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Review

Control at the heart of life: a philosophical review of perceptual control theory

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Perceptual-control theory offers a physically reductive way to account for teleology or goal-directedness, ranging from the initial emergence of life to creatures capable of regulating their own consciousness. This broad framework motivates key aspects of the perceptual-control model including the flexibility of behaviour, the hierarchy of aims or values, and the links between control and affective states. In this way, perceptual control theory integrates the psychological constants of representation, evaluation, and action.

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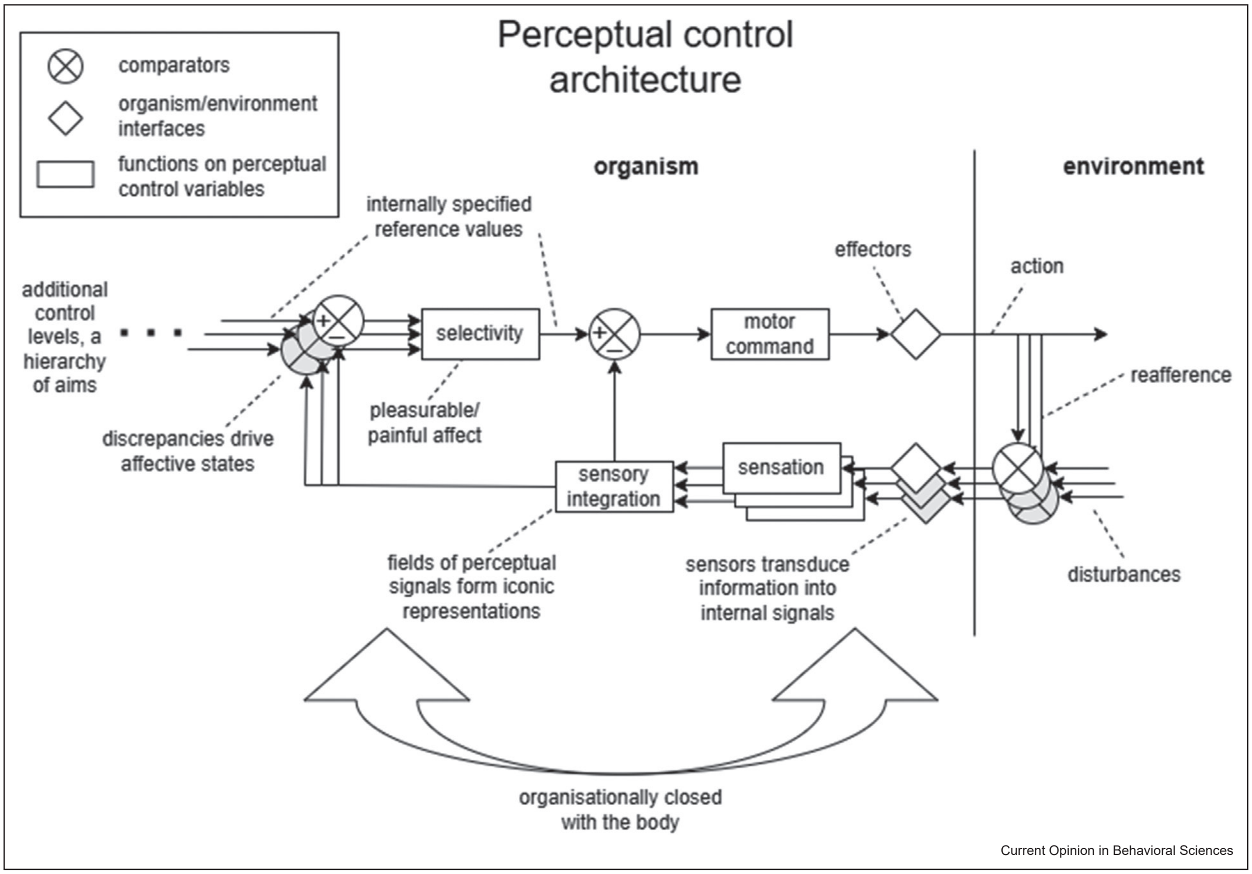
Perceptual control theory is an attractive theory of the mind because it is simple, extremely broad in scope, and fruitful in stimulating new theoretical and experimental approaches. The closed loop at the base of the theory is like a psychological version of Euler's identity ($e^{i\pi} + 1 = 0$), an equation celebrated by mathematicians for the elegant way that it relates basic mathematical constants. Likewise, the perceptual control loop relates the basic psychological constants of mental representation, evaluation, and action. For in comparing an input signal with a reference value and then guiding a response aimed at reducing the discrepancy between the two, the perceptual control loop must simultaneously represent the way the world is, prefer that the world be one way rather than the other, and, on this basis, drive behaviour (see Figure 1). The various elaborations of perceptual control theory all maintain the interdependence of these three constants.

The main point of appealing to closed-loop control is to capture, in a physically reductive fashion, the psychology of aim-driven behaviour. The deep problem underlying this project is that while we often explain the behaviour of living creatures by appealing to their aims, such explanations are teleological. That is, they are explanations in terms of the states of affairs to be brought about, but it is mysterious how future states of affairs can be causally efficacious. For instance, we dismiss as unscientific Aristotle's claim that stones fall to the ground because that is where stones prefer to be [1]. What makes the Einsteinian theory of gravity respectable is not that there is some future goal at which moving objects aim, but that there is something concrete — curved spacetime — with which things directly interact. In the same way, we wish to achieve a comparable physical plausibility in our account of psychological causation.

In fact, the concept of curved space has been used to clarify the nature of control. The state at which control systems aim — such as the target temperature of a thermostat — can be modelled as a mathematical basin of attraction [2,3]. Like a ball rolling towards the bottom of a bowl, conditions will tend towards the stable point despite perturbations. This is called 'persistence' [4]. Moreover, systems with different initial conditions will still move towards the target state. This is called 'plasticity' (ibid.) (or sometimes 'equifinality'). Persistence and plasticity are crucial for characterising the way that control systems compensate for all sorts of disturbances [5]. They are behind the point often made by perceptual control theorists that organisms do not produce fixed responses to stimuli and that it is wrong-headed to model psychological science on the measurement of fixed responses to independent variables [6–11]. Rather, we should be measuring how systems maintain internal target states, determined in particular by what is called the 'test for the controlled variable', in which we search for variables that produce relatively *less* disturbance in a system or its relation to other things, precisely because the system is controlling against them [8].

Not all physical systems that are modelled as a basin of attraction qualify as closed-loop control systems, however. To qualify as a closed-loop system, the attractor

Figure 1



The perceptual control loop integrates the psychological constants of perception, evaluation, and action. Signals from the environment are transduced and integrated. Discrepancies between these signals and internal reference values then generate regulative motor commands. In our model, painful and pleasurable affect are a function of the loss and gain of control over signals. Note that for some perceptual systems, like proprioception or interoception, the environment is the body itself, and thus reafferent feedback is internal to the organism. Note also that the hierarchy of reference values has a branched organisation beyond what is depicted here.

dynamics must be physically realised by component processes that jointly achieve negative feedback. Consider, for example, how over geological time, the Earth's climate is regulated by silicate weathering. Higher levels of CO_2 cause higher temperatures and, thus, higher rainfall. Atmospheric CO_2 is dissolved in rainwater, breaking down and reacting with silicate minerals in rocks to form bicarbonate ions in rivers. These eventually form carbonate rocks in the ocean (e.g. limestone), acting as a sink for CO_2, thus lowering temperatures. Here, perturbations feed into a physical mechanism that causally compensates for the perturbation.

The preceding example shows how negative feedback can result in a system stabilising around certain values. Yet a key difference between organisms and other naturally occurring feedback systems is that, in organisms, feedback is mediated by signals. When our bodies thermoregulate, heat is transduced into an internal signal that is compared to an internally specified reference value — physically instantiated perhaps in a voltage threshold — which then triggers a physically distinct response. Control by means of signals allows an organism to be sensitive to changes in the environment whilst maintaining system boundaries and overall system integrity (see Figure 1). Achieving control by means of signals also has a special role to play in perceptual control theory because it allows for the growth in complexity. While our interactions with the world can radically differ in form, signals translate our interactions into a single format. As a result, reference values can then be combined in more elaborate forms as we ascend a hierarchy of control [12–15]. Higher-order controllers can adjust lower-order references on the fly, and in the most sophisticated creatures, mental simulations can substitute for perceptual signals, underwriting cognitive flexibility [16,17].

As Cisek [18] describes, the development of organisms over evolutionary history can be mapped as the development of more and more elaborate forms of signalling and control. Early filter-feeding eumetazoans exhibited a diffuse neural network, with photo- and chemoreceptive inputs at one pole of the organism (apical) modulating basic contractile behaviour at the other (blastoporal). The move to anterior locomotion in bilaterians drove anterior cephalisation, with the emergence of *exploit* (feeding), *explore* (foraging), and *escape* control loops. In the move to land, early tetrapods were faced with greater depth of visual field and less reliable chemical gradients, resulting in the evolution of landmark tracking strategies for foraging control loops. Throughout this process, more complex nervous systems were needed to control (the causes of) ever more complex sensory signals, where the complexity of the sensory information was driven by changing niches as well as by the sophistication of the organism's own behavioural output (by reafference).

At what point signals become mental representations in this story of development is uncertain. But at least one major landmark is the transition between tracking singular chemical signals as occurs in basic homeostasis and the organisation of signals into a unified field or picture that is characteristic of perception. Meanwhile on the output side, an important revolution in agency is where it becomes purely mental, as when we aim only to bring certain ideas to the working memory [19], or when we shift our attention to control variables like informational complexity and novelty. Agentic control over mental contents has recently been theorised to play a decisive role in contrasting conscious and unconscious cognition [20–22].

So far, we have described how control relies on more or less complex signal functions to bring about a target state in a persistent and plastic way. However, this falls short of the concept of an aim where a system *prefers* to be in a certain condition. The thermostat, for instance, though it is often given as the intuitive model for psychological control, does not in its own right prefer one temperature to another. That preference comes from the people who design and use it, making them an ineliminable part of the control system. To properly capture preference, then, it is necessary to consider how the reference value of a control system gets established. Some theorists think that the distinctive characteristic of living creatures is that they set their own aims, giving them intrinsic goal-directedness (e.g. [3,23,24] though see Refs. [25,26] for dissent). This is known as 'teleonomy' [27].

One observation that is often made about living systems is that their regulative processes keep them out of thermodynamic equilibrium with their surroundings. This gives the control system a certain physical distinctness. It also requires the system to actively draw energy from its environment, as it maintains a dynamic organisation that persists through constant material turnover. Yet this does not equate to a preference. A hurricane is a system in a state of constant material turnover that stays out of thermodynamic equilibrium with its surroundings in a persistent and plastic way. But the hurricane presumably does not aim at anything, so additional conditions are required. An influential contemporary account [28,29], building on earlier ideas of self-organisation or autopoiesis [30], is that a system out of thermodynamic equilibrium is intrinsically goal-directed if its components are *organisationally closed*. To be organisationally closed is for the components of a system to causally constrain each other's operation in the continuous generation and upkeep of those very components. The basic idea is that the system simply would not exist if organisational closure were not achieved, and that, therefore, the system and its components have specific intrinsic functions, viz. those activities that underwrite organisational closure. This precarious sort of self-maintenance may indeed be characteristic of all and only living creatures [11,31,32]. It has also, to our awareness, not (yet) been realised in artificial systems, although systems have been built that can set their own reference values to some extent [33–35].

The idea that maintaining the components of one's own existence delivers teleonomy has been criticised, however. Corti [36] argues that it is not explained why parts depending on each other for their existence should imply that this is the function or goal of a system. The fact that the water cycle depends upon the sun does not mean that it is the function or goal of the sun to drive the water cycle, so why should it make a difference if the dependence goes in both directions? Yet organisational closure does at least indicate that the reference value is intrinsically established, because converging on the reference value is not just what the system does, it is what the system *is* as an emergent entity. As Mossio and Bich put it, "biological systems are what they do." [28, p.1090]. Meanwhile, although the system may draw on environmental sources of energy, the reason why it takes the particular form that it does is the mutual feedback of its component parts. No external agent or entity dictates its organisation.

A control system that, by means of signals, sustains its own physical components in a persistent and plastic way may be enough to establish intrinsic goal-directedness. Yet the full-blown sense of an aim that we recognise in our own actions also requires that the reference value be treated as good or desirable where alternatives are not so good or desirable [37]. That is, at a minimum, the creature *selects* what reference values to act upon. Presumably, such an ability is not available across all organismic control systems. In the most basic cases, the organism either achieves control over its reference value or it dies. Yet in more complex cases, organisms manage many possible opportunities simultaneously. To achieve this, higher-level control systems can monitor the success or failure of lower-level control systems. Some successes or failures can have greater weight within the larger system, due, for instance, to their intensity or number of associations with fundamental homeostatic needs. As a result, prioritisation occurs, such that additional metabolic, behavioural, and cognitive resources are devoted to the control task. This suffices for selectivity.

Though brief, it seems to us that the elements we have surveyed in this review are sufficient to deliver an account of aim-driven control in a full-blooded sense. Aim-driven control occurs when (1) an organisationally closed system (2) transduces internal or external variables into signals that are (3) compared to internally specified reference values, and the discrepancy feeds into the (4) selection or prioritisation of responses (5) that cause the system to align with those reference values in a persistent and plastic way. These components are illustrated in Figure 1.

At the same time, it is striking that the function we have described seems to correspond to an affective or emotional state. Indeed, several theorists have noticed that the basic structure of the perceptual control loop is well-suited to the modelling of emotions as states that trigger bodily responses for the sake of regulating conditions of concern to the organism [31,38–42]. The hierarchy of control can also be applied to the modelling of affective states of greater sophistication. Cochrane [31,42] argues that while it is sufficient in simple affective states like nausea and hunger to be directed at the current condition of the body, emotions necessarily represent a contrast between one's current condition and states that are past, future, counterfactual, or social. For instance, fear represents harm not as currently present but as coming up in the future, while relief represents harm as passing away or avoided. Gratitude represents a good that, in some counterfactual situation, would not have occurred. Envy represents a good that someone else possesses instead of you.

Alongside this, experiences of pain and pleasure can be drawn from the failure and success of control systems to regulate their targets and the selection amongst possible aims described above [20,31]. Corns [43] analyses suffering in general as the loss of control. Perceptual control theorists also emphasise that conflict between control systems — where incompatible reference values entail that neither can be achieved simultaneously — is of special significance and the source of chronic suffering [23,44,45]. Again, it is part of perceptual control theory as originally outlined by Powers and colleagues [46] that a persistent failure to achieve control necessitates the re-organisation of higher-level reference values in order to achieve harmony. The Method of Levels is a trans-diagnostic therapeutic practice that has been developed to enable such re-organisation to occur by guiding the patient towards maintaining awareness of the source of persistent control conflicts [44,47,48].

Meanwhile, on the positive side of life, well-being can be conceptualised as the harmonisation of one's various aims, particularly their organisation around those aims that sit at the highest levels of one's control hierarchy, one's pursuit of love, autonomy, or meaning, for example. It is important to us not only to have our needs under control but also to feel like we are making progress towards important goals [23]. Cooper further emphasises that the harmonisation of aims can be extended beyond the individual to the wider community or state. Perceptual control theorists are currently developing new approaches to moral and political theory as the regulation of interpersonal relatedness via multiagent control systems [49–55].

Across all of these developments, we emphasise once again the way that perceptual control theory draws an essential connection between our perceptual and cognitive capacities, our values or preferences, and our actions (including mental actions). None of these things can be fully understood except in their relation to each other. This places additional demands on our theoretical and practical investigations of these phenomena but also promises to deliver a more integrated approach to the mind.

At the same time, this demand may simultaneously be presented as a problem for the control-theoretic approach. Isn't it possible to have a perceptual or cognitive state without any preference or without any tendency to act? For instance, isn't it possible to simply see a tree and not care about it one way or the other? The response that we believe the perceptual control theorist should make here is that all perceptual and cognitive inputs do ultimately contribute to evaluation and action, but this does not imply that there is a specific evaluation or action tied to every bit of perceptual or cognitive data. The perception of the tree, for instance, may rather contribute to a wider spatial navigational task, which may itself contribute to the control of an aim like one's physical safety. It may alternatively contribute to the mental act of maintaining an optimal level of informational complexity as has been theorised as a control aim of consciousness. Not all available information needs to be relevant to whichever control processes are taking precedence at that moment. However, if information is being processed, it will ultimately be relevant to at least one control system.

Overall, there is no doubt that living creatures handle incoming information in subtle and flexible ways, and the specific ways that our behaviour is controlling that information flow need not be obvious to an outside observer. Yet the contention of perceptual control theory is that by placing a hierarchy of aims or reference values central to the functioning of organisms, we put the investigation of the perception, cognition, and action on a firm footing.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

Nothing declared.

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