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Editorial: Perceptual Control Theory and its application

M. M. TAYLOR
369 Castlefield Avenue, Toronto, Ont., Canada M5N 1L4. email: mmt@interlog.com

The fundamental idea of Perceptual Control Theory (PCT) has been known since at least the time of Aristotle, and was well expounded by William James. It is that people act so as to bring about the conditions they desire—to perceive their world as they wish it to be. They control their perceptions. However, the technical understanding required to turn this idea into a theory was largely developed only in this century. This editorial illustrates the nature of hierarchic control, and shows how control tasks can be partitioned between a human and a machine. It then considers some common but incorrect objections to PCT as a basis for psychology, and finally describes the eight papers that constitute this Special Issue.

1. Introduction

The fundamental idea underlying Perceptual Control Theory (PCT) has been known at least since Aristotle, and probably much longer. It is that people act so as to get what they want, in the face of unpredictable events in the world in which they live. Novelists and playwrights have known this, but apart from a few shining exceptions such as William James, scientific psychologists seem to have largely ignored it in favour of theories based either on the "stimulus–response" notion that people will tend to behave the same way when confronted again with the same pattern of stimulation from the outer world, or on the "cognitive" notion that people preplan their actions to achieve their goals, despite that preplanned actions will work if and only if the world is as the plan expects it to be. Neither of these underlying notions is appropriate to the world of everyday life, to which PCT is addressed.

Neither Aristotle nor William James had access to the technical knowledge required to turn the basic idea into a testable theory. That knowledge developed in the field of electrical engineering before and during the Second World War, under the name of servo theory or control theory. Norbert Wiener introduced the concept of Cybernetics (1948), using the theory of control systems as a basis for studying "The human use of human beings" (Wiener, 1950). In the early 1950s, W. T. Powers noted that "acting to get what is wanted" is the defining characteristic not only of humans and other animals, but also of engineered control systems, and began a long investigation into the implications of this fact, leading in 1973 to the publication of "Behavior: the Control of Perception", a book still considered the "bible" of PCT.

This issue of the International Journal of Human-Computer Studies consists of papers solicited both to illustrate PCT and to exemplify the wide range over which the theory can be, and is being, applied. The eight papers range from experiments on simple

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tracking and demonstration by simulation of how hierarchic control systems can work, through applications to human-computer interaction, to the use of the theory in personality and social psychology. This Editorial introduces some of the main concept of hierarchic PCT.

2. The necessity of Perceptual Control Theory

There is one overwhelming fact about life: to survive, any organism must in some way stabilize its essential internal chemistry in the face of disturbances from a turbulent outer world. At least one major theory proposes that the species that survived the mass extinction that ended the Cretaceous were precisely those best able to achieve this stabilization in the face of large disturbances. Our bodies are thermodynamically unstable, and decay away as soon as we cease to act to counter the influences that would destroy us. Every living thing has ancestors all of whom behaved so that they stabilized their internal chemistry at least long enough to propagate their genes.

Protection against the buffeting of the outer world can be done in two ways, and life employs them both. The first way is to develop passive armour, such as a membrane, skin or shell. But the armour cannot be so perfect as to isolate the organism completely from the outer world; if it did, the organism would die an entropic death. Just to sustain a minimal internal organization, any living thing must at least take in high-quality energy from the outer world, and excrete less organized waste energy. Most do much more.

The second, and more important, way an organism can protect itself against the disturbances of the world is to counter them as they occur, actively and powerfully. To do this, the organism must be able to sense important states of the outer world; it must be able to compare the sensed states with desirable conditions for those states; and it must be able to act to influence them so that it can bring about and maintain the desirable conditions.

"To sense" means to alter some internal state, such as a chemical concentration or a neural firing rate, in correspondence with changes of something in the outer world. In PCT, such an internal state is called a "perceptual signal", and the value of a perceptual signal is a "perception". To stabilize a state near some reference condition is the technical definition of "control". Hence, when an organism is countering the disturbances form the outer world, it is controlling its perceptions.

"Perception", in PCT, carries no connotation of consciousness. It is just the value of signal. A perception may be related directly to the current state of some property of the outer environment, but very rarely is the connection so direct. The value of perceptual signal in most cases depends not only on the current state of the physical variables that affect sense organs, but also on the current values of other internal variables, which often depend on the history of the organism.

The external variables that affect the value of a perceptual signal might be very complex and context-dependent—such as those that relate to the perception of the commitment of one's government to democratic values—or they might be as simple as the rate at which visible photons impinge on the retina, which relates to the perception of brightness. Both perceptions—democratic values and brightness—according to PCT, are just values of a signal, and neither need be conscious to be effective.

Bringing a perception of some state to desired (reference or goal) value with which it is compared, and maintaining it there, is control in the strict engineering sense of the word. The *perception* of the external state is what is stabilized, not the external state itself, and still less the action that the organism uses to influence the external state—hence "Perceptual" Control Theory. For this reason, PCT has core tenet: "All behavior is the control of perception". The actions that stabilize the perception may vary dramatically as the environmental influences change, but a well-controlled perception varies only when its reference value changes.

Not all perceptions can be controlled. Many, such as the perception of the height of the sun in the sky, exist as signals that one's actions cannot influence. Other perceptual signals, such as a perception of the democratic commitment of the government, can be influenced only slightly by one's action. Yet other perceptions can be controlled with ease, such as, for most people, the perceived location of one's hand.

3. Perceptual control systems: engineered and human

It is not only living things that contain signal values. Inanimate objects such as computers do, too. If those values are consequent on states of the world outside the computer, they may legitimately be called "perceptions". If a computer acts so as to maintain at a reference level a signal value that corresponds to a state of the outer world, it is controlling a perception, just as a living organism might do. This does not mean that the computer is considered to be alive, but it does mean that the analytic techniques of control can be applied to the relevant operations of the computer, just as they can to the relevant processes of a living thing. Human and computer both control perceptions by sensing some aspect of the world and acting to influence the resulting signal toward a reference value, in the face of external influences that would alter its value.

An engineered control system is designed to bring some variable to a desired value and maintain it there. We will use the aiming direction of a gun as an example, not for any war-like reason, but because it highlights several of the important characteristics of PCT, including the control hierarchy, logical variables and reorganization (learning). It also introduces the problem of task allocation between human and machine.

A control system is supplied with a reference signal, the value of which is the desired value of the controlled variable—the desired aiming direction in the case of the gun. The actual aiming direction is not directly available for comparison with the reference. What is available is instead a signal derived by a sensing device from the aiming direction of the gun. This derived signal is a "perception" of the aiming direction, and it can be compared with the supplied reference value. The difference between the two values is called the "error" in PCT. If the error is non-zero, the control system produces output that drives motors that alter the actual aiming direction, and thus the perception of the aiming direction, in such a way as to reduce the error, thus completing a "negative feedback loop".

The "error" is the difference, not between the actual aiming direction and the desired aiming direction, but between the perception of the aiming direction and its reference value. It is always perceptions that are controlled, never the outer world states to which they correspond, even though it is the true values of the outer world states that are important. The actions of the controller can influence the true values, but it is the perceptual values derived from the sensors that are compared with the desired values and controlled. The true values are unknowable, and therefore uncontrollable.

In the case of a fixed land-based gun, a gunner who knew the currently perceived aiming direction could bring the gun to its desired aiming direction by driving a motor of a known torque for a predetermined time. If, however, the gunner's knowledge of the motor torque or of the gun's moment of inertia and frictional resistance happened to be in the slightest degree inaccurate, the resulting aiming direction would not be what the gunner wanted. To assure that the gun was pointed correctly, the gunner would have to look at the gun's position through some different sensors, such as his own eyes, and correct any remaining error, completing a negative feedback loop through himself.

Neither can the gunner set the aim accurately by driving a motor a predetermined amount if the gun is on a ship subject to the vagaries of the waves. But a control system can sustain the perception that the gun is aimed in the right direction, despite variations in motor torque or the effect of the waves. The control system, whether it be engineered or inside a human gunner, continually senses the current aiming direction and compares the derived signal value—the perceived aiming direction—with its reference value, and acts continuously to keep the error near zero.

3.1. PERCEPTUAL CONTROL HIERARCHY: LEVELS OF CONTROL

The reference value for the aim of the ship's gun in determined by considerations that have nothing to do with the motion of the ship, and everything to do with the intentions of the gunner. The gunner wants the gun to point at the intended target, regardless of the wave action. The gun-aiming control system allows the gunner to ignore the waves, and to concentrate only on providing it with a reference value for the direction in which to aim.

The gunner can choose the right aiming direction by selecting a target and using some instrument to determine its direction. As the target or the gun platform move, the gunner must continually determine the target's direction and communicate it as a changing reference signal value to the gun control system. The gunner acts as part of a second-level negative feedback loop that corrects the error between the ever-varying desired aiming direction and the aiming direction apparently produced by the gun control system.

Using, say, radar, an elaborated control system could relieve the gunner not only of the need to keep observing the gun direction, but also of the need to keep observing and measuring the direction of the target. The second-level control task could be allocated to the machine rather than being performed by the gunner. The gunner could give an automated second-level control system a reference signal that identifies which among the radar returns is that of the target.

The reference signal from the gunner to the new second-level control system corresponds to a choice of identifier, not a direction of aim. It allows the second-level system to lock onto the gunner's desired target among the various possibilities. If the chosen target moves, this second-level system would send to the first-level control system a new reference value for the desired aiming direction, bringing the gun direction back onto the shifted target, but not changing which entity in the perceived world was targeted.

3.1.1. The "meaning" of a perceptual signal

The reference signal for the second-level control system is what the human gunner sees as "target identity". An error at the second level would be interpreted by the human gunner as the system having locked onto the wrong target, whereas an error in the first-level control system would be seen as a bad aim at the correct target.

There is nothing mystical about perceptual signals, whether they are in an electronic system or in human. In itself, a perceptual signal has no "meaning". All the control system does is to keep an electrical voltage, a neural spike rate or a chemical concentration near its reference value. An external observer may determine that a perceptual signal corresponds to a gun-aiming direction, to the identity of a target, or to something else. The external observer sees that the gun aims accurately, and that it aims at the right target. The control systems do not. They "see" only that their perceptual signals have the values that they should have.

Either the human gunner or an engineered control system can keep the gun trained on a moving target despite variations in the power of the gun-motor and in the motion of the platform. Either the human gunner or the engineered control system creates a negative feedback loop that acts on the environment (the physical gun) so that perceptual signals representing different aspects of the environment (the aiming direction of the gun, and the target on which the gun is to be aimed) are brought to and maintained near their reference levels. The control system may be mechanical, electronic or inside the human. Functionally, it does not matter, though the choice may well affect the gunnery performance.

According to PCT, all behaviour is of this kind: all intentional actions are performed so as to bring the values of perceptual signals closer to their reference values. Elementary control systems similar to the gun-aiming control system and the target-following control system are organized into a layered network or hierarchy, in which the reference value for any one elementary control system is derived from the output of one or more higher-level control systems, and in which the perceptual signal of any one elementary control system may contribute to the perceptual signals of one or more higher-level control systems. At the highest level in an engineered control hierarchy, the reference signal is supplied by the human user or the system designer. At the highest level in an organic hierarchy, there may be no explicitly variable reference signal. A top-level negative feedback loop may simply stabilize its perceptual signal at some arbitrary but fixed value.

An engineered control system has a behaviour that can be accurately predicted from a knowledge of its design and the values of its variable parameters. If living organisms are indeed living control systems (Powers, 1989, 1992), the same should in principle be true of them. Of course, a living control system is vastly more complex than an engineered control system. Nevertheless, in experimental situations ranging from simple tracking studies (Bourbon & Powers, 1999, this issue) to the study of self-image (Robertson & Goldstein, 1999 this issue), it has proved possible to use simple control systems to model humans and to simulate their behaviour with high accuracy.

4. The "reality" of perception: reorganization

Consider now how perception relates to "reality"—how perception can be calibrated. What might happen if the sensors that signal the aiming direction of the gun are miscalibrated?

Suppose that when the gun is actually aiming north, the sensors report it to be aiming north–northwest. If now the gunner (or the second-level control system) provides to the gun-aiming first-level control system a reference signal corresponding to a perception of "North" (where the gun is actually pointing) there will be a mismatch between the perceived and the reference direction. Because of the mismatch, the gun will slew round until the direction sensor reports that it points north, though it will then actually point north–northeast. All will seem to be well, since there is no way that the gunner or the second-level control system could tell that the gun is pointing wrongly, without using a different sensor.

When the gun is fired, however, the fall of shot may be observed using sensors quite different from those used to report the aiming direction of the gum. If the shot falls to the east of the target, observation of the miss permits a correction to how the gun is aimed, in preparation for the next shot. A new negative feedback loop has come into play, one that acts, not on the gun's aiming direction, but on the aim control system. It changes the function that relates the sensor data to the perceptual signal. The new function says, in effect, "perceive the aiming direction to be 22.5° clockwise of where the sensors indicate". The aim control system will then equate a desired reference aim of "North" with a perception derived from a sensor signal corresponding to north–northwest, and in the real world the gun will be aimed accurately. Even though the sensors are mistaken, the perceptions derived from them may accurately correspond to reality.

"Fall of shot" is a perception for which there is no signal in the gun-aiming hierarchy. It is a signal from a different sensor, one that relates to the gun's ultimate task of firing a shell that hits the intended target. But the effect of an error in the "Fall of shot" perception is a change in a parameter of the gun-aiming perceptual control hierarchy. In the language of PCT, the new control system has "reorganized" the existing two-level control hierarchy by altering the values of the perceptual signals that correspond to particular states of the world. Such a reorganization is possible only when the action of the two-level hierarchy is tested against reality by observing the success of the action—in this case the accuracy of the fall of shot.

In PCT, reorganization is the name given to changes in the perceptual control hierarchy that are induced by error in some perception related to the ultimate task of the organism—hitting the target in the case of the gun, staying alive (or propagating the species) in the case of a living organism. Reorganization in PCT takes the place of such concepts as adaptation and learning in other psychological theories. Reorganization has many forms, of which we have illustrated only one—a change in the parameter values of the function that generates a perceptual signal from sensory input.

The reorganization that corrects the gun's miscalibrated direction sensor has a direct analogy in experiments on humans wearing spectacles that have prisms for lenses. Many such experiments were conducted between the 1930s and 1960s. Several of the later experiments compared the relative ability of people to "adapt" to the prism spectacles when they were able to act on the world as compared to when they were moved passively around the world. Adaptation (subjectively, the perception of the world as "normal") occurred much more quickly and completely when the subjects could act on the world than when they could not, and occurred with respect to those aspects of the world the subjects could affect more quickly than for those aspects over which the subjects had no influence (e.g. Hein & Held, 1962; Taylor, 1962; Held & Rekosh, 1963; Held, 1965).

According to PCT, these results could hardly have been otherwise, if the relationship between sensory data and perceptual signals is affected by a control system that reorganizes according to its success in performing its task.

In the case of the gun, the task for which the perceptual control system is ultimately responsible is that a shell should hit its target. What is the "ultimate" task in the case of the human? One may presume it is to keep the structure and the internal chemistry of the body in a state that sustains life, at least long enough for it to pass on its genes to the next generation. The body's "internal chemistry" is represented by a set of "intrinsic variables" that correspond to the chemistry in the same way that the values of perceptual signals correspond to states of the outer environment. Each individual is born with a set of reference values for these intrinsic variables, reference values that may change over the course of a lifetime, but over which the individual has no control.

If the sensed values of the intrinsic variables deviate from their reference values, the reorganizing system acts to reduce the deviation. It acts, not directly on the outer world, but by changing the perceptual control hierarchy that perceives and acts on the outer world, just as the control system that observes the fall of shot acts on the gun-aiming control hierarchy, not on the gun. Reorganization may, as in the gun-aiming example, change what is perceived; it may change how the output of a control system is connected to influence the reference values of control systems at lower levels in the hierarchy; or it may change any other parameter of the control system hierarchy. It may even add totally new perceptual control systems into the hierarchy, as seems to happen during maturation. When the totality of perceptions being controlled has effects on the outer world that keep the intrinsic variables near their reference values, reorganization will have done its job.

5. Objections to Perceptual Control Theory

The idea that humans operate as a network of elementary control systems has been discounted on various grounds, largely specious.

5.1. THE "SIMPLISTIC" OBJECTION

The first objection is the intuitive notion that the theory seems too simplistic to account for the manifest complexity of behaviour. To this one can only ask in return whether the simple electromagnetic interactions among a small variety of simple atoms are too simplistic to account for the beauty and complexity of the chemical (and biochemical) world. Simple interactions among simple things can very quickly produce results of astounding complexity.

5.2. THE "TOO SLOW" OBJECTION

A second objection, one that sounds more reasoned, is that control systems are too slow to account for some observations. To counter this objection, control theory must be compared with the proposed alternatives, of which there are two classes: direct stimulus–response linkage, and preplanned action.

According to the notion of direct stimulus–response linkage, when some stimulus pattern is observed in the world, "immediately" an action is performed that is linked to the stimulus pattern. The objection to control systems here is that a control action will be too slow, as compared to a direct stimulus–response linkage. This is a strange argument, since the connection from sensation to action through the control system is almost identical to the stimulus–response connection. Any intrinsic delay in the effect of the action on the world is the same in the two systems. Furthermore, the control system has a technical advantage in speed, since it inherently has output amplification, which speeds the action in a way not available to a directly linked system without feedback. As a demonstration that control systems are slower than the alternatives, this first alternative fails spectacularly.

The second class of alternatives that is said to be faster than a control system is a preplanned action system that anticipates the need for action to produce an intended future state of the world. Such a system can accommodate delays in the effect of action on the world, by starting the action early enough that when the need arises the action will have had its desired effect. Here, the objection is that the control system cannot act until a changed perception causes an error (deviation from the reference signal). But this is not true, since higher-level control system can mimic the effect of a preplanning system by altering the reference signal well in advance of the need for action. To see how, let us return to the gunnery analogy.

The two-level gun-aiming hierarchy has an upper-level control system that asks a lower-level control system to keep the aim of the gun in a direction corresponding to the changing direction of the target. But there is a time lag between the moment the shell leaves the gun and the moment it arrives at the target, by which time the target may have moved. If the higher-level control system were to ask for the gun to be aimed at the place where the target would be when the shell arrived, the shell would hit it instead of falling behind it. How could this be achieved? In the simplest way, the target-following reference value could be replaced by a value built not just from the current position of the target on radar, but also from the time derivative of the position. The resulting output signal that tells the lower control system where to aim would then be correct if the target maintained its velocity. The effect would be just as fast as with a preplanned action system, but would be based on observation of the current and recent behaviour of the target (as would the preplanned action).

The objection that control systems are too slow fails when compared with the non-control alternatives. A well-designed control system is actually faster than the corresponding direct stimulus–response linkage when dealing with unexpected events in the outer environment, and is no different from preplanning systems when dealing with a predictable need for action. A control system has a further advantage over both alternatives, in that it does not depend strongly on the consistency of the effect of action.

5.3. THE "DECISION-MAKING OBJECTION

A third kind of objection to seeing humans as control systems might be called the "discrete-perception" or "decision-making" objection: humans are cognitive beings, using logic to make decisions, whereas control systems are analogue devices that correct errors incrementally. The objection is that a human chooses one course of action and executes it, whereas a control system just outputs some signal that is a function of its present and past error, implying no choice among alternative actions.

The "decision-making" objection is more subtle than the erroneous "too-slow" objection. The "discrete-perception" aspect of the objection is readily dismissed. Both electronic and neural systems have several mechanisms where by the value of a perceptual or a reference signal may be constrained to remain close to either of a binary pair of values that we can call "A" and "B". If the reference signal takes on the value labelled "A" and the perceptual signal happens to be "B", an error signal will be generated, leading to an output that alters the reference values for (possibly continuous-valued) lower-level control systems until the perceptual signal takes on the value "A". Control of discrete values of a perceptual signal is equivalent to the control of perceptual categories: I want to perceive a "cabbage" in my shopping basket, as opposed to a "lettuce"or a "fish".

To consider the "decision-making" part of the objection, we return once more to the gunnery analogy. Thus far, we have considered two levels of control: one that keeps the gun aiming in the desired direction despite the vagaries of platform motion, and one that changes the desired direction to keep the gun aiming at a desired target as the target moves. We now add a third level of control that we might call "strategic" or "logical".

In order for the second-level control system to operate, we had to assume that the radar return is processed in some way so that the direction and distance to a potential target is continuously available. This vector, possibly together with its derivative, provides a reference value for the gun direction, which is compared in the second-level control system with the perceptual signal corresponding to the gun direction.

We now add the assumption that the processed radar return embodies not just one direction–distance pair, but list of directions and distances to several potential targets. In the example so far, the human gunner chose the target from this set of possibilities. The third level of engineered control that will substitute for the human gunner makes this choice as a controlled perception. The reference for this controlled perception is a logical form provided by the human gunner (though in real life such a choice would probably not be left to an automated system).

For illustration, we use a trivial strategic rule which can put into words as "aim at the closest target". To aim at the closest target requires that the closest target be perceived and selected as the one to be tracked in providing the reference direction for the second-level control system. To perceive "the closest target" involves a "logic-level" perception. At the logic level, perceptions correspond to Boolean relationships—AND, OR, XOR, GREATER THAN, and so forth. A reference perception might be, for example, that the perceived distance of the chosen target be LESS THAN that of each other potential target. The AND of all these logical comparisons would then have a reference value of TRUE. If the gunner changed the reference value to FALSE, he would be directing the gun to ignore the closest potential target and to aim at any of the other potential targets, each of which would satisfy the new reference value for the logical variable.

5.4. THE "INVERSE KINEMATIC" OBJECTION

A fourth kind of objection to PCT is what we might call the "inverse kinematic" objection. The argument is that the inverse kinematic equations are underdetermined, because there are so many ways to accomplish any given desired end result. The consequence is supposed to be that the appropriate control actions cannot be uniquely specified for execution.

The "inverse kinematic" objection is invalid when applied to PCT, though it does present a problem to any theory of action that involves precomputing ways to achieve a planned result. In PCT, action is not precomputed. Each elementary control unit merely supplies output when the value of its perceptual signal does not match the value of its reference signal. This output may be distributed through an arbitrary number of mechanisms that might affect the outer environment so as to influence the perceptual signal. So long as the cumulative influence of the output on the perceptual signal is such that it reduces the magnitude of the error, the desired result will be achieved. One of the mottos of PCT, along with "All behavior is the control of perception", is "Many means to the same end; many ends by the same means". The inverse kinematic objection turns out to be more of an argument in favour of than an objection to PCT.

A more interesting question inspired by the inverse kinematic objection is: given that a perceptual control system that operates by setting reference values for lower-level control systems will achieve its intended objective, will it do so in a way that is like the way a human does the same thing? For example, will the trajectory of a simulated hand reaching for a target be like the trajectory of a human hand under the same circumstances?

It appears that the answer to these questions is a qualitative "Yes". In this issue, Powers describes a simulation of a system that uses stereo vision and an arm jointed like a human arm at the shoulder and the elbow to keep a "fingertip" on or close to a target that moves in a three-dimensional (3-D) space. An ongoing project to follow up this simulation is a 14-degree-of-freedom arm that has weights, elasticities, and muscle strengths like those of a human arm, to test whether the trajectories that look qualitatively like those of human arms will be qualitatively accurate when following a moving target.

This editorial is not the place to attempt a full description of PCT. The presentation in Powers' (1973) "Behavior: the control of perception" remains valid for the most part. A selected bibliography of writings on PCT is available through the World Wide Web site of the "Control Systems Group", which is devoted to PCT (at http://www.ed.uiuc.edu/csg). There one can also find introductory material about PCT, links to other relevant sites, and instructions for joining the mailing list on which technical discussions of PCT are conducted. Java-based demonstrations of various aspects of PCT can be found at http://home.earthlink.net/~ rmarken.

6. About this issue

The special issue of the International Journal of Human-Computer Studies was solicited by the Journal Editor, Dr B. R. Gaines, with the goal of illustrating the breadth of application of PCT. This goal clearly extends the scope of the articles beyond the usual realm of "Human-Computer Interaction", though as it happens, most of the papers either use computer simulation or are concerned with easing the human use of technology.

The papers in this issue are arranged to progress from simple one-level control, through hierarchic control, human–machine interaction, to areas usually considered more "soft"—personality and social interaction.

The issue starts with a paper by Bourbon and Powers in which the three main classes of behavioural theory—stimulus–response, preplanned action, and control—are stripped to the bare essentials, and compared in their ability to predict the results of a simple tracking task under successively less restrictive conditions. A simple single-level control model provides almost exact prediction under all tested conditions, whereas models based on the other foundations are successful only under restricted conditions. Bourbon and Powers argue that the restrictions are generic, and can properly be applied to the more complex circumstances of everyday life.

In the following paper, Powers demonstrates hierarchic PCT in application, by simulating an arm with shoulder and elbow joints, showing that the so-called degrees-of-freedom problem is not a real issue. A "Little Man" observes a moving target in a 3-D space, using stereo vision, and attempts to keep a fingertip on the target as it moves, using a three-level control hierarchy.

The next four papers deal with the use of PCT or the related Layered Protocol Theory (LPT) in considering human interaction with each other or with machines. Marken introduces a form of task analysis called Percolate, built around PCT, and discusses it in the context of a satellite control system. Farrell *et al.* discuss PCT and LPT in the context of an interface to a navigation and radio communication unit in a helicopter. In a companion paper, Taylor *et al.* examine an element of LPT, called the General Protocol Grammar, which is central to the design of interface dialogues, as well as being applicable to interactions between humans. In the last paper of the group, Haakma uses LPT/PCT to analyse a set of possible interfaces to a digital recording device for the consumer market.

Extending the scope of the discussion of PCT into the realm of personality, Robertson *et al.* report experiments on controlling the perception of self-image. Self-image is a very high-level perception within the hierarchy of levels postulated by Powers, which therefore is sustained by many different kinds of actions in a variety of realms. Nevertheless, Robertson *et al.* are able to use PCT to study it in a precise manner.

The last paper in this issue, by Tucker *et al.*, deals with people in crowds. Using a simulation program devised by Powers, they show that certain patterns of arcs and rings that often form in natural crowds also occur in crowds of simulated people, each "person" being defined by a very small number of simple one-level control systems relating to the perception of distance to a target person and to the avoidance of collisions with other people. The simulation program itself is available as freeware for further experimentation. Beyond demonstrating the arcs and rings, the program shows that a simulated individual controlling very simple perceptions can escape from traps or dead-ends, by moving away from the target toward which it is trying to go.

It is impossible in one journal issue to give a full impression of the power and versatility of PCT, nor of its precision in those circumstances in which quantitative prediction is possible. The intention of the Special Issue Editor has been instead to provide hints, and to suggest that PCT is a robust foundation both for theoretical psychology and for human factors engineering.

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