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Control of Perception Should be Operationalized as a Fundamental Property of the Nervous System

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Abstract

This commentary proposes that ''cognitive control'' is neither componential nor emergent, but a fundamental feature of behavior. The term ''control'' requires an operational definition. This is best provided by the *negative feedback loop* that utilizes behavior to control perception; it does not control behavior per se. In order to model complex cognitive control, Perceptual Control Theory proposes that loops are organized into a dissociable hierarchical network (PCT; Powers, Clark, & McFarland, 1960; Powers, 1973a, 2008). In this way, behavior is dynamically adaptive to environmental disturbances, rather than being formed by, or superimposed upon, learned associations between stimulus and response.

Keywords: Control theory; Cybernetics; Negative feedback; Interdisciplinary; Integrative; Hierarchy

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The target articles illustrate how the field of ''cognitive control'' has become an exciting focus of research within neuroscience and psychology over the last two decades (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Houghton & Tipper, 1996). Interestingly, the importance of ''control'' as a central concept within human functioning was a key feature of early psychological accounts such as the ''pursuit of fixed ends by various means'' (James, 1890) and the ''reflex arc'' (Dewey, 1896). Both of these accounts regarded behavior not as an outcome but as part of a purposeful, goal-directed system within which perceptual feedback is critical. A recent article explains the unfortunate drift of psychology away from concepts of control during the 20th century and a return to this field of interest within recent times (Mansell & Carey, 2009).

Cooper (2010) defines ''cognitive control'' as ''the processes or mechanisms invoked in generating or regulating behavior when that behavior goes beyond the application of learned stimulus-response associations.'' This view is echoed throughout the works

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reviewed here (Alexander & Brown, 2010; Cragg & Nation, 2010; Mandik, 2010; Stout, 2010). Cooper (2010) continues to discuss whether cognitive control arises from the interaction of multiple control processes or whether the phenomena of cognitive control are emergent. In contrast, I will present the view that ‘‘control’’ is a fundamental property of the nervous system that does not require stimulus-response associations. Thus, basic cognitive control is neither componential nor emergent, but fundamental to the simplest of tasks. I will then explain how more complex cognitive control can build upon these fundamentals.

With regard to definitions, Mandik (2010) helpfully explains the difference between *open loop* and *closed loop* control. He describes open loop control as ‘‘shooting in the dark’’ because it leads to a fixed behavioral response—essentially having very little capacity to reach one’s target. Essentially there is no real ‘‘loop’’ in what is termed an ‘‘open loop’’ system. Interestingly, the open loop model is exactly what a system of learned stimulus-response associations would lead to—behavior being the outcome and endpoint rather than the means to achieve a goal. On the other hand, closed loop control relies on feedback from perception of the environment so that behavior changes in an ongoing manner. This means that individuals can ‘‘shoot at a moving target’’ and achieve the experience they wish to achieve. Arguably, control can *only* be achieved through a closed loop system, not through a ‘‘shooting in the dark’’ open loop system that does not rely on feedback. This will be explained from the perspective of Perceptual Control Theory, whose origins are within control engineering rather than neuroscience or psychology (PCT; Powers, Clark, & McFarland, 1960; Powers, 1973a, 2008).

The argument described here has been rehearsed on many occasions in discussions between behaviorists, cognitivists, and control theorists (e.g., Powers, 1973b; Vancouver, 2005). A control theory approach proposes that there are no fixed stimulus response associations, because behavior needs to *constantly* adapt and change for an organism to maintain its perceptual goals. The principle is summed up in a simple phrase—‘‘behavior is the control of perception’’ (Powers, 1973a). A classic example is balance—muscle contractions need to change flexibly online as disturbances from the environment (e.g., wind, rocky surface) disrupt the balance. The closed loop system operationalizes control as a *negative feedback loop*. Input signals are constantly compared to the *reference value* for that signal (the ‘‘goal’’ or ‘‘standard’’). The difference between them (*error*) drives the output of the system to act against the environment to bring the input signal into line with the organism’s reference value.

According to PCT, this process of control through negative feedback is a fundamental feature of the nervous system, and it is also not unique to top-down cognitive processes. An early mathematical modeling paper shows how the PCT model provides a more accurate model of shock-avoidance behavior than a stimulus-response model (Powers, 1971). Similarly, in a computerized paradigm, Marken (1985) shows how adaptive behavior can emerge despite random (noncontingent) reinforcement. In a more recent example, detailed quantitative studies show that the movement of a cricket as it balances on slanted surfaces is an example of negative feedback control (Pellis, Gray, & Cade, 2009).

Yet the field of cognitive control appears not to provide an operationalized definition of control like the one provided by PCT, and there is an attempt to interface behavioral concepts, such as stimulus-response learning, with control systems (e.g., Cooper, 2010). This leads to a model that is a hybrid of an open and closed loop system that would not dynamically control its perception, and instead ‘‘shoots in the dark’’ as it emits behavior without utilization of ongoing feedback. Mandik (2010) claims that a *pseudo-closed loop* system is required because closed loops have delays that can make them unstable. Contrary to this received wisdom (e.g., Lashley, 1917; Wolpert & Ghahramani, 2000), the closed loop is not a serial system that computes each stage in turn, as would be carried out by a serial computer. It is a biological system made from neurons that each operate at the same time (Powers, 1973a). Because all components of the loop operate simultaneously and in parallel, this actually means that signal delays have little impact on effective control when these models are developed to operate in parallel. The mathematical proofs and computer models that illustrate this point are provided in a range of published works (e.g., Powers, 1978, 2008). In essence, a ‘‘pseudo’’ closed loop seems unnecessary to stabilize oscillations.

The field of cognitive control proposes that reduction of error, often due to response conflict, drives the adaptive control of action (Alexander & Brown, 2010). Yet, in contrast to these accounts, PCT proposes that conflict occurs between reference values for perception rather than between different responses, and that learning is implemented as trial-and-error changes of the properties of control systems (Marken & Powers, 1989), rather than any specific response being ‘‘reinforced.’’ Arguably, this allows behavior to remain adaptive to the environment as it unfolds, rather than relying on learned action patterns that may not fit the current context.

A further important difference is how hierarchies of control are constructed. In a review of the evolution of theories of cognitive control, Stout (2010) provides a clear explanation of how hierarchical models of *action* control may have developed, utilizing archeological and neuroanatomical evidence. Yet the possibility of hierarchies of *perceptual* control are not reviewed. Interestingly, while the PCT hierarchical control model has been around for 50 years (Powers et al., 1960), it is only in recent years that such hierarchical models have gained pace within neuroscience (e.g., Botvinick, 2008).

Within hierarchical PCT, the output of an upper level of a control system in PCT sets the perceptual reference values for next level down in the hierarchy rather than controlling any specific action (Powers, 1973a). This means that upper-level goals can be achieved through flexible means delegated to lower levels. It also allows for a horizontal dissociation in the hierarchy, whereby upper-level systems can control their perception based on stored reference values, independently from the processing in lower-level systems. The proposed circuitry of this *imagination mode* is described in detail (Powers, 1973a). This mode would be experienced as ‘‘thinking while acting’’ (e.g., planning your meal while driving home from work).The upper-level system can then later be reconnected to the lower systems to implement the rehearsed plan. Thus, facets of cognition such as learning, memory, and even imagination, can be implemented in an exact manner *within* the organization of the control system (Powers, 1973a), which entails that they are functional and adaptive to environmental fluctuations.

The hierarchy is relevant to the role of language and thought in cognitive control. In their decisive review, Cragg and Nation (2010) provide evidence that the capacity for ‘‘inner speech’’ is closely associated with greater cognitive flexibility in a range of different tasks. In a somewhat similar manner, Stout (2010) recognizes the importance of ‘‘internal self-regulation.’’ Within PCT, the process of inner speech would be managed through the imagination mode—allowing people to verbally rehearse plans before putting them into action—a marker of cognitive flexibility. Taking a further step, it is proposed that mental imagery can also be controlled internally and arguably forms a more accurate representation of the outside world than linguistic symbols (see also Pezzulo & Castelfranchi, 2009). A PCT approach would predict that the capacity to dissociate higher levels of control is common to inner speech and mental imagery, and that both skills complement one another in performance on tasks requiring cognitive flexibility.

Finally, a PCT approach provides suggestions as to the developmental origins of language and cognitive control abilities and how to model them that are not found within the account of cognitive control. According to PCT, a hierarchical organization of negative feedback loops forms during child development, whereby the output of new higher level systems forms the reference signals for the level below (Plooij & van de Rijt-Plooij, 1990). Computer models of hierarchical systems derived from PCT produce highly accurate matches to the actual behavior of participants, for example, in studies of tracking and catching (Marken, 1986, 2001).

This brief commentary has illustrated that while it is critical to understand control in approaching the cognitive sciences, to do so effectively requires an operational definition of control. When such a definition is modeled dynamically, it appears that the control of perception is a fundamental feature of the nervous system, even in the simplest organisms. In this model, the processes of learning and memory occur *within the context* of control. Thus, any account that regards stimulus-response associations as fundamental, and control as superimposed on these, would lead to models that ‘‘shoot in the dark’’ rather than working in an adaptive, purposeful manner. It is the view of control theorists that perceptual feedback is fundamental, behavior only the means to achieve desired feedback. Perceptual Control Theory provides a shift in perspective, and an operational model of control, that may transform the progressive ideas about cognitive control into working models for the future.

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