explain why a given neural structure P was selected in a given M function. And this grounds the identification of M with P ”.

The alternative CIIP formula includes some of the claims that were made earlier: that M is D-functionalizable was argued for in section 3. The claim that a neural property fitting the causal specification for each M -state is an outcome of the neural growth theory exposed in 4. A sketch for how this claim can be articulated as a result of a control structure relating brain states and environment is drawn in section 5, where vehicles are seen to acquire a double content, as implementing a command, and as representing the fact that they do, in virtue of their control properties. What we need to argue for, now, is that such control structures necessarily operate under laws. These make the connection of D-functionalization to physical states (neural and environmental) a nomological one.

My suggestion will, I think, appear obvious. There are mathematical laws which are necessarily true of adaptive filters; these laws describe the capacity of a system to converge on a solution given the dynamic properties of the system itself and of the statistical environment to which it is coupled, i.e. the linear or non-linear characteristics of the signal and noise statistics in that environment. Among the mathematical theories for adaptive filters, Viability Theory, being in the business of extracting the universal constraints that allow a system to evolve in a viable way, provides us with lawful regularities concerning the dynamics of viable systems. According to VT, dynamic control trajectories necessarily fall under *regulation* and *feedback laws*. Regulation laws associate with a given state and command a certain rate of evolution. Feedback laws determine what portion of the regulation space is accessible to an organism with a given control history. We will concentrate on these two sets of laws, constituting as they do nomological constraints for a mind-brain with viable trajectories. Let us examine each type of regularity in turn, in order to see whether and how it provides us with a potential nomological account for our mind-brain evolutionary-developmental trajectories.

Regulation laws: These regulation laws, intuitively, tell us that cellular development, or mental activity, could not have developed in environments whose rate of change exceeds the rate at which the system can track or select adaptive solutions. Regulation laws can predict viability crises, and the kinds of transitions that can restore viability. More to the present

point, they provide adequate mathematical models for explaining the evolution described by brain growth/mental development theorists.

Three types of regulation laws will illustrate our point. The first attaches to stationary environments (where statistics are stable). In such a case, there is an optimum command that an adaptive filter can converge on in a finite amount of time.³² In nonstationary conditions, however, there must be a given kind of relation between the system and the rate of change in the environment for adaptive control to be possible: the system can only track adaptive types of feedback if its adaptation rate is faster than the rate of objective statistical change in the world. A third regulation law has to do with inertia, i.e. the rate at which a system will change its regulation parameters or routines. Granting resource limitation constraints, viability theory translates the “principle of inertia” into functional terms: controls evolve only when viability is at stake. Biological and cognitive evolutions tend to exhibit a hysteresis effect, or time lag, when confronted with the need for strategic change. “Punctuated equilibrium” illustrates this principle in evolutionary biology: most species experience little change for most of their history; when evolution occurs, it is localized in rare, rapid events of branching speciation. “Resistance to change” expresses the same dynamic phenomenon in belief, behavior or institutional revision.³³

Feedback laws: Intuitively, a developing cognitive system cannot master complex forms of learning before mastering their components. Feedback laws deal with the constraints applying to strategy selection (i.e. choice of a given set of commands at a given time) as a function of the present and past history of the control system. In other terms, feedback laws describe the evolution of the regulation space over time. Feedback laws explain the relationship between exploration and exploitation as the two main functions in learning. They also explain the existence of control cascades.

CONCLUSION

Let us summarize what this section contributes to our initial problem. Although at present there is no bridge-law showing how these two types of dynamic laws apply in the general domain of cognitive development, the

³² See Zaknich (2005), p.4.

³³ A negative attitude to change is thus seen as having a dynamic distal cause.

existence of viable trajectories in a developing mind-brain entails that there is a regulation map for such a system, which obeys dynamic laws of the two kinds discussed above. The present point is that this level of analysis should allow us to identify the parameters that allow certain regulations to emerge, and causally explain why the regulations in operation develop, and why they may be kept, conservatively, even when alternative regulations would allow their targets to be attained more efficiently.

In the light of the mathematical model of evolution sketched above, one can explain cascade effects in development and in evolution as the selection of a sequence of capture-basins, achieved on the basis of prior feedback, that will minimize a trajectory to a target control. VT thus provides, given initial conditions on a dynamic system, an explanation for why development follows such and such patterns, and why dedicated brain structures exchange information in the way they do so as to control behavior in the most flexible way available.

Finally, and surprisingly, the mathematics of control also accounts for why representational functions were selected, and why representations are constantly acquired and updated: homomorphic representations of the dynamic changes in the world are formed and memorized by mental systems because they are conditions for flexible control: this is an optimum that a variational system had to converge on. That is so because neural vehicles acquire their double function – that of directly implementing commands, and that of representing these or other potential commands, as a consequence of the structure of regulation spaces.

What causal role does this account leave for information? From Conant & Ashby's theorem, one can infer that information is a constraint on a control device to be flexibly adaptive. This idea can be articulated on the basis of Dretske's useful distinction between “structuring” and “triggering” causes.³⁴ Informational properties (such that the fact that quick/reliable information can be carried by certain color patterns or neuro-chemical properties) have a “structuring role”, in that they help stabilize certain regulations; for example, the fact that this external object is represented by that neural network is in part caused by the informational constraints attached to the regulations involving that object. Triggering properties, however, do not belong to “purely mental” representations, but to their vehicles. “Purely mental” representations do not have a specific causal roles; rather, the physical realizers of the control system to which they belong have them;

³⁴ Dretske (1988).

they do not have additional causal power, as Kim (1993) has convincingly shown (the present contribution is a dynamical variant of Kim's theory of psychological causation). Information is not what triggers neural pruning or growing. What triggers these is the differential production of neurotrophins (and other mechanisms resulting from dendritic activity as a consequence of adaptive control). Information is a constraint on the optimal design of a device meant to be flexibly adaptive. This constraint works as a structuring, not a triggering cause. Information is the causal dimension enabling optimal learning structures and learning conditions to be selected. As Dretske has taught us, it is because a property G always follows property F (because, say, F causes G as a law of nature), that G carries information about F . The temporal succession of physical events thus carries statistical information, which is then used as a constraint for finding predictors for G . This is what adaptive filters are meant to do. The enterprise of reducing mental properties to cerebral events needs to use adaptive filters as a mechanism providing the ontological common ground allowing reduction to be performed in a way that preserves the properties of the reduced entities.

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REFERENCES

- Aubin, J.P. & Frankowska, H. 1990. *Set-Valued Analysis*. Basel: Birkh user.
- Bickle, J. 1995. "Psychoneural Reduction of the Genuinely Cognitive: Some Accomplished Facts", *Philosophical Psychology*, 8:3, pp.265–285
- Churchland P. & Sejnowski, T. 1992, *The Computational Brain*. Cambridge: MIT Press.

- Changeux, J.P. & Dehaene, S. 1989. "Neuronal Models of Cognitive Function". *Cognition*, 33, pp.63–109.
- Christensen, W.D. & Hooker, C.A. 2000. "An Interactivist-Constructivist Approach to Intelligence: Self-Directed Anticipative Learning", *Philosophical Psychology*, 13:1, pp.5–45.
- Clark, A. & Chalmers, D.J. 1998. "The Extended Mind", *Analysis*, 58, pp.10–23, 1998. Reprinted in (P. Grim, ed.) *The Philosopher's Annual*, XXI, 1998.
- Cleeremans, A. & Jimenez, L. 1999. "Stability and Explicitness: In Defense of Implicit Representation", *Behavioral and Brain Sciences*, 22:1, pp.151–152.
- Conant, R.C. & Ashby, W.R. (1970). "Every Good Regulator of a System must be a Model of that System", *International Journal of Systems Science*, 1, pp.89–97.
- Cosmides, L. & Tooby, J. 1994. "Beyond Intuition and Instinct Blindness: Toward an Evolutionarily Rigorous Cognitive Science", *Cognition*, 50, pp.41–77.
- Craver, C.F. & Bechtel, W. 2007. "Top-down Causation without Top-down Causes", *Biology and Philosophy*, 22, pp.547–563.
- Dehaene-Lambertz G. & Dehaene, S. 1997. "In Defense of Learning by Selection: Neurobiological and Behavioral Evidence Revisited", *Behavioral and Brain Sciences*, 20:4, pp.560–561.
- Dretske, F. 1988. *Explaining Behavior*. Cambridge, Mass: MIT Press.
- Duncan, J. 2001. "An Adaptive Coding Model of Neural Function in Prefrontal Cortex". *Nature Neuroscience Reviews*, 2, pp.820–829.
- Edelman, G.M. 1987. *Neural Darwinism: the Theory of Neuronal Group Selection*. New York: Basic Books.
- Grush, R. 2004. "The Emulation Theory of Representation: Motor Control, Imagery, and Perception". *Behavioral and Brain Sciences*, 27, pp.377–442.
- Hall, B.K. 1992. *Evolutionary Developmental Biology*. New York : Chapman & Hall.
- Hawkins, R.D. & Kandel, E.R. 1984. "Is there a Cell Biological Alphabet for Simple Forms of Learning", *Psychological Review*, 91, pp.375–391.
- Jaenisch R. & Bird, A., 2003. "Epigenetic Regulation of Gene Expression: how the Genome Integrates Intrinsic and Environmental Signals". *Nature Genetics* 33, pp.245–254.
- Gintis, H., Bowles, S. Boyd, R. & Fehr, E. 2007. "Explaining Altruistic Behaviour in Humans", in R.I.M Dunbar & L. Barrett (eds). *Oxford Handbook of Evolutionary Psychology*, 2007, Oxford: Oxford University Press, pp.605–619.
- Griffith, P.E. 1996. "Darwinism, Process Structuralism and Natural Kinds". *Philosophy of Science*, 63, pp.1–9.
- Hurford, J., Joseph, S., Kirby, S. & Reid, A. 1997. "Evolution might Select Constructivism". *Behavioral and Brain Sciences*, 20:4, pp.567–8.
- Hurley, S. 2008. "The Shared Circuits Model: How Control, Mirroring, and Simulation can Enable Imitation, Deliberation, and Mindreading". *Behavioral and Brain Sciences*, 31, pp.1–58.
- Karmiloff-Smith, A. 1992. *Beyond Modularity*. Cambridge, Mass.: MIT Press.
- Karmiloff-Smith, A. 2006. "Ontogeny, Genetics and Evolution: A Perspective from Developmental Cognitive Neuroscience". *Biological Theory*, 1:1, pp.44–51.

- Katz, L.C. & Shatz, C.J. 1996. "Synaptic Activity and the Construction of Cortical circuits". *Science*, 274. p.1133–1138.
- Kim, J., 1993. *Supervenience and Mind*. Cambridge: Cambridge University Press.
- Kim, J., 1998. *Mind in a Physical World*, Cambridge, Mass.: MIT Press.
- Kistler, M. 1999. "Multiple Realization, Reduction, and Mental Properties", *International Studies in the Philosophy of Science* 13, 2, 135–149.
- Kistler, M. In press. Mechanisms and Downward Causation, *Philosophical Psychology*
- Koechlin, E., Ody, C. & Kouneiher, F. 2003. "The Architecture of Cognitive Control in the Human Prefrontal Cortex". *Science* 14 November 2003: Vol.302. no.5648, pp.1181–1185.
- Marr, D. 1982. *Vision*. New York: W.H. Freeman and Co.
- Nagel, E. 1961. *The Structure of Science*. London: Routledge and Kegan Paul.
- Noe, A. 2004. *Action in Perception*. Cambridge, Mass.: MIT Press.
- Place, U.T. [1956] 1990. "Is Consciousness a Brain Process?" Reprinted in W.G. Lycan (ed.) *Mind and Action, A Reader*, Oxford: Blackwell, pp.29–36.
- Proust, J. 2006_a "Agency in Schizophrenics from a Control Theory Viewpoint", in W. Prinz & N. Sebanz (eds.), *Disorders of volition*, Cambridge, Mass.: MIT Press, 2006, pp.87–118
- Proust, J. 2006_b. "Rationality and Metacognition in Non-human Animals", in S. Hurley & M. Nudds (eds.), *Rational Animals?* Oxford: Oxford University Press, 2006.
- Proust, J. 2009. "What is a Mental Function?" in: A. Brenner & J. Gayon (eds.), *French Studies in the Philosophy of Science. Contemporary Research in France, Boston Studies in the Philosophy of Science*, 276: pp.227–253. New York: Springer.
- Putnam, H. [1967] 1975. "The Nature of Mental States". In *Mind, Language and Reality, Philosophical papers* Cambridge: Cambridge University Press, vol. 2, pp.429–440.
- Quartz, S.R. & Sejnowski, T.J. 1997. "The Neuronal Basis of Cognitive Development: a Constructivist Manifesto". *Behavioral and Brain Sciences*, 20, pp.537–596.
- Sterelny, K. 2000. "Development, Evolution and Adaptation", *Philosophy of Science*, 67, pp.369–387.
- Sterelny, K. 2003. *Thought in a Hostile World, The Evolution of Human Cognition*, Oxford: Blackwell.
- Thelen, E. & Smith, L.B. 1994. *A Dynamic Systems Approach to the Development of Cognition and Action*, Cambridge, Mass.: MIT Press.

- Wimsatt, W.C. 1986. “Developmental Constraints, Generative Entrenchment, and the Innate-acquired Distinction”, in W. Bechtel, ed., *Integrating Scientific Disciplines*, Dordrecht: Martinus Nijhoff, 1986, pp.185–208.
- Zaknich, A. 2005. *Principles of Adaptive Filters and Self-learning Systems*, London: Springer.