A Quarter Century of Research on Perceptual Control Theory: Opening the Door to Closed-Loop Psychology

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I would like to thank South China Normal University and the Chinese Research Council on Complexity and Philosophy of Systems Science for giving me the opportunity to talk with you today. Actually, you have given me both an opportunity and a challenge. The opportunity is to tell you about my 25 years of research on Perceptual Control Theory (PCT). The challenge is to do it in 45 minutes. Fortunately, in preparing for this talk I realized that I can compress 25 years into just a few minutes because all of my work on PCT is really about just one thing: opening the door to closed-loop psychology. What I mean by this is that my research has been aimed at trying to introduce scientific psychologists to a new approach to studying human behavior, one that is based on the fact that people are closed rather than open-loop systems.

While my efforts to reform scientific psychology have been persistent, I'm afraid they have not been very successful. This has been disappointing but not surprising because I am a scientific psychologist myself and I know that the methods of psychology are the foundation of our discipline. This foundation is currently built on the assumption that humans are open-loop systems. Take away the open-loop assumption and you take away scientific psychology as we know it. This is not a comfortable option for many scientific psychologists and it has led some to treat research on PCT as a threat rather than an invitation. Still, I plan to keep holding the door open to closed loop psychology, though my arm is getting a bit tired. This talk will describe what I have done, to date, to try to convince scientific psychologists to take a step through that door into the world of closed-loop psychology.

Scientific Psychology of Open-Loop Systems

The fundamental dogma of scientific psychology is that human behavior is caused and that the way to determine the causes of behavior is to use the experimental method, which consists of manipulating an independent (or stimulus) variable (IV) and measuring its effect on a dependent (or response) variable (DV) under controlled conditions. This IV-DV approach to psychology is based on the assumption that the system you are studying is an open-loop or input-output system, where output (o, the DV) is a function of input (i, the IV): $o = f(i)$. The goal of this research is to determine whether or not particular inputs have an effect on particular outputs and, if so, what the nature of this effect is. This is "bread and butter" psychology, which is described in every introductory textbook. It is the psychology that I learned and then taught for over ten years as a professor of psychology.

PCT shows that the IV-DV approach to psychology makes sense only if the system you are studying is open-loop, one in which outputs depend on inputs and inputs *do not* depend outputs. But there is good reason to believe that living systems – such as people -- are actually closed-loop systems. Because of the way people are designed, with sensors sitting on a body that moves in response to what is sensed, it is easy to show that what people sense depends on what they do as much as what they do depends on what they sense. For example, what a fielder sees (input) when catching a fly ball depends on what the fielder does (output) as much as what the fielder does depends on what the fielder sees.

PCT shows that the closed-loop nature of living systems requires that we conceive of behavior in a new way: as the control of perception. PCT also shows that the IV-DV approach to studying behavior no longer makes sense when behavior is a closed loop process. This was the startling conclusion of a paper by William T. Powers that appeared in *Psychological Review* in 1978 (Powers, 1978), the paper that changed my life.

Spadework at the Foundations of Scientific Psychology

The IV-DV approach to studying behavior is the cornerstone – the foundation – on which scientific psychology is built. I knew that if this cornerstone were removed the entire edifice of scientific psychology would come tumbling down. Powers knew this too, as implied in the subtitle to his *Psychological Review* paper: *Some Spadework at the Foundations of Scientific Psychology.* If Powers were right about the inappropriateness of IV-DV methodology for the study of closed-loop systems it would invalidate scientific psychology as it currently exists. Given these implications, it seemed to me that the ideas expressed in Powers' *Psychological Review* paper should be given serious consideration and put to the test.

My first tests of PCT focused on the open-loop input- output model of behavior. I thought that if I could show that the open-loop model of behavior is wrong I could convince psychologists to look for alternatives to IV-DV psychology. My tests of the open-loop model were done using a simple tracking task, which makes it easy to see the relationships between the variables involved in behavior. The basic tracking task I used is illustrated in Figure 1. This is called a compensatory tracking task. The participant in this task is asked to keep the cursor aligned with a target (shown from the subject's point of view in the upper left corner of Figure 1). To do this, the subject must move a handle (or mouse) to compensate for a time varying disturbance that is "pushing" the cursor back and forth.

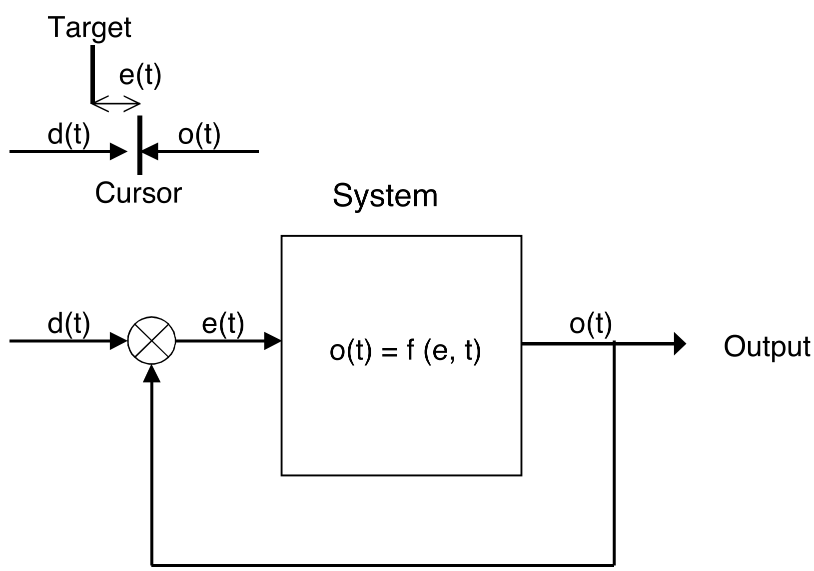

Figure 1. Input output model of basic compensatory tracking task.

What seems at first like the obvious explanation of how tracking occurs is that, at each instant, the distance between the cursor and the target-- called "error" in the tracking literature – causes or guides the response outputs that keep the cursor near the target. Time variations in error, e(t), are the inputs that must be the cause of time variations in output, o(t). So we would expect to see a very high correlation between e(t)) and o(t). But Powers (1978) showed that the correlation between e(t) and o (t) is very low (on the order of 0.0) as is the correlation between time variations in the disturbance, d(t), and e(t). But the correlation between d(t) and o(t) is very high (on the order of .99). A demonstration of this basic tracking task is available on the web at http://www.mindreadings.com/ControlDemo/BasicTrack.html. An example of the correlations between variables that are observed in this task is shown in Figure 2.

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d(t)  →  0.17 →e(t) → 0.08 →o(t)
|                            |
 -------------→ 0.99-----------→
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Figure 2. Example of correlations found between variables in a basic compensatory tracking task.

What is the cause of behavior?

The problem posed by the data in Figure 2 is that error is the variable that the participant can see; it's the input variable. But outputs – handle movements – are related, not to this input variable but, rather, to the disturbance, which is not visible to the person doing the tracking. The error variable – the combined result of disturbance and output -- is all that is seen in this tracking task. How can the outputs in a tracking task be guided by a variable (the disturbance) that can't be seen? The input-output model of behavior seems to break down in this closed-loop task. This is very bad news for the IV-DV approach to studying behavior.

I showed the results in Figure 2 to several colleagues when I first encountered it and the response was always that there *must be* something about the error that is guiding behavior. The idea that error was not the cause of behavior implied that the behavior – the handle movements that compensate for the disturbance and keep the cursor on target – occurred by magic. The mathematically sophisticated suggested that the low correlation between e(t) and o(t) resulted from the fact that it was not e(t) but, rather, some unknown function of e(t) that was causing the output variations. This seemed like a plausible possibility and led to my very first published experiment on PCT (Marken, 1980). This experiment tested the idea that the input-output model of tracking was correct and that the low observed correlation between input and output variations in this task resulted from the fact that it is an unknown function of the input, e(t), that is the actual cause of the outputs in a tracking task.

There are an infinite number of different functions of the error, e(t), that could be the variable that is the cause of the outputs in a tracking task. Instead of testing every possibility I took a different tack. The input-output model suggests that, if the same output variations occur on two occasions it must be because the same input variations occurred on those two occasions as well. And if the same input variations caused the outputs on the two occasions it must be because the same error variations occurred on both occasions, regardless of what the function is that transforms error into the input variable that actually causes the outputs. So I developed a tracking experiment where the same disturbance variations were repeated on two occasions. Since output variations are highly correlated with disturbance variations (see Figure 2) I knew that the same disturbance variations presented twice would produce the same output variations twice, and indeed, it does. Then I looked at the correlation between the error variations on the two occasions when the same output variations occurred. The correlation between error variations on these two occasions should have been very high – as high as the correlation between the output variations, which is typically close to .99. But what I found is that the correlation between error variations on the two occasions was typically quite low, less than .2. This test proved, it seemed to me, that there is no function of the error variations in a tracking task that can be considered the cause of the output variations.

A simulation of this "repeated outputs" experiment is available on the net at http://www.mindreadings.com /ControlDemo/Cause.html. An example of the kind of data found in the experiment is shown in Figure 3. The traces of the output variations (responses, R) in the first and second periods of the experiment (with the same disturbance in both periods) are nearly identical (the correlation between the traces is .995). The traces of the error variations (stimulus, S) on both trials are almost completely different (correlation between the traces is .17). Clearly, there is nothing about the error variations in the two periods that can account for the fact that the output variations are identical. These results, however, are completely consistent with a closed-loop model of behavior. It is possible to build a PCT control of input model that behaves very much like the subject in this experiment (as can be seen in the demo). That is, on repeated trials with identical disturbance variations, the model's response (output) variations on the two trials are nearly identical while stimulus (error) variations on the two trials are quite different.

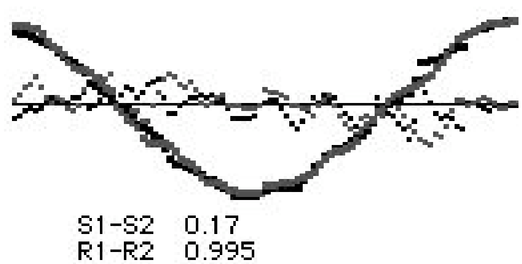

Figure 3. Results of repeated output experiment. Output variations (R1, R2) repeat though the error variations (S1, S2) are different. Clearly, there is no aspect of the error that can be said to be causing the outputs.

Mind Reading: The Test for the Controlled Variable (TCV)

I thought that the publication of this little experiment would cause some commotion in the scientific psychology community given its rather obvious implications for the foundations of scientific psychology. But scientific psychologists were unfazed and continued using the IV-DV approach to psychology, despite the distinct possibility that they were using it improperly to study the behavior of a closed-loop system. After publishing a couple more demonstrations of the fact that inputs do not cause the outputs of a closed-loop system I decided that the problem might be that psychologists didn't know what to do if they had to abandon the IV-DV approach to psychology. So I started to develop demonstrations of how psychologists might go about studying the behavior of closed-loop systems.

The first step in developing a psychology of closed-loop systems is to understand what closed-loop systems do. They *control*. That is, they vary their outputs, as necessary, to bring perceptual variables to pre-selected (reference) states and keep them in those states, protected from disturbance. The goal of research on closed-loop systems is to determine the nature of the perceptual variables that these systems are controlling. The method of determining what variables are being controlled by a closed-loop system is called the test for controlled variable or

TCV. The TCV is the alternative to IV-DV psychology. It is the basis for a psychology of closed-loop systems.

In order to introduce the TCV I thought I should first try to show why such a methodology is necessary. I wanted to show that the TCV is necessary because it is not possible to tell what a closed-loop system is doing by just watching its behavior. In order to tell what a closed-loop system is doing you have to determine what perception(s) it is controlling. And you can't do that using IV-DV methodology. You have to use the TCV.

The demonstration I developed (Marken, 1983; 1989) involved having a person move one of three different objects around on a screen using a mouse. The mouse actually influenced the movements of all three objects so that when one object was intentionally moved the other two objects moved as well. A diagram of the situation is shown in Figure 4. In this case the objects are squares of different sizes that move around a computer screen. If the intentionally moved square is moved in an arbitrary pattern it is impossible for an observer to tell, by looking at the movements of the three squares, which is being moved intentionally. Moreover, the person is free to start intentionally moving a different square at any time during the demo. It is again impossible for an observer to tell when such a "change of mind" has occurred. This demonstration creates a situation where you can't tell what a person is doing (what square is being moved intentionally) by simply looking at what the person is doing (moving all three squares).

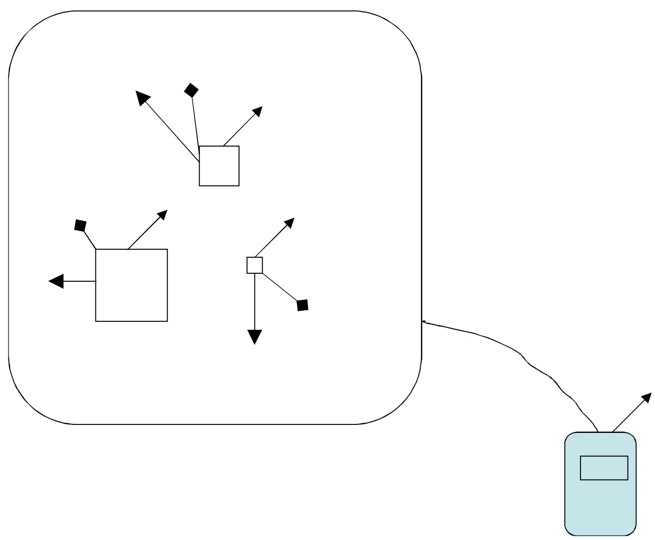

Figure 4. Display of the "mind reading" demonstration with 3 squares of different size as the objects whose movements on the screen can be controlled.

The computer *can* tell which of the three squares is being moved intentionally at any time by performing a version of the TCV. Figure 4 shows that the movement of all three squares is influenced in the same way by movements of the mouse (the small arrow) and in different ways by a disturbance (the large arrow). The resulting movement of each square (indicated by the line with a filled square at the end) is the combined result of both of these influences. The intentionally moved square is the one whose movement on the screen is being controlled. In order to control the movements of a square a person must compensate for disturbances that would move the square from its intended positions. To the extent that a person can successfully control the position of a square, the controlled (intentionally moved) square will not be strongly influenced by disturbances. This means that there will be a *low* correlation between movements of the intentionally moved square and the disturbances to that square. On the other hand, there should be a fairly high correlation between movements of the unintentionally moved squares and the disturbances to those squares because the person is not acting to prevent those disturbances from having an effect on the movements of the uncontrolled squares.

A version of this demonstration of the TCV is available on the net at http://www.mindreadings.com/ControlDemo/ThreeTrack.html. I call it the "mind reading" demonstration because, as Bill Powers once said, the TCV "is the closest thing I know to mind reading" because it reveals intentions (which are mental phenomena) that may not be obvious in overt behavior (as in this demonstration).

Modeling Complex Behavior

Again, despite what seemed to me to be a very compelling demonstration of the need to use the proper methods to study closed-loop systems, scientific psychologists remained unimpressed and continued with their research aimed at determining the causes of behavior (assuming an open-loop system) using IV- DV methodology. I thought this might be because my examples used behavior, like the tracking task, that seemed too simple. So I next tried to develop some demonstrations of closed-loop behavior that were more complex because they involved controlling two perceptual variables simultaneously. I billed these experiments as studies of coordinated action because, in order to control two inputs simultaneously, the participant must produce outputs in two dimensions simultaneously. These outputs must be perfectly coordinated in order to keep the inputs under control.

One of these studies of coordinated action (Marken, 1991) involved a two-dimensional tracking task where the participant was to keep the cursor aligned with the target in both the horizontal (x) and vertical (y) dimension. The cursor was disturbed in both the x and y dimensions so the participant had to move the mouse appropriately in two dimensions simultaneously in order to compensate for the disturbances and keep the cursor on target. Of course, the participant was able to do this task, even when actions in one dimension were a disturbance to the position of the cursor in the other dimension.

The point of the demonstration was to show that several control systems could act simultaneously to control several inputs without getting into conflict. The demonstrations also illustrated the important role of modeling in the study of the behavior of closed-loop systems. The current approach to modeling in psychology uses statistical analysis, which is based on an open-loop, input-output model called the general linear model. This model is tested every time an IV-DV experiment is performed. The fit of the model to the data is evaluated in terms of the proportion of variance in the output variable that is "explained" by the variance in the input variable. An IV – DV experiment is considered a great success if the input variable(s) explain more than 40% of the variance in the output variable.

The PCT approach to modeling closed-loop systems is not statistical. Closed-loop models are dynamic (they produce behavior that varies over time) and the fit of the model is measured in terms of how closely the model behavior matches the observed behavior. That is, goodness of fit is measured in terms of the proportion of variance in the observed behavior that is accounted for by the model behavior. My studies of coordinated action show that closed-loop models of complex behavior -- behavior that involves actions that vary in two or more dimensions -- fit the data quite well. The PCT model of coordinated behavior typically accounts for well over 97% of the variance in the complex behavior observed in my experiments on multi-dimensional control (Marken, 1991)!

Real Behavior

The modeling of complex behavior – like the demonstrations that behavior is not open - loop and that the TCV is the only way to know what an organism is doing (controlling) – did not coax scientific psychologists away from the use of IV-DV research. So I thought that perhaps the problem was that my demonstrations of the need for a closed-loop psychology were done in an artificial environment, mostly on a computer screen. So my latest approach to getting the attention of scientific psychologists has been to try to show how closed-loop psychology could be used to understand real behavior -- the behavior that occurs in real life situations. My work in this area has focused on two very different but very real behaviors: catching fly balls and making errors when prescribing medications.

Catching Fly Balls. My interest in how people catch fly balls was stimulated by an article that appeared in *Science* (McBeath et al, 1995), which was aimed at determining what fielders are seeing when they catch balls. This work was interesting because it seemed to recognize that catching involved the control of a perceptual variable. The researcher placed video cameras near the fielder's eyes and recorded what the fielder saw as well as how the fielder moved during each catch. I developed a PCT-based model of catching that fits the data obtained by these researchers quite well (Marken, 2001). The model catches fly balls by controlling two optical variables: vertical optical velocity and lateral optical displacement. A demonstration of the model is available on the web at http://www.mindreadings.com/ControlDemo/CatchXY.html.

Prescribing Error. While working at the RAND Corporation on healthcare safety issues I developed a framework for understanding why highly skilled individuals, such as physicians, occasionally make errors when performing tasks at which they are quite skilled, such as writing prescriptions (Marken, 2003). The framework, which, of course, is based on PCT, views a skill such as prescription writing as a control process. Prescribing errors occur on the rare occasions when this process is interrupted. The controlled perception (the prescription) is "close enough" to the reference specification, from the writer's point of view but not close enough to produce a prescription that is correct from an observer's point of view. The framework makes it possible to determine which aspects of the prescription writing process are likely to have the greatest effect on error rates. One surprising result of this modeling effort was the discovery that environmental disturbances, such as look alike/sound alike drug names are expected to have very little effect on prescribing error rate when the error rate is already low. This result is surprising because it contradicts a basic tenet of the field of human factors engineering – a field in which I have also worked. Human factors engineering is based on the premise that the main cause of human error is environmental disturbance in the form of poor system design (such as a poorly designed medication naming system, which gives similar names to very different medications). A control model shows that such environmental disturbances cannot be a major contributor to error when error rates are low because, the fact that error rates are low means that the control process is already effectively compensating for these disturbances.

Next Steps

My ultimate goal in life is to be a force for change in scientific psychology. I want to change the way scientific psychologists do their business. I want to move scientific psychology from a discipline aimed at the study of open-loop systems to a science aimed at understanding the behavior of closed-loop systems. I am again going to try to do this from inside the educational establishment which I left over 20 years ago when I realized that what I was learning about behavior from PCT was inconsistent with what I was supposed to teach students about behavior based on the information in their textbooks (one of which I myself had written). But I think I would like to start teaching again. I would like to teach students of scientific psychology how to study the closed-loop systems that people actually are.

Changing scientific psychology from inside the educational establishment will not be easy. There are curriculum requirements and textbooks geared to meet these requirements. It will be necessary to teach students IV – DV psychology before I can teach them what's wrong with it. It will be difficult to offer a regular class that is dedicated to the study of closed-loop psychology. There is currently no curriculum requirement for such a course. Nor are then any texts for such a course because there is no market for them. The inertia in the academic establishment is overwhelming. Maybe the door to closed-loop psychology can only be opened in a new world – such as in the US many years from now or, perhaps, in China today.

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