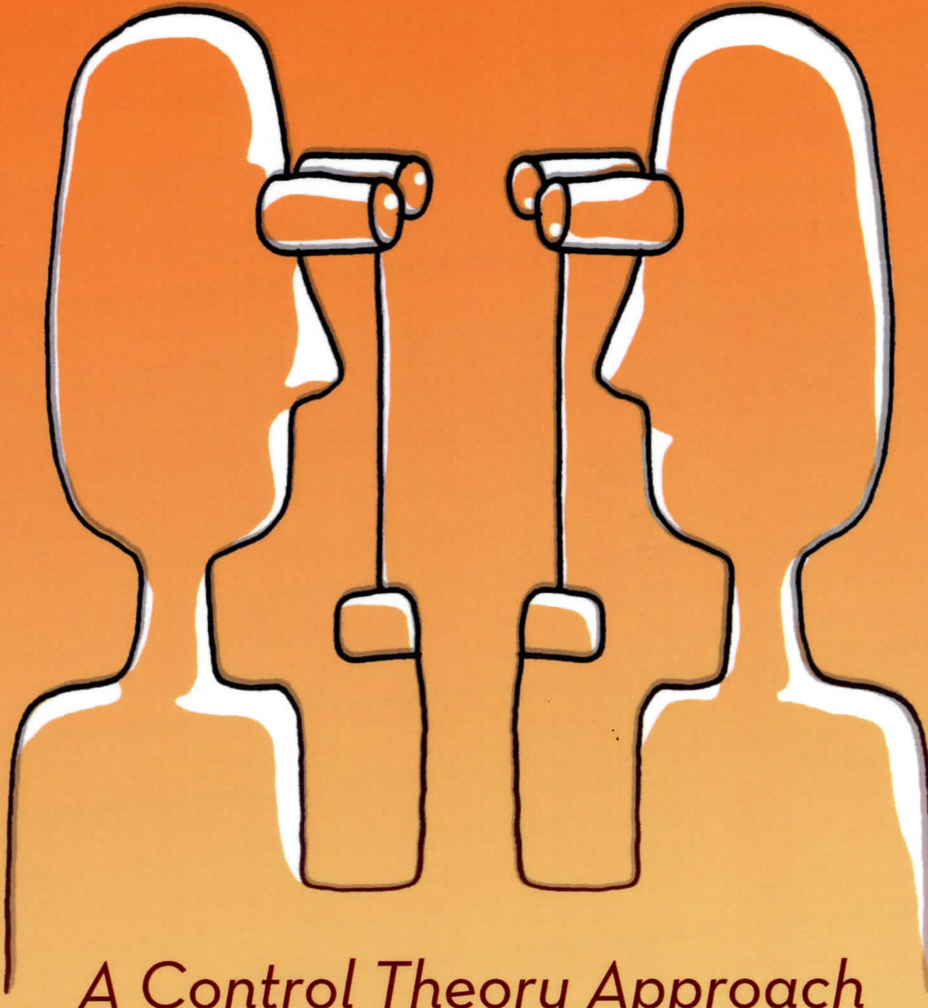
DOING RESEARCH ON PURPOSE



A Control Theory Approach to Experimental Psychology

Richard S. Marken

The title of this book refers to the somewhat paradoxical situation of the experimental psychologist. Such psychologists are living organisms who have the purpose of studying the behavior of other living organisms whose behavior is as purposeful as their own. They are "doing research on purpose" in both senses of that phrase; purposefully doing research on behavior that is purposeful.

"Richard Marken has for decades been one of the foremost interpreters of Perceptual Control Theory. The collection of his articles in Doing Research on Purpose includes an excellent selection of his classic articles on PCT and also several recent articles destined to become classics in the field. This book is essential reading for anyone who wants to gain a deep understanding of PCT and the radical challenge it poses for business as usual in experimental psychology."

Kent McClelland
Professor of Sociology
Grinnell College

"Dr Marken's ingenuity and skill as a pre-eminent researcher of living control systems is splendidly showcased in this compendium of his work. Marken's rigorous experimental work, meticulously explained in this collection of papers, has profound implications for research activity in the life sciences. This book will be an invaluable resource for researchers in the life sciences who are seeking to improve the accuracy and precision of their work and understand more clearly the nature of living systems."

Professor Tim Carey PhD, MAPS
Deputy Director, Head of Research
Central Australian Mental Health Service

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DOING RESEARCH ON PURPOSE

Also by Richard S. Marken

MIND READINGS: Experimental Studies of Purpose

MORE MIND READINGS: Methods and Models in the Study of Purpose

Dedicated to

William T. Powers

(1926 – 2013)

Teacher and Friend

In memory of his remarkable contributions to our understanding of the nature of purposeful behavior

In this groundbreaking collection of papers, Marken presents a devastating critique of methodology within contemporary behavioral sciences. Yet in its place he provides the methodological key to unlock the potential of an alternative theoretical perspective - that of Perceptual Control Theory. This volume complements, extends and advances Marken's earlier books to form the third pillar of support for the theory in its journey into mainstream science.

Warren Mansell
Reader in Clinical Psychology
University of Manchester, UK.

DOING RESEARCH ON PURPOSE

A Control Theory Approach to Experimental Psychology

Richard S. Marken

A MindReadings.com Book

new view

St. Louis, MO

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Contents

Foreword

This book is the third collection of papers from Richard Marken. Together these three volumes represent a body of scientific work that has secured their author a permanent place in the history of psychology, a unique distinction among living psychologists.

I urge readers to read this book, above all because it is a valuable introduction to the science of psychology. My emphasis is on the word science because in traditional psychology what you find is not so much science as a promise of a science. But if you wish to learn what a mature science of psychology is like and how it can help you achieve an understanding of the behavior of living organisms, yourself included, then this book is a good place to start.

Some may wonder why after so many centuries psychology as a science is still not quite ready to be launched. The answer is found in this book. As Marken explains, psychologists have unwittingly strayed from the right path by abandoning the study of purpose. Over a century ago the idea that behavior is purposeful was still popular. But although these early psychologists, such as William James, had the right intuitions about purpose, they did not understand it well enough to launch a true science. Marken's aim in this book is to provide the understanding they lacked. The foundation of this understanding is Perceptual Control Theory (PCT), a model of purposeful behavior first proposed by William T. Powers. PCT provides a scientific explanation of folk psychological notions of purpose in terms of a hierarchy of negative feedback control systems. Psychology, thus, is shown to be a teleological science – a science of purpose – as rigorous as the non - teleological sciences of physics and chemistry.

Some might object to the claim that psychology has neglected purpose since the term "purpose" (or related terms like "goal" and "intention") appears in the titles of many publications in the field. As Marken shows in this book, however, psychologists typically use these teleological terms incorrectly and informally, with no description of what they refer to or how they might work. The papers in this book describe what goals, intentions, and purposes are in terms of observable behavior and explain how they work using quantitative working models of purposeful behavior.

In restoring purpose Marken has also restored the other concept missing in psychology—the individual. Of course traditional psychologists would often pay lip service to the individual. But as soon as we read any article in psychology carefully the individual disappears as the statistical average emerges. If the individual ever appears it is in the idealized form of the group average, a Gaussian person whom nobody has ever met before.

The challenge to any true individualistic psychology is to develop a scientific method, just as rigorous as those in the physical sciences, that does not rely on averaging across individuals. How can we use a single subject as the basis of a science? How can we make statements about individuals that are always quantitative but not statistical? Again this book offers the answers. Marken explains the test for the controlled variable and the method of modeling, tools that can be applied to individuals—and actually predict the details of the individual's behavior with great accuracy. I believe the experiments that Marken describes here are similar to the experiments using pulleys and inclined planes from the early days of physics. In the future they will become standard classroom demonstrations in a psychology laboratory course.

One day, I hope in the not too distant future, the methods introduced here will become standard practice in experimental psychology. Future readers will look upon everything described in the papers herein as obvious and correct, perhaps even with the boredom that school children today associate with balls rolling down inclined planes. But future generations might not remember how such work was accomplished or the price paid for independent thinking. What might not be apparent to them is a story of courage. For although it is only natural for the current generation to accept that the earth is round, it was not always so.

Imagination is needed to appreciate the courage needed to say that the earth is round for the first time, when all around you say it is flat. It is with such courage that Marken has produced the work included in this book, laboring in obscurity and against the prevailing dogma of our time. Future generations will face new challenges, and once in a while courage will again be required to defy the compact majority. On such occasions, I hope some will also find inspiration in the remarkable intellectual journey documented in this book.

Henry Yin
Duke University
December, 2013

Introduction

The title of this book refers to the somewhat paradoxical situation of the experimental psychologist. Such psychologists are living organisms who have the purpose of studying the behavior of other living organisms whose behavior is as purposeful as their own. They are "doing research on purpose" in both senses of that phrase; purposefully doing research on behavior that is purposeful. Yet experimental psychologists have carried out their research purposes as though the behavior they study is not as purposeful as their own. Indeed, experimental research in psychology is based on a model that assumes that behavior has causes but no purposes; the apparent purposefulness of behavior is either ignored or treated as an illusion.

But the behavior of organisms is, indeed, purposeful, a fact that many experimental psychologists claim to be aware of even though their approach to research suggests otherwise. The feeling among these psychologists seems to be that simply being aware of the purposeful nature of behavior is a sufficient basis for saying that one is taking purpose into account in one's research. This book can be considered a rebuttal to this point of view. The papers collected together here have one central theme: It is not enough to simply be aware of the purposeful nature of behavior in order to properly do research on purpose; one also has to know what purposeful behavior is and how it works. Once this is known, research on purpose will be done in a way that is rather different than the way most research in experimental psychology is currently done. In particular, the focus of research will be on determining the purposes rather than the causes of the behavior under study.

A scientifically rigorous description of what purposeful behavior is and how it works was given by William T. Powers in his classic book *Behavior: The Control of Perception* (Powers, 1973). Powers makes a convincing case for viewing purposeful behavior as equivalent to the phenomenon of control since both involve the production of intended (goal) results in the face of unpredictable (and often undetectable) disturbances. Powers goes on to show how control theory – the theory of how control works – can be used to explain how purposeful behavior works. When applied to the purposeful behavior of living organisms, control theory has come to be called Perceptual Control Theory (PCT) to emphasize the fact that what living organisms control is their perceptual input, not their behavioral output.

Powers discussed the implications of PCT for experimental psychology in only one short chapter of *Behavior: The Control of Perception*. He later published a more detailed discussion of the topic in *Psychological Review* (Powers, 1978), a journal that was (and probably still is) regarded as the premier journal of scientific psychology. It was this article that sparked my own interest in the experimental study of purpose and led me to do the research that is described in the papers collected in this book. Thus, this book can be considered an elaboration of the main argument of that *Psychological Review* article: that an understanding of purposeful behavior as a process of control requires a new approach to doing experimental research in psychology.

Control Theory Psychology

The first section of the book contains two papers that describe the PCT approach to understanding purposeful behavior. The first, *Looking at Behavior through Control Theory Glasses*, describes the control theory view of purposeful behavior as a process of control. It gives several examples of behavior that demonstrate what control is and how it can be seen in the behavior of living organisms.

The second paper in this section, *Taking Purpose into Account in Experimental Psychology*, gives a fairly detailed description of the PCT model of control (purposeful behavior) as it applies to experimental psychology and introduces the central concept of this model: the *controlled variable*. A controlled variable is a perceptual aspect of the environment that the behaving system is acting to bring to a pre-selected or goal state. Controlled variables are the attributes of behavior that are missed by approaches to research that ignore purpose. But they are the central focus of research based on PCT: research on purpose.

Looking for the Purpose of Behavior

The papers in the next section of the book describe the basic methodology used to study purpose as control. This methodology, called the Test for the Controlled Variable or TCV, is aimed at determining the perceptual aspects of the environment – the controlled variables – around which purposeful behavior is organized. The first paper in this section, *Making Inferences About Intention: Perceptual Control Theory as a "Theory of Mind" For Psychologists*, describes the basic logic of the TCV and an experimental approach to carrying it out.

The next paper in this section, *Testing for Controlled Variables: A Model-Based Approach to Determining the Perceptual Basis of Behavior*, describes an approach to doing the TCV that is based on the use of computer simulations – models – to evaluate the results of experimental studies of purpose when the identification of controlled variables cannot be made using experimental manipulations alone.

The last paper in this section, *Optical Trajectories and the Informational Basis of Fly Ball Catching*, shows how the TCV can be used to determine the controlled variables around which a more "ecologically valid" behavior – object interception, in the form of catching fly balls – is organized.

Illusions and Confusions

Perhaps the main reason experimental psychologists have felt comfortable doing research in a way that ignores purpose is because this kind of research seems to work. In a successful psychology experiment, variations in the experimental conditions – the independent variable – appear to cause concomitant variations in behavior – the dependent variable. Results like these provide what appears to be convincing evidence that behavior is ultimately caused by the circumstances in which it occurs; purpose does not seem to be involved at all. The PCT model of purposeful behavior suggests that the apparent causal relationship between circumstance (independent variable) and behavior (dependent variable) seen in psychological experiments is likely an illusion (Powers, 1973a). The nature of this illusion, what Powers called the *behavioral illusion*, is explained in the next section of the book.

The first paper in this section, *The Illusion of No Control: A Perceptual Bias in Psychological Research*, explains the nature of the behavioral illusion and why it occurs. The illusion is that behavior is caused; that there is no purpose (no control) involved. It results from paying attention to only one aspect of control – the actions (dependent variables) that protect controlled variables from disturbances (independent variables) – while ignoring the controlled variables themselves.

The next paper in this section, *The Power Law: An Example of a Behavioral Illusion?*, describes a quantitative example of one aspect of the behavioral illusion; the fact that, in a control system, the form of the function relating independent to dependent variable reflects characteristics of the feedback connection between an organism's output and its input rather than characteristics of the organism itself.

The last paper in this section, *Control Theory for Whom*, is a review of a book that describes a control theory-based approach to understanding behavior yet succumbs to the illusion that purposeful (control) behavior can be studied by looking for causal relationships between independent and dependent variables.

A Methodological Revolution.

Clearly, PCT represents a very new approach to experimental psychology. Some would say it is revolutionary. But unlike previous revolutions in psychology – and there have been several, the latest having been the so-called "cognitive revolution" – the PCT revolution requires not only a new way of understanding behavior but also a new way of studying it. PCT implies that there must be a methodological as well as a theoretical revolution in psychology if the nature of purposeful behavior is to be properly understood. This is the subject of the two papers in the next section of the book.

The first paper in this section, *You Say You Had a Revolution: Methodological Foundations of Closed-Loop Psychology*, discusses why PCT requires a new approach to psychological research. It also discusses the difficulties this has presented for the development of a science of purposeful behavior based on PCT. These difficulties stem mainly from the existence of the huge edifice that is the scientific psychology "establishment" consisting of the textbooks, curricula and intellectual capital which support an approach to studying behavior that ignores its purpose. Tearing down and rebuilding this edifice will not happen overnight but this paper suggests steps that might be taken to start the process.

The other paper in this section, *Methods, Models and Revolutions*, is a comment on an article that described an analytical revolution that was occurring in psychology. My reply simply makes the distinction between an analytical revolution, which doesn't change the way psychological research is done, and a methodological one, which does. And, again, I argue that what psychology needs is a methodological as well as an analytical (theoretical) revolution in order to approach the study of purposeful behavior properly.

The Future of Experimental Psychology

In the final section of the book I allow myself to muse about what experimental psychology might look like once the accepted view is that behavior is purposeful and that the aim of research in psychology is to understand how purposeful behavior works. The paper, *Looking Back over the Next Fifty Years of Perceptual Control Theory*, was presented at a Festschrift for Bill Powers on the thirtieth anniversary of the publication of *Behavior: The Control of Perception*. It was based on the pessimistic assumption that it could take another fifty years until the PCT view of behavior becomes the default view of the nature of behavior and how it works. Ten years have passed since I presented that paper and in that time there have been many positive developments in PCT science – the science of purposeful behavior – not least of which is the addition to the PCT "team" of several very competent young researchers. So I now have hope that it will be considerably less than 40 years until there is a critical mass of experimental psychologists who are "Doing research on purpose".

Control Theory Psychology

1 · Looking At Behavior through Control Theory Glasses[1]

Abstract – Behavior is always seen through the theoretical preferences of the observer. These preferences act like different prescriptions for glasses. The most popular glasses use the causal theory prescription, through which an organism's behavior appears to be the result of external or internal causes. This article describes glasses that use the less familiar control theory prescription, through which behavior looks like the organism's purposeful efforts to control its own perceptions. The consequences of looking at the same behavior through these different "glasses" are demonstrated by comparing examples of real life behavior to the behavior of computer simulations that are available on the Internet. A method is described which makes it possible to determine which "glasses" give the best view of any particular example of behavior.

Psychologists try to understand the mind by looking at behavior, including the behavior of the brain and nervous system. Scientific psychologists do this by looking at behavior in carefully controlled experiments. Clinical and counseling psychologists do this by looking at behavior in various kinds of interpersonal interactions (therapies). Psychologists look at behavior in order to get an objective view of the mind, one that allows inter-observer agreement about what an organism is doing (Mitchell, 1979; Page and Iwata, 1986). For example, psychologists might not be able to agree about what is on a chess player's mind when a pawn is moved from one square to another but they should be able to agree that

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1 Reprinted from Marken, R. S. (2002) Looking at Behavior through Control Theory Glasses, *Review of General Psychology*, 6, 260–270 with permission of the American Psychological Association.

the pawn was, indeed, moved. But such inter-observer agreement has proven to be elusive in practice. The same behavior can look quite different to different observers, leading to different conclusions about the nature of the mental processes that produced it. What looks like "moving a pawn" to one observer may look like "protecting the knight" to another.

Ambiguous Behavior

The fact that the same behavior can look different to different observers is not surprising when we realize that behavior can be no more objective than anything else we perceive. Behavior is a perception because it can only be experienced via our senses. Moreover, behavior is an ambiguous perception, like the famous "young woman/old woman" picture shown in Figure 1.

Figure 1. "Young woman/old woman" ambiguous figure.

In ambiguous perception, what we know to be the same physical situation can be experienced in two or more distinct ways. In the case of the "young woman/old woman" picture, the very same set of lines drawn on paper can be seen as a beautiful young woman facing away from the observer or an unattractive old woman seen in semi-profile. We are looking at the same picture – the same set of lines – in both cases. All that changes is what we perceive.

The same kind of perceptual ambiguity occurs when we are looking at behavior: we can see what we know to be the same behavior in at least two different ways. A behavioral analog of the "young woman/old woman" picture can be seen by asking a friend to keep a fingertip aligned with yours as you move your finger randomly about. There are at least two ways to see your friend's behavior in this situation. You can see your friend's finger movements as being caused by your finger movements or you can see your friend's finger moving with the purpose of staying near your finger. One perception, the one favored by scientific psychologists, is of behavior as caused (Marken, 1988). The other perception, the one that is apparently favored by most lay people, adults and children, is of behavior as purposeful (Gelman et al., 1995; Gergeley et al., 1995; Premack, 1990).

Through a Glass, Behaviorally

The way we resolve perceptual ambiguities depends, to a great extent, on what we expect to perceive (Bruner and Postman, 1968). If we expect to perceive an attractive young woman, then we will tend to see the "young woman/old woman" picture as the "young woman," at least at first glance. Similarly, if we expect to perceive a reaction to stimuli, then we will tend to see our friend's finger movements as a reaction to our own, at least at first glance.

In psychology, expectations about how behavior is perceived are embodied in the theoretical preferences of the observer. These preferences act like different prescriptions for glasses. It is as difficult to see our own theoretical preferences as it is to see the prescriptions for the glasses we are wearing, but these preferences, like the glasses, do influence the way we perceive behavior. Psychologists have used two importantly different prescriptions that have influenced what they see when they look at behavior. These can be called the *causal theory prescription* and the *control theory prescription*.

The causal theory prescription. The causal theory prescription reflects a theoretical preference to see behavior as caused by internal (mental) or external (stimulus) events. When behavior is seen through causal theory glasses, it looks like "a show put on for the benefit of the observer" (Powers, 1978) rather than as something the organism is doing for its own sake. The show seen through causal theory glasses consists of a pattern of actions, such as movements of the mouth and tongue, and the results of those actions, such as sharp words, that occur because they are caused by events that are inside or outside of the organism.

The causal theory prescription was first used by psychologists of the behaviorist persuasion whose theoretical preferences inclined them to believe that all behavior is caused by external (stimulus) events. So an early result of looking at behavior through causal theory glasses was an approach to understanding behavior called stimulus-response (S-R) psychology, where behavior was seen as a response to external stimulation. But other scientific psychologists, including cognitive scientists, now use the causal theory prescription as well (Bargh and Ferguson, 2000). The cognitive revolution produced a "bifocal" version of causal theory glasses, making it possible to see behavior as being caused by either external *or* internal events. But the basic prescription is still the same: behavior is seen as the last link in a causal chain that begins in the world outside the organism (with stimuli, cues or situations, according to behaviorists) or in the mind inside the organism (with plans, schema or programs, according to cognitive scientists).

The control theory prescription. The control theory prescription reflects a theoretical preference to see behavior as purposeful. When behavior is seen through control theory glasses, it looks like the organism's efforts to produce results for its own sake, on purpose (Marken, 1992). The control theory prescription focuses on the fact that organisms vary their actions in whatever way is necessary in order to produce intended results and protect those results from unpredictable and often undetectable environmental disturbances, a process called control (Marken, 1988). Since the results produced by a control process are known to the organism only as perceptions, the behavior seen through control theory glasses appears to be the control of perception (Powers, 1973). This observation provides the fundamental basis for distinguishing the control from the causal theory view of behavior. Causal theory views internal or external events as the cause of behavioral output. Control theory views internal purposes as specifications for perceptual input.

The control theory prescription made an early appearance in the purposive psychology of Tolman (1932). Tolman saw that animals would vary their actions as necessary in order to produce particular results on purpose. For example, Tolman saw that a rat that would run to get food in a goal box would also swim to the same goal box if the maze were filled with water. The rat seemed to have the purpose of getting to the goal box and would do what was necessary to get there. Some psychologists besides Tolman, particularly those influenced by the development of cybernetics (Wiener, 1948; Powers, Clark and McFarland, 1961), have looked at behavior through control theory glasses. But the dominant prescription in psychology has been and remains the causal theory prescription.

Philosophers of mind who talk about behavior in terms of purpose or intention (Dennett, 1989, Searle, 1986) seem to be looking at behavior through control theory glasses. But a closer look reveals that the purpose under discussion is being interpreted in terms of a causal model of behavior. The purpose described by these philosophers, whether it is called an internal program or a rational expectation, is an internal cause of output, not a specification for input. Behavior that is called "purposeful" or "intentional" is not necessarily behavior that is seen though control theory glasses. Behavior seen through control theory glasses looks like (and is described as) controlled input, not caused output.

Mother Goose

The consequences of looking at behavior through different theoretical preferences – through "glasses" using different prescriptions – can be illustrated by looking at some examples of behavior and comparing what you see to what psychologists have said they see when looking at the same behavior. One classic example of behavior that has been carefully described by psychologists is the egg-rolling behavior of the greylag goose. You can see this behavior for yourself in a short video segment that is available on the Internet[2]. A still from the video is shown in Figure 2.

The video begins with a goose rolling an egg into her nest. This is followed by another shot of the egg rolling behavior but this time a researcher removes the egg just after the rolling begins, as shown in Figure 2. The Nobel Prize winning ethologists Lorenz and Tinbergen (1938) give a classic description of this behavior. What they describe seeing is a "fixed action pattern". The egg rolling seems to consist of a pattern of neck movements which, once begun, are carried out whether or not the egg is actually being retrieved. If the egg slips away or is taken away by an experimenter

2 QuickTime video of greylag goose egg rolling behavior is available at: www.pigeon.psy.tufts.edu/psych26/images/gray.MOV

during the course of the action the goose does not stop its action but completes it instead, exactly as it occurs when the egg is present. So it looked to Lorenz and Tinbergen as if the goose's behavior were caused by what would now be called an internal program for action – a motor program. Once the program starts, it continues to run off in a fixed pattern until completion.

Figure 2. Greylag goose in the process of continuing egg rolling movements after egg is removed.

Lorenz and Tinbergen saw the goose's behavior as a fixed action pattern because they were looking at behavior through causal theory glasses. Indeed, they were looking through the cognitive version of these glasses since they saw the cause of the goose's behavior as being inside the goose. When you look at the Internet video I think you will find it easy to see the goose's behavior just as Lorenz and Tinbergen saw it. Indeed, it might be hard to imagine any other way to see this behavior. But let's take a look at the video again, this time through control theory glasses.

When you look at the goose's behavior through control theory glasses you see the goose trying to produce a perception for herself.

But what perception could the goose be trying to produce? If we try to experience the situation from the goose's perspective then we can see that one perception being produced by the goose is the feeling of pressure from the egg against the back of the bill. Indeed, all the goose knows of the egg, once it starts rolling it, is the pressure on the bill. The goose can't see the egg at all. Rolling the egg into the nest, from the goose's perspective, means keeping the sensed pressure of the egg centered against the back of the bill. This is done by arching the neck around the egg and drawing back toward the nest, thus pushing the egg up against the back of the bill.

What happens when the egg is removed looks very different through control theory glasses than it did through causal theory glasses. Through control theory glasses the continued movements of the neck are not the continuation of a fixed action pattern but an attempt to restore pressure against the bill from the now non-existent egg. The goose acts like a control system would act if its actions suddenly had no effect on the intended result of those actions. You can illustrate this for yourself by performing a simple tracking task that is available on the Internet[3]. In that task you try to keep a cursor aligned with a target by moving the mouse appropriately. The cursor is analogous to the egg and the target is analogous to pressure on the back of the bill. Movements of the mouse that keep the cursor on target are analogous to neck movements that keep pressure on the back of the bill.

At some point during the tracking task the connection between mouse movements and the cursor is surreptitiously broken; actions

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3 A demonstration of continuation of action ("fixed action pattern") when connection between action and result is removed is available at: www.mindreadings.com/ControlDemo/Goose.html

no longer have an effect on the intended result. This is analogous to removing the egg during rolling; actions (neck movements) no longer have an effect on the intended result (pressure on the bill). What happens in the tracking task is exactly what happens in egg rolling. When the action is no longer effective it doesn't just stop; rather it continues in a way that would produce the intended result if the action still had an effect on that result. This is shown in the graph of the results that is plotted at the end of a tracking trial. The graph shows mouse movements continuing on after they no longer have an effect on the cursor, in a futile effort to produce the intended result: cursor on target.

Three's a Flock

The greylag goose's egg rolling behavior looks like a "fixed action pattern" through causal theory glasses and an attempt to maintain pressure against the bill through control theory glasses. A more familiar kind of bird behavior provides another opportunity to compare the view through these two different types of glasses; it is the behavior of a flock of birds.

Flocks of birds are a familiar and beautiful sight. The birds fly in various patterns including the familiar wedge, with one bird in the lead and the rest following behind. When we look at this wedge of birds through causal theory glasses it looks like the movements of each bird, other than the one in the lead, are caused by the bird in front of it. When the lead bird moves left it seems to cause the birds behind it to move left; when it moves right it seems to cause the birds behind to move right. A flock looks like a stimulus-response (S-R) phenomenon: movements of the birds in front are the stimuli that cause the movements of the birds behind.

Many computer models of flocking behavior have been built on the assumption that each bird is an S-R device, like the vehicles designed by Braitenberg (1986). Braitenberg vehicles have sensor inputs (S) connected by rules to motor outputs (R). The birds in animated computer simulations of flocking behavior are often described as though they were this kind of S-R vehicle, with the rules connecting S to R being quite complex (Wilhelms and Skinner, 1990). These S-R models of flocking birds, sometimes called "boids" (Reynolds, 1987), are clearly based on a concept of behavior that comes from looking at flocking birds through causal theory glasses. A computer model of flocking boids can be seen in action on the Internet[4].

Through control theory glasses flocking looks like each bird's attempt to produce a particular perceptual result for itself: to keep a constant distance between itself and the birds in front of it. This is a very different view of flocking behavior and computer models based on this view assume that each bird in the flock is a control system rather than an S-R device. The organization of a control system is quite different than that of an S-R device. In particular, a control system doesn't respond to stimuli. Rather, it acts to keep some perceptual aspect of the world in a reference state, protected from disturbances.

A computer model of flocking that is based on the assumption that the individuals in the flock are control systems is known as the CROWD program (McPhail, et al., 1992). This program can simulate a crowd (flock) of up to 255 individuals moving around on a field. The individuals will follow other individuals at a specific distance while maintaining a specific direction and avoiding collisions with each other and with stationary obstacles. Each individual in the simulation contains up to six simple control systems,

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4 A simulation of "boids" flocking is available at:
www.red3d.com/cwr/boids/

each controlling perceptions such as their distance to neighbors and obstacles and their direction relative to a target destination.

The CROWD program can be seen in action by downloading it from the Internet and running it on a PC or PC compatible[5]. You will see that the behavior of the individuals in this control theory model of flocking is just as realistic as is the behavior of the individuals in the S-R models of the same behavior. Indeed, a close look at the S-R models shows that they are actually control systems in disguise. This is because the S-R models exist in a closed loop relationship with respect to the environment in which they act. In a closed loop, S causes R while, at the same time, R causes S. A closed loop is also called a feedback loop because the effects of responses (R) are fed back as effects on the causes (S) of those very responses. The feedback in this loop is negative when responses tend to cancel out the stimulus cause of those responses. This is the case with the S-R bird models. Because they exist in a negative feedback loop, these so-called S-R models are actually negative feedback control systems (Marken, 1993). They are controlling the perception of the stimulus (S), maintaining it at some constant value.

Say Hey Willie

The difference between causal theory and control theory glasses works on the behavior of people as well as that of birds. One of the interesting things people do is play baseball. One of the great events in baseball history was Willie Mays' famous miracle catch made in the 1954 World Series. This catch is available as a video

5 The CROWD simulation program can be downloaded for PC compatibles from: www.livingcontrolsystems.com/demos/tutor_pct.html. Download the file crowd_win.zip from that page. The file also contains documentation describing how the model works.

on the Internet[6]. When you look at this catch through causal theory glasses it looks like Willie's movements are caused by internal mental calculations. He seems to be mentally predicting the path of the ball, anticipating where the ball will land and calculating the speed and direction in which he should run in order to get to the ball. Models of baseball catching often assume that such predictive calculations are, indeed, required for successful baseball catching (Tresilian, 1995).

When you look at the same catch through control theory glasses things again look quite different. It looks like Willie is trying to control some perception of the current state of the ball rather than calculating the movements that will get him to where the ball will be in the future. But what perception might Willie be controlling? In fact, several possibilities have been proposed but the most likely may be the one originally proposed by Chapman (1968): the optical velocity of the image of the ball on the eye. The idea is that the fielder catching a ball moves toward or away from home plate so as to keep the image of the ball rising at a constant rate relative to the background. Similarly, the fielder moves left and right so as to keep the image of the ball from moving horizontally with respect to the background.

A model of baseball catching that is based on the view through control theory glasses is available as a Java simulation on the Internet[7]. Like Willie Mays in the film clip, the simulated fielder keeps his "eye on the ball" while it is in flight. The simulated fielder gets to the ball by controlling the optical velocity of the image

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6 A YouTube video of Willie Mays' miracle catch in the 1954 World Series is available at: www.youtube.com/watch?v=1vrsg_-dV7Q

7 A simulation of a baseball outfielder catching fly balls is available at: www.mindreadings.com/ControlDemo/CatchXY.html

of the ball relative to the background. After the catch is made, the simulation shows a graph of what the catch looks like from the fielder's perspective. The fielder's view while catching several different fly balls is shown in Figure 3. The graph shows the nearly straight paths of the image of the ball that are seen by the model fielder who is controlling the horizontal and vertical velocity of the image of the ball relative to the background. These visual paths correspond to the paths seen by real fielders who caught fly balls while carrying a shoulder mounted video camera to record what they saw (McBeath et al., 1995).

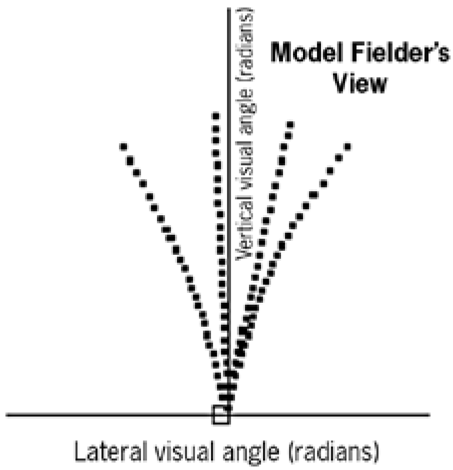

Figure 3. Model fielder's view of the optical path of fly balls hit in several different trajectories relative to the fielder.

Based on data like that shown in Figure 3, McBeath et al. concluded that fielders catch fly balls by controlling the optical trajectory of the ball, keeping it straight (linear). Others have suggested that fielders catch fly balls by controlling the optical acceleration of the ball, keeping it equal to zero (Babler and Dannemiller, 1993). The Internet Java fielder simulation catches fly balls by controlling the optical velocity of the ball, keeping it equal to a value greater than zero (so that the image of the ball is always rising). These are three different hypotheses about the type of purpose being carried out by a fielder catching a fly ball.

When we look at behavior through control theory glasses one of the main questions to be answered is "What type of purpose is being carried out"? The control theory view of behavior suggests that the answer to this question will be given in terms of the type of perception (in this case, optical trajectory, acceleration or velocity) that is being controlled (Marken, 2001).

Getting the Point

All the behaviors that we have looked at so far involve an organism taking action with respect to something in the outside world. The goose takes action with respect to an egg; the bird in a flock takes action with respect to the other birds; the fielder takes action with respect to the fly ball. Because of this, it has been easy to see behavior as either a caused or a controlled result of action. But some behavior looks only like action; there are no obvious results produced by the action. For example, the neck movements that move the egg, the wing flapping that moves the bird and the leg motions that move the fielder are apparently irreducible actions. It might seem that these behaviors would look the same through both causal and control theory glasses. But this is not the case. Even the actions that produce behavioral results look different through causal and control theory glasses.

For example, look at your arm as you point to different places in the room. The movements of the arm look like pure actions; outputs produced by your nervous system. But this view of your arm movements is actually the way things look through causal theory glasses. The arm movement is seen as a response to your mental commands (causes). Things actually look quite different through control theory glasses. You can experience the difference for yourself by closing your eyes and noticing what you feel (perceive) as your arm moves from one place to another. You will notice that your arm movement is not just an action; it is a set of perceptions – of muscle tension and joint angle. These are called proprioceptive perceptions and what you can see yourself doing through control theory glasses is manipulating (controlling) these perceptions. Even an apparently simple movement (action) is not a response when seen through control theory glasses; it is still the control of perception. In the case of behaviors like arm movements, however, the perceptions that are under control are completely invisible to outside observers.

A program that shows how arm movements are produced by control of proprioceptive perceptions is available on the Internet[8] for PC compatible computers. The program, which was written by Powers (1999), is a simulation of a person reaching out with one arm to touch a target that moves in three dimensions. The person's arm has three degrees of freedom and employs realistic models of the muscles that drive the arm and the physics that convert muscle forces into arm movements. What is important about the model for present purposes is the fact that arm movements are produced by systems that control different proprioceptive perceptions, such as the angles of the force applied at the shoulder and elbow.

When you run the program you will see a "little man" moving his arm to point at a moving target. It may look like the little man's

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8 The "Little Man" movement simulation is available for PC compatibles from: www.livingcontrolsystems.com/demos/tutor_pct.html. Download the file arm_one_win.zip from that page. The file also contains documentation describing how the model works.

arm movements are responses to internal commands. But this is the view through causal theory glasses. And in this case it is the wrong view. What the little man is actually doing is producing intended perceptions: proprioceptive perceptions of joint angles and muscle tensions that are invisible to the observer of the little man's behavior.

Balancing Act

While it may be difficult to see arm movements as anything more than responses, some actions are so remarkable that we know there must be more to them than just what meets the eye. A dramatic example of this comes in the form of the balancing acts done by circus acrobats. We take the most common kinds of balancing behaviors, standing and walking, completely for granted. But when the standing or walking takes place on a narrow wire a hundred feet above our heads, we notice. We see behaviors such as walking the high wire as amazing because we know there is more to it than producing walking responses. We know that the wire walker's skill is knowing how to control his or her own body. When it comes to balancing acts, most people seem to be amazed because they are looking at these acts through control theory glasses.

The problem of understanding how people are able to perform remarkable feats of balance is seen differently depending on whether one sees the problem through causal or control theory glasses. Through causal theory glasses, the problem of maintaining balance is seen as one of calculating the corrective forces needed to restore balance when it is lost. The corrective forces must be the exact inverse of the forces (dynamics) that are causing the imbalance so this approach to balance maintenance is called inverse dynamics. The inverse dynamic approach to balance maintenance makes the development of simulated balance maintenance systems very difficult because the forces that restore balance must be calculated with very high precision. Calculations that are off by only a fraction of a percent will have the opposite of their intended effect, increasing imbalance rather than restoring balance (Bizzi, et al., 1991).

Through control theory glasses, the problem of maintaining balance is seen as one of determining the perceptions which, when controlled, result in balance being maintained. An excellent example of a balance maintenance simulation based on control theory is available on the Internet[9]. The simulation program, which runs only on PC compatibles, keeps an inverted pendulum balanced on a moving cart. A motor on the cart can accelerate it left and right to keep the pendulum balanced upright on the cart. A multi-level hierarchy of control systems keeps the pendulum balanced by controlling perceptions such as that of the pendulum's angular position, velocity and acceleration. The systems control these perceptions by accelerating the cart to the left or right, as necessary.

Daring to Disturb the Universe

The examples of behavior described in this article make it clear that you can't tell what an organism is doing by simply looking at its behavior. What you see when you look at behavior depends on which glasses you happen to have on at the time. The view through causal theory glasses is just as believable as the one through control theory glasses. One view is not *ipso facto* more believable than the other is. The goose's egg rolling can be seen as a fixed action pattern or a purposeful attempt to produce pressure on the back of its bill. The flocking birds can be seen as S-R devices (boids) or proximity controllers. The baseball fielder can be seen as a movement

9 A control system model of a cart balancing an inverted pendulum is available for PC compatibles from: www.livingcontrolsystems.com/demos/tutor_pct.html. Download the file invert_pend_dos_win.zip from that page. The file also contains documentation describing how the model works.

producer or a visual velocity controller. Arm movements can be seen as responses to mental events or controlled proprioceptive perceptions. Balancing can be seen as calculation of the inverse of dynamic equations or control of a hierarchy of perceptions. There is, however, a way to test which of these views is the more legitimate way of looking at any particular behavior. The process is called the test for the controlled variable (TCV) and doing it requires a bit more than just looking at behavior. One has to be willing to disturb the universe – of behavior, that is (Marken, 1997).

The TCV tests the assumption that the view through control theory glasses is the correct one. It assumes that the behavior under observation is the organism's efforts to control some aspect of its own perceptual experience and tests whether this behavior is, indeed, the control of perception. You start the TCV with a hypothesis about the perception the organism is controlling. Hypotheses about possible controlled perceptions come naturally when one looks at behavior through control theory glasses: the pressure of the egg against the back of the goose's bill, the distance between birds, the velocity of the image of the ball relative to the background, sensed muscle tension and angular velocity are all examples of perceptions that could be controlled.

What all hypothetical controlled perceptions have in common is that they are variables. The pressure on the back of the goose's bill, for example, is a variable because it can take on many different possible values, from very low pressure (no egg) to very high pressure (rolling the egg up an incline). Control can be viewed as the process of keeping a variable in some pre-selected (or reference) state, protected from disturbances. If the variable were not under control, the disturbances would cause the variable to vary right along with them. Control keeps the variable from varying along with disturbances. Control forces the controlled variable to do what the organism wants it to do – to remain constant or to vary as desired.

It is this disturbance-resisting nature of control that is the basis of the TCV. Once you have identified a hypothetical controlled perception, you can test this hypothesis by trying to "push this variable around." That is, you act as a disturbance to the variable. If the variable is not under control, your disturbances will be completely effective; the hypothetical controlled variable will vary right along with your disturbances. If, however, the variable is under control, there will be little or no relationship between your disturbances and what the variable actually does. Indeed, if the aim of the organism is to keep the variable in some fixed state then your disturbances will appear to have no effect on the variable at all; the organism will act to protect the variable from your disturbances, keeping the variable in the desired state. The TCV is, thus, something like the inverse of conventional behavioral test methodology. Conventional methodology is aimed at detecting an effect of one variable (the independent variable) on another (the dependent variable). The TCV, on the other hand, is aimed at detecting a lack of effect of one variable (the disturbance variable) on another (the hypothetical controlled perceptual variable).

The TCV is a method for validating (or invalidating) the view of a particular behavior through control theory glasses (Marken, 1997). If application of the TCV shows that a hypothetical controlled variable actually is under control then the view of that behavior through control theory glasses is validated. The behavior you see does, indeed, involve the control of a perceptual variable: the behavior has a purpose. If, however, application of the TCV shows that the hypothetical controlled variable is not under control then the view of the behavior through control theory glasses is invalidated. The behavior you see does not involve control, at least of that particular variable: the behavior seems to have no purpose. It is impossible, of course, to prove a negative such as that a behavior has no purpose. It is always possible that the organism is controlling some other variable. But the TCV can rule out the possibility that the organism has certain types of purpose. In particular, it can rule out the possibility that the organism has the purpose of controlling the variable that was hypothesized to be under control. This purpose is ruled out if the variable is not protected from disturbance; it is ruled in (at least tentatively) if it is protected from disturbance.

Detecting the Purpose in Life

A demonstration of the use of the TCV to detect purpose is available on the Internet[10]. The demonstration is a Java program that shows three cars following a red car around the display area. One of the three following cars actually has the purpose of following the red car; the other two cars are just moving in the same path as the red car by coincidence. So the behavior of one car actually has the purpose of following the red car: to control for being behind that car. The following behavior of the other two cars is just a coincidence.

It is impossible to tell, just by looking at the behavior of the three cars (their movements around the screen) which car actually has the purpose of following the red car. Taking an "intentional stance" (Dennett, 1989) will not reveal which is the purposefully (intentionally) following car in this situation. All three cars appear to be intentionally following the sports car. The only way to tell

10 A demonstration of the use of the TCV to determine which of three behaving systems is actually behaving with a purpose is available at: www.mindreadings.com/ControlDemo/FindMind.html.

which car has the purpose of following the red car is to use the TCV.

The TCV begins by looking at the following done by all cars through control theory glasses. This involves looking at all three cars as though they were controlling a perception of following the red car: distance behind the red car is, therefore, the hypothetical controlled variable. This variable can be disturbed by moving the red car off its current path, which can be done by moving the mouse. The purposefully following car resists these changes and stays behind the red car; this car is keeping its perception of being behind the red car under control. The other two cars continue on their original course; they don't correct for the disturbance – the changes in position of the red car. So when you move the mouse you should be able to tell almost immediately which car is following on purpose and which cars are not. The car with the purpose remains behind the red car, protecting its perception of being behind from the disturbances you created by moving the red car.

The TCV in the Real World

The application of the TCV in real world applications rarely involves actually physically pushing on a variable that is thought to be under control. For example, suppose that the hypothetical controlled variable is personal space; you suspect that a person is moving around in order to maintain a certain distance between himself and others. This variable can be disturbed by simply walking into what you presume to be the person's personal space. If the person backs away, protecting the space from disturbance, then you have obtained evidence that the person is controlling personal space without having directly pushed on the person.

Because language is such an important aspect of human activities, you can disturb many of the variables people control simply by talking. This means that you can do the TCV verbally. For example, if you suspect that a person is controlling for "self-respect" you might occasionally insert mildly disrespectful comments into a discussion to see if these disturbances are resisted. Resistance can take the form of anger or contradiction. This verbal approach to the TCV can be used to detect very sophisticated purposes. Indeed, a form of the TCV is used informally in therapeutic interviews to determine the purposes of the client. Some of these purposes may turn out to be in conflict with one another and may be the reason why the client is in therapy in the first place.

Conclusion

This article shows how different theoretical preferences act like glasses that make the same behavior appear to be either internally or externally caused output (through causal theory glasses) or purposefully produced input (through control theory glasses). The less familiar view through control theory glasses was illustrated with models available on the Internet. These models are built on the assumption that behavior is the control of perception. Once one has learned to see behavior through control theory glasses it is possible to test the validity of this view using the TCV. The TCV can be used to tell whether any particular behavior involves the control of perception.

2 · Taking Purpose into Account in Experimental Psychology: Testing For Controlled Variables[11]

Abstract – Experimental research in psychology is based on a causal model – the General Linear Model (GLM) – that assumes behavior has causes but not purposes. Powers (1978) used a control theory analysis to show that the results of psychological experiments based on such a model can be misleading if the organisms being studied are purposeful (control) systems. In the same paper, Powers presented evidence that organisms are such systems. Nevertheless, psychologists continue to use methods that ignore purpose because the behavior in most experiments appears to be non-purposeful (a caused result of variations in the independent variable). The experiments described in this paper show how purposeful behavior can appear to be caused by the independent variable when an organism's purposes are ignored. The results show how taking purpose into account using the control theory-based "Test for the Controlled Variable" can provide a productive new methodological direction for experimental research in psychology.

Scientific psychologists have the purpose of determining the causes of behavior (Anderson, 2001; Levitin, 2002), yet they pursue this goal using research methods that ignore the possibility that the behavior they study is as purposeful as their own (Marken, 1997; 2009). It is actually their methods that ignore purpose, not the psychologists themselves. Indeed, purpose, in the form of goals or intentions, is an important component of many theories of

11 Reprinted from Marken, R. S. (2013) Taking Purpose into Account in Experimental Psychology: Testing for Controlled Variables, *Psychological Reports*, 112, 184-201with permission of Ammons Scientific.

mind (e.g., Newell & Simon, 1972; Rumelhart, & Norman, 1981). But the methods used to test these theories ignore the purposes they propose. The cost of this oversight was described in a classic paper by Powers (1978), which showed that the results of experiments that ignore purpose are likely to be misleading, revealing more about an organism's environment than its psychology. Based on his analysis, Powers recommended that scientific psychologists consider adopting experimental methods that take the purpose of behavior into account (Powers, 1973; Runkel, 2003).

Powers' paper, though published in the very high impact journal *Psychological Review*, had very little impact on the practice of experimental psychology. This may be because the analysis described in the paper did not seem relevant to the kind of behavior studied in most psychology experiments. Powers' analysis was based on the assumption that purposeful behavior is closed loop, where responses have feedback effects on the events that cause them. But the behavior seen in the typical psychology experiment appears to be open loop; the responses observed in these experiments – the dependent variable – appear to have no obvious effect on their presumed cause – the independent variable.

The present paper will show that a closed-loop analysis can be applied to the apparently open-loop behavior in psychology experiments. It will also show that an analysis that takes purpose into account can provide the basis for a new approach to experimental research in psychology, one aimed at determining precisely what the purpose of any behavior actually is.

Closed-Loop Tracking Task

The idea that purpose plays an important role in psychological experiments comes from an analysis of the behavior in a compensatory tracking task like the one shown in Figure 1 (Powers, 1978).

The participant in this task is asked to keep a cursor – the dark grey bar in Figure 1 – aligned with a target – the two light grey bars. The participant does this by moving an output device – a mouse in this case – to compensate for a time-varying disturbance that is causing the cursor to move in a random pattern. The disturbance is equivalent to the independent variable in an experiment because its effect on the cursor is independent of that produced by the participant's output (mouse movement). The participant's output is equivalent to the dependent variable in an experiment.

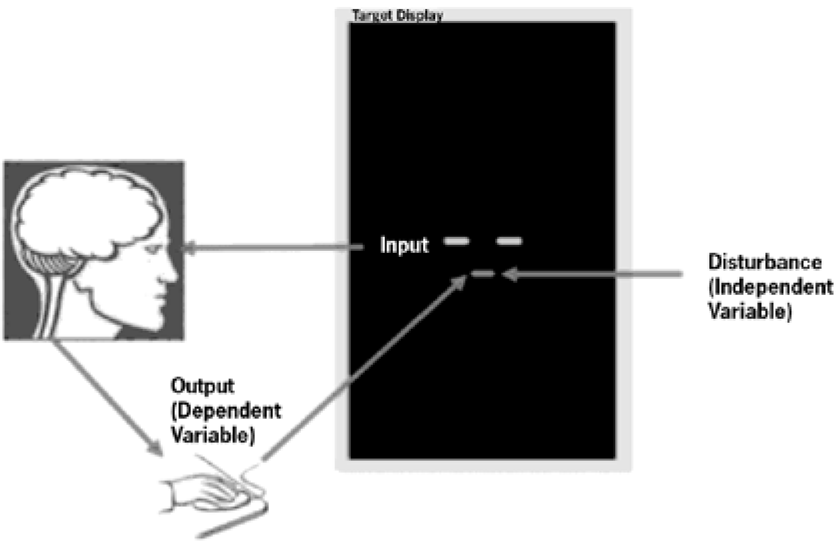

Figure 1. The compensatory tracking task.

Typical results of a compensatory tracking task are shown in Figure 2. These are data from a single participant performing a compensatory tracking task like that shown in Figure 1. The results are typical inasmuch as all participants produce the same results once they have learned to perform the task skillfully (keeping the cursor on target). The reader can see how these data were collected – and that the results presented in Figure 2 are, indeed, typical – by performing an equivalent compensatory tracking task that is available on the Internet[12].

The graph in Figure 2 shows time variations in the value of the disturbance (independent variable, iv), cursor (input, i) and mouse (dependent variable, dv) during a 20 second segment of a 60 second test trial. The value of all three variables is measured in terms of screen units (pixels). The horizontal line at the zero pixel position represents the location of the target. The Input line, which represents cursor position, remains very close to the target line, indicating that the participant was able to keep the cursor "on target" throughout the run. Indeed, the RMS deviation of the cursor from the target during this run was 10.6 pixels, which is about 1% of the possible range of cursor movement. The participant achieved this level of tracking accuracy by moving the mouse so that its effect on the cursor was precisely opposite to that of the disturbance. The precise opposition of mouse to disturbance is seen in the mirror image relationship between these variables.

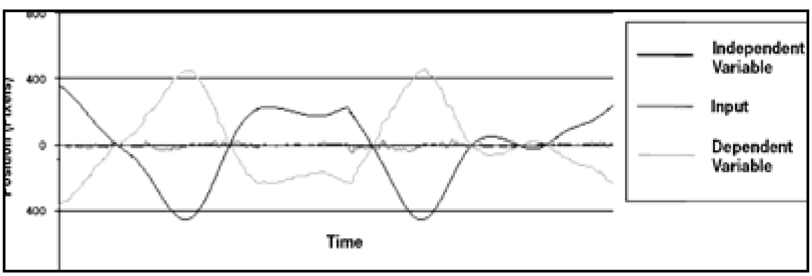

Figure 2. Typical results of compensatory tracking task with smoothly varying random disturbance. The graph shows variations in the disturbance (independent variable), cursor (input) and mouse (dependent variable) during a 20 second segment of a 60 second trial.

12 Marken (1996) Basic Control Demo, http://www.mindreadings.com/ControlDemo/BasicTrack.html.

Causal Model. Several researchers have tried to account for the results of this compensatory tracking task using a causal model of behavior (Bourbon and Powers, 1999; Marken, 1980; Powers, 1978). The most familiar form of this model is the General Linear Model (GLM), which is the basis of experimental research in psychology as well as the statistical methods that are used to analyze the results of these experiments (Cohen & Cohen, 1983). According to the causal model, variations in the dependent variable – mouse movements, in this case – are caused by variations in the independent variable – the time-varying disturbance. But the independent variable (disturbance) in the compensatory tracking task is not directly observable by the participant; it can be seen only via its effect on the input variable – cursor position or, equivalently, the deviation of the cursor from the target – which is all that the participant sees on the screen (see Figure 1).

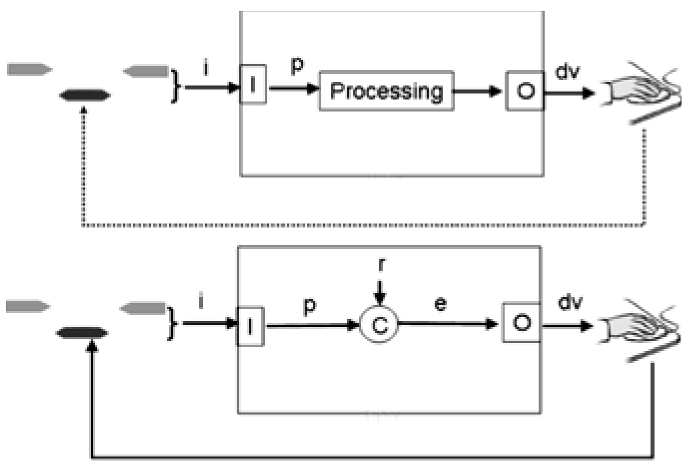

Figure 3. Causal (top) and control (bottom) models of compensatory tracking.

Application of the causal model to the compensatory tracking task assumes, therefore, that there is a causal relationship between input and dependent variable: variations in the dependent variable (dv) are a function of variations in the input variable (i). The simplest assumption about the form of this function is that it is linear, as in the GLM. A diagram of the causal model of the behavior in this task is shown at the top of Figure 3. The input variable, i, is the distance between the cursor and target. This distance is transformed, via an input function, I, into a perception, p, which is processed and turned, via an output function, O, into the muscle forces that produce the mouse movements, dv, that keep the cursor on target.

The line connecting the dv back to i at the top of Figure 3 represents the physical feedback connection between mouse movements and cursor position that exists in the compensatory tracking task. The line is dotted because this connection is not taken into account by the causal model, which deals only with the causal path going from i to dv. Expressed as an equation, the causal model of this tracking task is:

(1) $dv_t' = a + b * i_t + \varepsilon$

where i_t is the difference between cursor and target at time t, dv_t' is the predicted value of the dependent variable at time t, a and b are constants and ε is random error.

The best-fitting causal model is found using linear regression, with the observed cursor variations (input variable, i_t) as the predictor variable and observed mouse movements (the dependent variable, dv_t) as the criterion variable. The resulting regression equation is an open-loop model of the behavior in the compensatory tracking task. The fit of the model is evaluated using R^2, which is a measure of the proportion of variance in dv_t accounted for by dv_t'. For the data in Figure 1, $R^2 = .05$, meaning that only 5% of the variance in dv_t is accounted for by the open-loop causal model.

This is the typical value of R^2 that is obtained when a causal model is used to account for the behavior in a compensatory tracking task (Marken, 1980; Powers, 1979).

The poor fit of the causal model to the behavior in this tracking task may have resulted from using the current value of i to predict the current value of dv, ignoring the possibility that the current value of dv is likely to be a function of earlier values of i due to neural delay. So a series of regressions were done, with i leading dv by different amounts, to find the time lead that produced the best fit for the causal model. That is, $i_{t-\tau}$ rather than i_t was used to predict dv_t, where τ is the number of time samples by which i leads dv. For the data in Figure 1, the best fit of model to data was obtained when τ was 10, which at the sampling rate used in the experiment corresponded to 600 msec. The resulting R^2 was .12; the best the causal model could do is account about 12% of the variance in the behavior in this task.

Control Model. A control model of the behavior in the compensatory tracking task takes into account the fact that there is a closed-loop of cause and effect in this task: mouse movements (dv) are caused by cursor movements (i) while at the same time cursor movements are caused by mouse movements. A diagram of the control model of the compensatory tracking task is shown at the bottom of Figure 3. As is the case in the causal model, the input variable, i, is transformed, via an input function, I, into a perception, p, which is processed and turned, via an output function, O, into the muscle forces that produce mouse movements, dv. The control model assumes that processing consists of comparing the perception, p, of the difference between cursor and target to a reference specification, r, for that perception; the difference between p and r is an error signal, e, that produces the mouse movements via an output function, O.

The main difference between the causal and control models in Figure 3 is that the feedback connection between mouse movements and cursor position is explicitly taken into account by the control model. This is indicated by the fact that a solid line connects the dv back to i. The control model must, therefore, be represented by two simultaneous equations, one representing the "forward" causal path from i to dv and the other representing the feedback path from dv to i. The two equations can be written as follows:

(2a) $dv_t' = k * (r - i_t)$

(2b) $i_t = dv_t' + iv_t$

Equation 2a is called the "system" function because it represents the forward causal processes that are assumed to be running through the behaving system from i to dv. Equation 2b is called the "environment" function because it describes the physical events outside the system that determine the state of the input variable. The position of the cursor at time t is the input variable, i_t, and equation 2b takes into account the fact that the value of i is at each time instant determined by the combined effect of the disturbance, iv_t, and mouse position, dv_t'. The environment function "closes the loop" by incorporating the feedback effect of the system's output, dv_t', on the cause of that output, the input variable, i_t.

A Formal Definition of Purpose. A linear version of the system function of the control model (equation 2a) is used to show its similarity to the causal model (equation 1). The causal model and the system function of the control model are essentially identical, differing mainly in terms of the presence of r in the system function (equation 2a). This little difference turns out to make all the difference because r is the reference specification for the desired state of the input variable, i. That is, r is equivalent to the system's goal or purpose since a closed-loop system acts to achieve the purpose of bringing i into a match with r. So r can be considered the organism's inner purpose when the term "purpose" is used as a synonym for "goal". The phrase "carrying out a purpose" can then be seen as a description of the process of control: acting to keep an input variable, i, at its reference (goal) state (r).

Computer Simulation. The control model described by equations 2a and 2b was implemented as a computer simulation. During each time unit of the simulation the model produces outputs, dv_t', as a function of inputs, i_t, per equation 2a, as in the GLM. And each input is the sum of the model-generated output, dv_t', and the current value of the disturbance, ivt, per equation 2b. In order to simulate the fact that input is affecting output at the same time as output is affecting input, the system function (equation 2a) is modeled as a leaky integrator so that the value of dv_t' is the value of the dependent variable that is in progress at the time it is added to iv_t. The computer code implemented the integration as the following difference equation:

(3) $dv_t' := dv_{t-1}' + (k * (r - i_t) - dv_{t-1}')/s$

where s is a slowing factor for the integration. The slowing factor simulates the rate of integration, which must be inversely related to system gain; as gain (k) increases the rate of integration (s) must decrease in order for the control system to maintain dynamic stability.

Like the causal model, the control model has two parameters that affect the fit of the model to the data: the constant k in equation (2a), which represents the gain of the system (amount of output generated per change in input) and the slowing factor, s. The reference value, r, was not used as a parameter in the model; it was assumed to be a constant equal to zero, which is equivalent to assuming that the participant's purpose was to keep the cursor on target, as instructed. When these two parameters are adjusted properly the model acts to control the input variable, i, keeping it close to the reference value, r.

As with the causal model, the fit of the control model can be evaluated using R^2 as a measure of the proportion of variance in the observed values of dv that is accounted for by the values of dv' produced by the model. For the data in Figure 1, R^2 was equal to .99, meaning that 99% of the variance in the dv was accounted for by the dv' produced by the closed-loop control model. This is the typical value of the R^2 obtained when using the closed-loop model to predict the behavior of a well-practiced participant in a compensatory tracking task (Bourbon and Powers, 1999).

Closed-Loop Tasks and Closed-Loop Organisms

The causal model gives a very poor fit to the behavior in the compensatory tracking task (accounting for at most only 12% of the variance in the behavior) while the control model fits the behavior almost perfectly (accounting for 99% of the variance). It is results like these that led Powers (1978) to conclude that purpose, in the form of a closed-loop control model of behavior, should be taken into account in the analysis of the results of psychological research. But it could be argued that the causal model does poorly in this situation simply because it doesn't take the existing feedback connection into account. The argument would be that while the control model applies to tasks like compensatory tracking that are clearly closed loop (with an obvious feedback connection from output to input), the causal model applies to tasks like those used in most psychology experiments that are clearly open loop (with no feedback connection from output to input). Thus, Powers' conclusion about taking purpose into account in behavioral research would apply only to the behavior seen in closed-loop tasks.

But Powers (1978) argument was that it is not the task (open or closed loop) but, rather, the nature of organisms themselves that makes their behavior closed loop. Behavior is closed loop because what an organism does – its output – always has strong and immediate feedback effects on what it is sensing – its input. Therefore, a model of behavior that takes purpose into account would always be more appropriate than one that doesn't, even when the behavior under study occurs in an apparently open-loop task. We tested this hypothesis by comparing the ability of the causal and control models to account for the behavior in a clearly open-loop task.

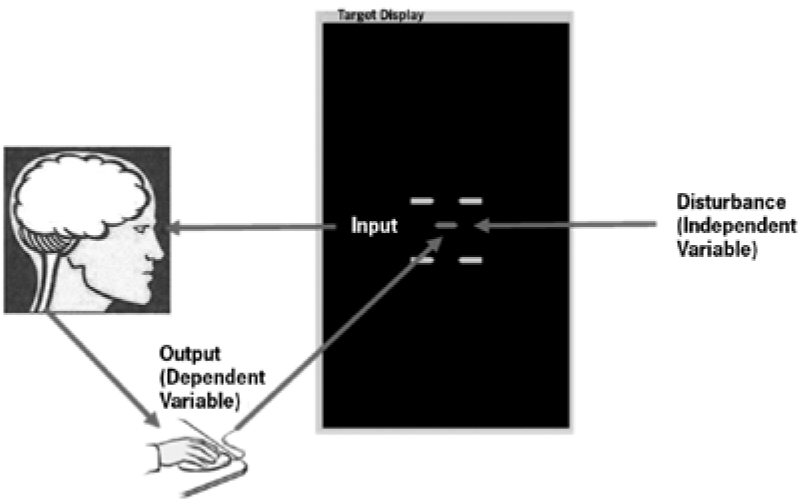

Figure 4. The open-loop reaction-time version of the compensatory tracking task.

Open-Loop Reaction-Time Task. An open-loop task equivalent to that seen in a typical psychology experiment (e.g. Sternberg, 1966) was developed in the form of a reaction-time version of the compensatory tracking task, as shown in Figure 4. There are two targets on the screen in the form of the upper and lower pair of pointers. The participant was to move the cursor as quickly as possible to the upper or lower target based on the color of the cursor. When the cursor was blue the participant was to move the cursor to the upper target; when the cursor was yellow it was to be moved to the lower target. A computer generated disturbance changed the color of the cursor at random times; the average frequency of color changes was adjusted to make the task of intermediate difficulty.

This reaction-time version of the compensatory tracking task is clearly open loop. The independent variable is the color of the cursor, which is also the input variable. The dependent variable is mouse movement, which causes the cursor to move towards the upper or lower target. Unlike the situation in the compensatory tracking task, there is no feedback link from dependent to input variable; mouse movements have no effect on the color of the cursor.

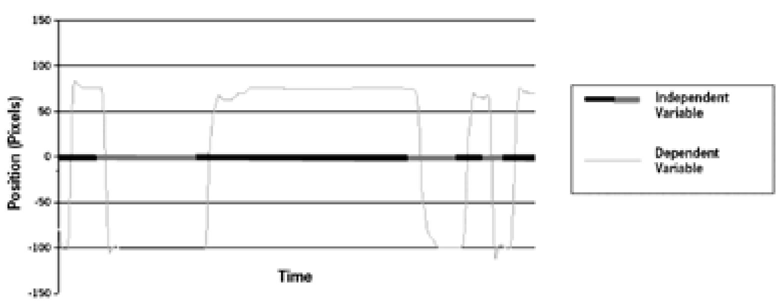

Figure 5. Typical results of the reaction-time version of the compensatory tracking task. The graph shows the state of the disturbance (the color of the cursor, which is both the independent and input variable) and mouse (dependent variable) during a 20 second segment of a 60 second trial.

A 20 second segment of the results of a 60 sec trial of this reaction-time experiment are shown in Figure 5. The color of the centerline indicates the state of the independent variable, which corresponds exactly to the state of the input variable –cursor color. The thin grey line indicates the state of the dependent variable–mouse position. Reaction time is clearly visible in Figure 5 as the delay between the change in the value of the independent variable (from dark grey to light grey and vise versa) and the change in the position of the dependent variable (mouse); on average this delay is ~ 400 msec.

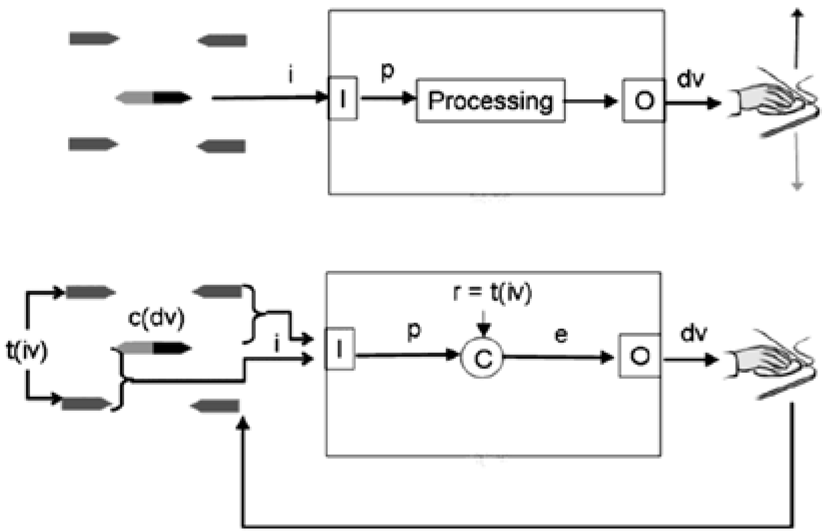

Figure 6. Causal (top) and control (bottom) models of reaction-time task.

Causal Model of Reaction-Time Behavior. A diagram of the causal model of the behavior in this reaction-time task is shown in the upper part of Figure 6. The color of the cursor is the independent variable, which is also the input variable, i – the ultimate cause of the mouse response. The cursor is shown as half blue (dark grey) and half yellow (light grey) to indicate that it is blue on a random half of the trials and yellow on the other half. If the cursor is blue it causes outputs that move the mouse upwards (indicated by the upward pointing blue line for the dv); if the cursor is yellow it causes outputs that move the mouse downwards (indicated by the downward pointing yellow line for the dv). There is no feedback connection from dv to i in this task.

A computer implementation of the causal model used the coded state of the independent variable (1 = blue, 0 = yellow) as the predictor variable and the observed value of the dependent variable as the criterion variable in a regression analysis. The independent variable is used as the predictor variable in this case because it is exactly equivalent to the input variable. So the causal model of this reaction-time task can be written in the more familiar form of the GLM as:

(4) $dv_t' = a + b * iv_t + \varepsilon$

The regression analysis yields the coefficients of equation 4 that give the best fit of predicted to observed values of the dependent variable. Again it was necessary to find the delay between input and dependent variable values that produced the highest value of R^2. For the data in Figure 5 the highest value of R^2 was .91, which was found when the input value (color of the cursor) led the dependent variable value (mouse position) by 400 msec. So the causal model does quite well in this apparently open-loop reaction-time task, accounting for 91% of the variance in the dependent variable. This is a considerable improvement over the performance of the model in the closed-loop compensatory tracking tasks, where the causal model accounted for only 12% of the variance in the dependent variable.

Control Model of Reaction-time Behavior. A closed-loop control model can also be applied to the behavior in the reaction-time task by assuming that there actually is a closed-loop relationship between input and behavior. A diagram of the control model of this task is shown in the lower portion of Figure 6. The model assumes that the input variable is the perceived position of the cursor, which is identified as c(dv) because cursor position depends on mouse movements, dv. The model sets a reference specification, r, for the target position of the cursor (designated t(iv) in Figure 6), based on the color of the cursor: upper target if the cursor is blue, lower target if the cursor is yellow. Thus, the model has the purpose of moving the cursor, c(dv), towards the appropriate target and it achieves this purpose by varying the dv. The model is closed loop because the input, c(dv) influences the output, dv, which simultaneously influences the input.

The control model of the behavior in the reaction-time task can then be represented by the following two simultaneous equations:

(5a) $dv_t' = k * (r_t - i_t)$

(5b) $i_t = dv_t'$

The system equation 5a is nearly the same as it was in the control model of the compensatory tracking task (equation 2a) except that the reference, r_t, is now a variable. The value of r_t is proportional to the value of iv_t, which specifies the target position of the cursor at time t. So $r_t = b * iv_t$. The value of r_t is assumed to be set by a higher - level control system that has the purpose of maintaining the correct relationship between the color of the cursor (iv_t) and the location of the target, $t(iv_t)$. A more detailed description of how control systems at two or more levels in a hierarchy of control systems interact can be found in Marken (1990).

The environment equation, 5b, differs from that for the compensatory tracking task (equation 2b) because the input, i, is no longer a function of both the iv and dv (as in equation 2b). The control model described by equations 5a and 5b was again implemented as a computer simulation using the leaky integration code (equation 3) to simulate the simultaneity of events in the closed loop.

The fit of the model was again evaluated using linear regression to measure the proportion of variance in the observed dv that is accounted for by the model-generated dv'. The best-fitting control model resulted in an R^2 of .91; 91% of the variance in the dv was accounted for by the closed-loop model generated dv'. Since the causal model also accounted for 91% of the variance in the dv, both models do equally well at accounting for the behavior in this reaction - time task. The models fit the data equally well in terms of all measures of goodness of fit that were used; R^2, RMS deviation and number of free parameters.

Reaction-Time Task with Disturbance

The fact that the causal and control models do equally well is actually consistent with Powers' (1978) analysis of open and closed-loop systems. Powers' analysis showed that the behavior of a closed-loop control system is equivalent to that of an open loop causal system when there are no disturbances acting on the variable that is being controlled by the control system. Control (purposeful) systems act to prevent such disturbances from having an effect on the controlled variable; causal (non-purposeful) systems do not. Therefore, in order to determine whether or not the behavior in the reaction-time experiment is purposeful it was necessary to repeat the experiment with a disturbance, d, added to the effect of the mouse, dv, on the cursor, i, as shown in Figure 6. The disturbance is the same as that used in the compensatory tracking task – a time varying number added by the computer to the effect of the mouse on the cursor – and it represents a second independent variable in the experiment.

The causal and control models make very different predictions about how the disturbance will affect the participant's behavior. The causal model predicts that the addition of the disturbance will have no effect on the causal connection between iv and dv. Therefore, the causal model of the behavior in the reaction-time task with d added is still given by equation 3; the model should account for the same amount of variance in the dv with the disturbance added as it did when there was no disturbance.

The control model says that the participant is controlling cursor position, which, when the disturbance is added, is a function of both mouse movements (dv) and the disturbance (d). Therefore, the environment equation for control model of the reaction-time task becomes:

(6) $i_t = dv_t' + d_t$

The control model will make the appropriate adjustments in the dv (mouse movements) that compensate of the addition of d; the causal model will not. Therefore, if the behavior in this reaction - time task is actually closed-loop, the control model should produce far more accurate predictions of the dv than the causal model.

A 20 second segment of the results of a 60 sec trial of the reaction-time experiment with disturbance d added to the dv is shown in Figure 7. The state of one independent variable – cursor color – is again indicated by the color of the centerline (dark grey = blue, light grey = yellow); the state of the dependent variable – mouse position – is again indicated by the thin grey line. Because a second independent variable – the disturbance – was added, the position of the cursor is no longer equivalent to the position of the mouse – the dependent variable – as it was in Figure 5, so cursor position is plotted separately as the dark grey line in Figure 7.

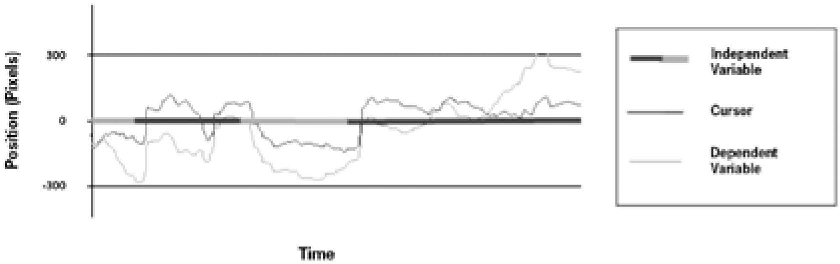

Figure 7. Typical results of the reaction-time version of the compensatory tracking task with a disturbance added to the position of the cursor. The graph shows the state of the disturbance (the color of the cursor, which is again the independent and input variable), the cursor and mouse (dependent variable) during a 20 second segment of a 60 second trial.

The results in Figure 7 show that the dependent variable (mouse movements) generally moves in the direction dictated by the state of one independent variable (cursor color). However, the size of these movements – and sometimes even the direction of the movements – differs from what would be expected from an open-loop causal analysis. Due to the addition of d some of the variations in the dv are compensating for the effects that d would have on the input variable. This interpretation is borne out by a comparison of the causal and control models. The best fitting causal model (with optimal delay between input and dependent variable) accounts for only 47% of the variance in this data; the best fitting control model accounts for 87% of the variance in this data.

The behavior in this reaction-time task with a disturbance added to the dv is much better explained by a closed-loop control model than by an open-loop causal model, suggesting that the apparently open-loop behavior in this task is actually closed loop; the participants are behaving with the purpose of keeping the cursor in the reference state specified by the color of the cursor

Purpose in Psychology Experiments

Controlled Variables. The studies described in this paper show how behavior that appears to be clearly open loop – such as that in the reaction-time task – can be explained better by a control model that views behavior as closed loop. The behavior in the reaction-time task appears to be open loop when its purpose is ignored, as it is in the causal model. However, the possible closed-loop nature of the behavior can be seen when the participant's purpose is taken into account.

Purpose is included in the control model as a reference specification for a perceptual input variable, i. The model achieves its purpose by acting as necessary (varying dv appropriately) to keep this input variable close to the reference specification, r, a process called control. The input variable that is being kept near the reference is called a controlled variable. According to the control model, the purpose of behavior is to maintain controlled variables in reference states specified by the behaving system itself (Marken, 2001, 2005; Powers, 1979).

Controlled Variables in Experiments with Humans. When purpose is understood in terms of controlled variables the possible role of purpose in experimental psychology can be explored by looking for evidence of controlled variables in psychology experiments. Mook (1984) describes many of the "classic" experiments in psychology where behavior (the dependent variable) appears to be caused by the independent variable. Purpose does not seem to be involved because the behavior in these studies appears to be open-loop. As per the GLM, variations in the dependent variable appear to be caused by variations in the independent variable. But a closer look shows that purpose is always involved in these studies.

The purpose of the participant in an experiment can be found by looking at what the participants are asked to do. The instructions given to the participants in an experiment define the participant's purpose in terms of the variables to be controlled and the references for those variables. For example, in the classic study of "mental rotation" by Shepard and Metzler (1971), participants were instructed to say "same" or "different" when pairs of perspective line drawings depicted the same of different objects, respectively. These instructions can be seen as asking participants to control a logical relationship between what they see and what they say and to keep that relationship in the state "correct" by saying "same" when the object pairs are the same and "different" when the object pairs are different. In other words, the participants are asked to have the purpose of correctly identifying the object pairs as same or different. The open-loop (causal) view of this experiment is that the line drawings are inputs that cause the responses ("same" or "different") and that these responses have no feedback effect on the inputs. The closed-loop (control) view is that the relationship between inputs and responses is a controlled variable that the participant keeps in the reference state "correct" by varying responses appropriately.

It is well known that the participants in psychological experiments must be encouraged to follow instructions accurately. Participants must agree to adopt the references for controlled variables described in the instructions if the experiment is to work at all. Experimental manipulations will have no effect on behavior if participants fail to adopt the purposes described by the instructions. For example, the angular difference between pairs of objects in the Shepard and Metzler (1971) experiment would have shown no effect on reaction time if participants did not adopt the purpose described in the instructions since people do not typically say "same" or "different" when shown pairs of objects unless they have the purpose of doing this.

The fact that purpose is an essential component of psychological experiments could explain why the causal model (GLM) typically accounts for only a small proportion of the variance in these experiments. For example, Marken & Horth (2011) estimate that the average proportion of variance accounted for in psychological experiments is .34. This estimate was based on 217 measures of proportion of variance accounted for (measured as R^2 or η^2) in experimental studies published in the journal *Psychological Science* during the first quarter of 2008. According to the control model, the independent variable in these experiments is a disturbance to a controlled variable; behavior (variations in the dependent variable) represents the participant's efforts to protect the controlled variable from the effects of this disturbance.

To the extent that participants have somewhat different purposes – they control somewhat different variables or control the same variable at different references – their behavior in response to the same disturbance could differ considerably (Powers, 1978). This suggests that by taking into account the participants' purposes it may be possible to explain much of the variance in the behavior in these experiments that is currently attributed to random noise. But taking purpose into account in this way cannot be done using conventional research methods. What are needed are methods that can be used to determine the purposes of a behaving system.

New Directions for Psychological Research

Taking purpose into account means being aware of the fact that purposeful behavior is organized around the control of input variables: controlled variables. Understanding purposeful behavior, therefore, requires the use of research methods that are aimed at determining the input variables that a organism is actually controlling (controlled variables) and how those variables are controlled.

The Test for Controlled Variables (TCV). An organism's purposes – the variables it controls – are not always obvious. This is illustrated by the problems encountered in research on the purposes involved when people run to intercept flying objects, as when a fielder runs to catch a baseball. All researchers in this field seem to agree that the fielder's purposes involve the control of optical input variables. But there is considerable disagreement about what variables are actually being controlled. For example, one possible controlled variable is vertical optical acceleration (Kistemaker et al., 2009; Fink et al., 2009). Another possibility is optical trajectory; the optical path the object traces out on the eye (McBeath et al., 1995: Shaffer et al., 2008). Still another possibility is vertical optical velocity (Marken, 2001). So there is disagreement about exactly what the fielder's purpose is when running to catch a baseball; that is, there is disagreement about the correct way to describe the controlled variable(s) involved in catching baseballs.

The aim of research on purpose, then, is to get an accurate – and preferably quantitative – description of the controlled variables around which the observed behavior is organized. This can be done using methods derived from control engineering, which are collectively referred to as "the test for the controlled variable" or TCV (Marken, 1983; Powers, 1973; Runkel, 1990b). The most basic version of the TCV is described by Runkel (1990a, p. 76-77). The steps in the TCV are: 1) guess – preferably in the form of a quantitative description – what variable is controlled, 2) apply disturbances that are expected to have an effect on the variable if it is not under control, 3) measure the actual effect of the disturbances, 4) if the effects are close to what is expected then the variable is not under control; return to step 1, 5) if none of the disturbances have the expected effect then the variable is under control; a controlled variable has been identified.

Research by Shaffer et al. (2004) provides a nice example of using the TCV to determine whether optical trajectory is the variable controlled in object interception behavior. These researchers started with a guess, based on previous research (McBeath, et al., 1995), that the variable controlled when catching a fly ball is optical trajectory and that the reference for this variable is "linear": this is called the linear optical trajectory or LOT hypothesis.

The next step was to test this guess by applying disturbances that would have an effect on LOT (making the trajectory non-linear) if this variable were not under control. Disturbances were applied by using a Frisbee, which has a highly irregular trajectory and will produce a non-linear optical trajectory if the linearity of the optical trajectory is not under control. The effect of the disturbances to optical trajectory produced by the Frisbee was measured by observing the optical path of the Frisbee captured in a video taken during each catch. The disturbances were found to be completely effective, in the sense that they resulted in a non-linear optical trajectory, ruling out the LOT as the variable controlled in object interception.

Once a hypothesis regarding a controlled variable has been ruled out, the next step in the TCV is to return to step 1) and test a new hypothesis. In the object interception field, several alternative hypotheses were available. One, suggested by Shaffer et al. (2004) based on the results of their Frisbee study, was that the controlled variable was "piecewise" LOT; a sequence of linear segments in different orientations. Others include the variables mentioned earlier: vertical optical acceleration and vertical optical velocity. Marken (2005) discusses ways to use the TCV to determine which of these hypotheses provides the best definition of the perceptual variables controlled in object interception.

Conclusion

While there are some other recent examples of the TCV being applied in experimental psychology (eg., Pellis et al., 2009) systematic use of the TCV is still rare. The use of the TCV requires recognition of the fundamental role of purpose, in terms of controlled variables and the reference specifications for these variables, in behavior. The TCV has rarely been included among the tools of experimental psychology because the behavior in experiments appears to be open loop (purposeless), as per the causal model that is the basis of this research. Thus, purpose has been ignored in favor of a focus on detecting causal relationships between independent and dependent variables. The aim of this paper was to show that all behavior is closed loop (purposeful) all the time, even when it appears to be open loop (purposeless), as it often does in psychological experiments.

Looking for the Purpose of Behavior

3 · Making Inferences about Intention: Perceptual Control Theory as a "Theory of Mind" for Psychologists[13]

Summary — Theory of Mind (ToM) assumes that humans and possibly other primates understand behavior in terms of inferences about intentions. While there is evidence that primates make such inferences, little attention has been paid to the question of their validity. In order to answer this question it is necessary to know the true intentions underlying behavior. The present paper shows that Perceptual Control Theory can provide a scientific basis for making such determinations using methods derived from control engineering. These methods—called the "Test for the Controlled Variable" (TCV)—are based on the assumption that intentional behavior is equivalent to the process of control. The TCV provides an objective approach to inferring the intentions underlying behavior in terms of the perceptual variables under control and the goal states of those variables. Thus, Perceptual Control Theory represents an empirical ToM for psychologists—one that can be used to understand behavior in terms of inferences about intention that are based on the results of active experimentation rather than passive observation.

The concept of Theory of Mind (ToM) was introduced to explain the apparent propensity of humans and other primates to make sense of behavior in terms of inferences about the mental states of the behaving system (Premack & Woodruff, 1978;

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13 Reprinted from Marken, R. S. (2013) Making Inferences about Intention: Perceptual Control Theory as a "Theory of Mind" for Psychologists, *Psychological Reports*, 113, 1269-1286 with permission of Ammons Scientific.

Baron-Cohen, 1991; Sommerville & Decety, 2006). ToM refers to the cognitive processes involved in inferring the mental states that are presumed to be the basis of the observed behavior. Much of the research on ToM is aimed at assessing whether various primates (such as chimpanzees and autistic humans) make such inferences (Baron-Cohen, Leslie, & Frith, 1985; Povinell, Nelson, & Boysen, 1990; Meltzoff, 1995; Hare, Call, & Tomasello, 2001; Horowitz, 2003; Call, Hare, Carpenter, & Tomasello, 2004; Call & Tomasello, 2008; Hamilton, 2009) and, if so, how they do it (Hayes, Barnes-Holmes, & Roche, 2001; Brass, Schmitt, Spengler, & Gergely, 2007; Csibra & Gergely, 2007; Rehfeldt & Barnes-Holmes, 2009; de Waal & Ferrari, 2010) and what the neural basis of these inferences might be (Rizzolatti & Craighero, 2004; Fogassi, Ferrari, Gesierich, Rozzi, Chersi, & Rizzolatti, 2005; Ferrari, Bonini, & Fogassi, 2009). What this research does not address is the question of the *validity* of these inferences—whether they are actually correct.

This paper will focus on inferences about one particular type of mental state: intention. In order to assess the validity of inferences about intention, researchers need their own ToM that explains what intentional behavior is and how it can be distinguished from unintentional behavior. This paper presents the argument that such a theory is available in the form of Perceptual Control Theory (PCT; Powers, 2005), which provides a ToM that can be used to validate the inferences about intention made by other organisms, as well as by researchers in other areas of psychology, to validate their own inferences about the intentional basis of the behavior under study (Marken, 2002).

Intentional Behavior: Real and Apparent

To be valid, inferences about intention must reliably and correctly distinguish behavior that is intentional from behavior that is not. To the extent that the validity of such inferences has been addressed, it has been evaluated in terms of the appearance of behavior (Bruner, 1981; Dasser, Ulbaek, &Premack, 1989); an inference is considered correct if the behavior deemed intentional *looks like* it was done intentionally, while that deemed unintentional *looks like* an accident (e.g., Call & Tomasello, 1998). However, correctly identifying behavior as intentional or unintentional based on its appearance does not necessarily mean that these identifications are valid. This is because the appearance of behavior is not a reliable reflection of its *true* intentionality (Marken, 1989).

The fact that the appearance of behavior does not necessarily reflect its true intentionality can be illustrated by the situation where a fugitive fleeing in a car suspects that he or she is being "tailed," or followed intentionally. The following car appears to be tailing the fugitive because it continues to be visible in the rear-view mirror. But the following behavior may actually be unintentional; the car in the rear-view mirror may just happen to be taking the same route as the fugitive; the following behavior is then just an unintentional result of this coincidence. So, the same behavior could be intentional or unintentional; which it is can not be determined based on appearance alone. However, the fugitive can determine whether he or she is actually being tailed by creating obstacles, such as random left and right turns, that the following car would have to overcome to keep following. If the following car stays in the rear view mirror despite these obstacles, then it is reasonable to deduce that the following is intentional: the fugitive is being tailed. If not, the following is probably unintentional: the car in the rear view mirror was simply taking the same route by coincidence.

William James showed how the obstacle-based approach to detecting intentionality could be used to distinguish the unintentional behavior of iron filings "running" to a magnet from the superficially similar, intentional behavior of Romeo running to Juliet (James, 1890). The distinction is made by placing an obstacle between the apparent pursuers and their goal—a card between the filings and the magnet and a wall between Romeo and Juliet. The filings, of course, stop their "pursuit" of the magnet as soon as they hit the obstructing card, while Romeo does what he can to work his way around the wall.

What William James understood is that goal achievement is a necessary but not a sufficient basis for determining intentionality. After all, when there are no obstacles, the coincidentally following driver and the filings appear to be just as successful at achieving their apparent goals as do the tailing driver and Romeo. Intentionality is seen when a goal is achieved *by doing whatever is necessary* to achieve it. Thus, the behavior of the tailing driver and Romeo is seen to be intentional because they do whatever is necessary to overcome obstacles; the behavior of the coincidentally tailing driver and the filings is seen to be unintentional because they do not. To paraphrase James, with unintentional behavior the path to the goal is fixed; whether or not the goal is reached depends on accidents; with intentional behavior it is the goal that is fixed and the path will be modified indefinitely to achieve it (James, 1890, p. 7).

Intention as Control

The idea that intentionality is revealed by behavior that involves doing whatever is necessary to overcome obstacles and achieve a goal is equivalent to viewing intentional behavior as a process of *control* (Marken, 1988). This can be seen by comparing the intentional behavior of the tailing driver to the controlling done by the familiar home thermostat. The behavior of the thermostat involves varying its actions, called *outputs*, so as to bring an aspect of the environment, called the *controlled variable*, to a goal or *reference state* and to keep it there, protected from obstacles, called *disturbances*. For the thermostat the controlled variable is room temperature and the reference state of this variable is 68°F; the output is the turning on or off of the heater/air conditioner and disturbances are the variations in outdoor air temperature and the number of people in the room. In the case of the tailing driver, the controlled variable is the distance between the cars and the reference state of this variable is "close behind"; the output is the direction of the tailing driver's car and the main disturbance is the direction of the car being followed.

The current state of a controlled variable is, at all times, a simultaneous result of both outputs and disturbances. To keep a controlled variable in a reference state (under control), outputs must vary in nearly exact opposition to these disturbances. When outputs cancel out the effects of disturbances to a controlled variable, the controlled variable is "under control." Thus, control can be seen to be precisely equivalent to intentional behavior inasmuch as both involve doing whatever is necessary to overcome obstacles (varying outputs to oppose disturbances) and achieve a goal (keep a controlled variable in a reference state).

Cause and Control

Viewing intentional behavior as a process of control solves a problem that has been a persistent impediment to the development of a theory of intentional behavior: the problem of backward causation. The problem exists because intentional behavior seems to require that a future event (reaching the goal, a result) be the cause of the current actions that are the necessary means of achieving that result. This would require causality to go backward in time, from effect (the goal result) to cause (the actions that lead to the goal), a physical impossibility.

The main approach to a solution to the backward causality problem has been to move the cause of the actions that produce a goal result back before those actions occur. So like James's iron filings moving to the magnet, or a ball rolling to the bottom of a bowl, intentional behavior is seen to follow the same laws of cause and effect as those that characterize the unintentional behavior of physical objects (e.g., Kugler & Turvey, 1987; Kelso, 1995; Turvey, Fitch, & Tuller, 1982; Fajen & Warren, 2003). But there is considerable evidence that the causal laws that explain unintentional behavior do not work as explanations of intentional behavior (Powers, 1978; Marken, 1980; Marken & Horth, 2011). Fortunately, there is no need to invent causal explanations of intentional behavior when such behavior is understood to be a process of control. There is already a very well developed theoretical explanation of control in the form of *control theory* (Black, 1934; Bennett, 1979). When control theory is applied to understanding the controlling done by living systems (organisms) it represents a theory of intentional behavior.

A Control Theory Model of Intention

A functional model of a system that controls (a control system) is shown in Fig. 1. The dashed horizontal line separates the control system itself (the "system") from the environment in which the controlling is done. The environment contains the controlled variable q_i and the two variables that influence its state or value: the disturbance variable d and the variable output of the control system q_o. The functions h() and g() are the physical laws that relate the output q_o and disturbance d, respectively, to q_i. The system side of Fig. 1 describes the processes inside the organism that produce the behavior seen as control. These are the processes that make it possible for the system to vary its outputs precisely in opposition to variations in the disturbance so that the controlled variable is kept in a reference state.

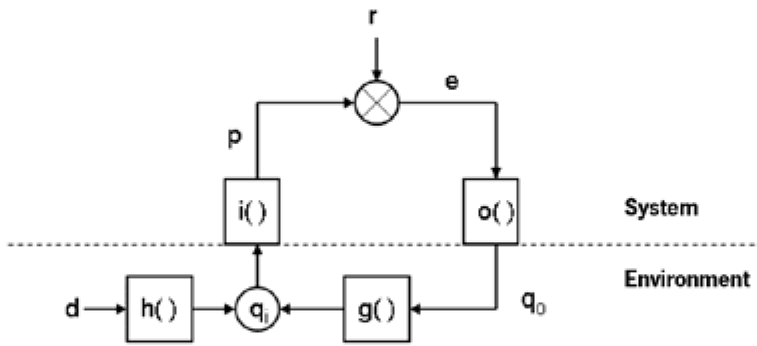

Fig. 1. Perceptual Control Theory (PCT) model of intentional behavior.

Central to this process is the reference signal r, which specifies the intended or reference state of the controlled variable q_i. The actual state of the controlled variable is represented in the organism as a perceptual signal p. The function i() represents the neural network that converts q_i into p. The perceptual signal is compared, via subtraction, to the reference signal r. The difference between r and p is an error signal e that drives the output q_o, via the output function o().

Causality still holds in the control theory model of Fig. 1: there is no backward causality. But in control theory, causality goes around in a circle rather than in a straight line. This is because there is a closed-loop relationship between the system and the environmental variable it controls. The first part of this loop goes from the input to the output of the system. The input is the controlled variable q_i, and the output is the output variable q_o. The causal path from input to output is described by the following equation:

$$q_o = o\,(r - p) \qquad \text{[Equation 1]}$$

Equation 1 is called the "system" equation because it describes the causal path from input to output via the control system. The equation says that system output q_o is caused by variations in the difference between the reference r and perception signal p. The difference between r and p is the error signal e, which is converted into output by the output function o().

The second part of the closed loop in Fig. 1 is the causal path from output back to input. This is the *feedback* path where the effect of input on output is "fed back" onto itself as described by the following equation:

$$q_i = g(q_o) + h(d) \qquad \text{[Equation 2]}$$

Equation 2 is called the "environment" equation because it describes the causal path from system output q_o to system input q_i via the external physical environment. The equation says that system input is simultaneously caused by system output q_o and environmental disturbances d. The function g(), called the *feedback function*, represents the physical laws that relate system output to input; the function h(), called the *disturbance function*, represents the physical laws that relate environmental disturbances to input.

The causal loop described by Equations 1 and 2 is a *negative feedback* loop because the product of the signs of the causal connections around the loop is negative. In a negative feedback loop, variations in output q_o cause the input q_i to move toward the reference state r, driving the error towards zero. The result is that the input variable q_i is kept under control in the sense that it is kept close to the reference specification, protected from disturbances: q_i, ≈ r. Thus, q_i is also called the *controlled variable*.

The model described in Fig. 1 is a particular application of control theory called Perceptual Control Theory (Powers, 2005). Perceptual control theory differs from most other applications of control theory in psychology in terms of how it maps theory to behavior. In particular, the theory explicitly places r, the reference specification for the goal state of the controlled variable, inside the behaving system in the form of an efferent neural signal, rather than outside in the environment in the form of a target (Jagacinski & Flach, 2002). The reference signal can then be seen as the physical embodiment of an intention inside the behaving system; it is a present-time, neural specification of the desired future state of a perceived aspect of the environment: q_i, the controlled variable. Placing r inside the behaving system also makes explicit that it is a perception of q_i that is actually being controlled. Hence the name of the theory, Perceptual Control Theory.

Modeling Intention

A computer implementation of the Perceptual Control Theory model of intentional behavior was used to simulate the fugitive driver possibly being followed. The simulation is available as an interactive demonstration on the Internet,[14] a frame of which is shown in Fig. 2. This "Detection of Intention" demonstration shows a small sports car followed by three other cars. The sports car moves around the screen in a winding path, part of which is shown by the dashed line with the arrow pointing in the direction of motion. The three other cars follow behind at different distances labeled q_{i1}, q_{i2}, q_{i3}. The movement of the sports car is a disturbance, d, to these three distances. The distances q_{i1}, q_{i2}, q_{i3}, are also a result of variations in the "outputs" of each of the following cars, q_{o1}, q_{o2}, q_{o3}. These outputs are what determine the changing positions of the following cars. The distances between each of the three following cars and the sports car (q_{in}) are proportional to the difference in the position of the sports car (d) and of the following ones (q_{on}) during each frame of the animation: q_{in} = d- q_{on}.

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14 Marken, R. S. (2011) Detection of intention, http://www.mindreadings.com/ControlDemo/FindMind.html

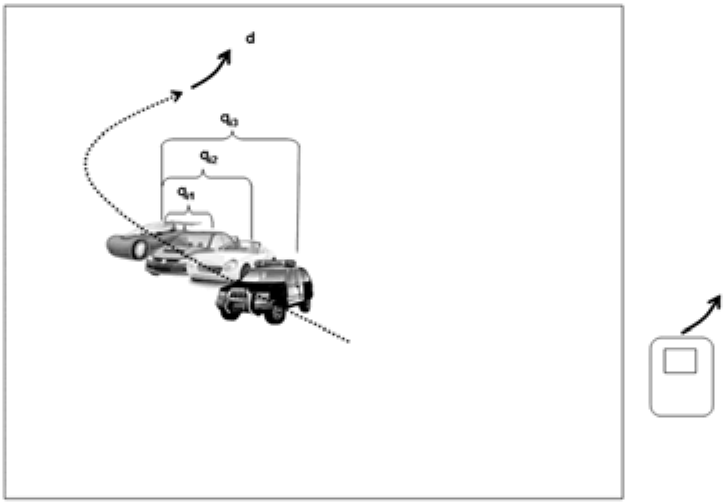

Fig. 2. One frame of the animated "Detection of Intention" demonstration

As the animation proceeds, one observes that all three following cars appear to be intentionally following the sports one, because each maintains a fixed distance from it; that is, q_{i1}, q_{i2} and q_{i3} remain constant (at different values) as the sports car moves around the screen. In fact, only one of the following cars is intentionally following the sports car. The other two are coincidentally moving in the same path (and at the same speed). The behavior of the car that is intentionally following the sports car is created using the Perceptual Control Theory model described by Equations 1 and 2. The intentionally following car controls its distance from the sports car (q_{in}), by varying its output (q_{on}), to compensate for the disturbance (d) to this distance created by the movements of the sports car. The value of the reference specification, r_n for the controlled variable (q_{in}) depends on which car is the controller; for example r_1, the reference when the gray sedan is the controller, is smaller than r_2, the reference when the white roadster is the controller. The controller car produces outputs (q_{on}) that compensate for the movements of the sports car (d) and keeps the distance between it and the sports car (q_{in}) nearly constant and equal to the reference specification for that distance, r_n.

When the demonstration starts, the computer program randomly selects one of the three following cars to be the controller car: the one that is intentionally following the sports car. One can determine which car is intentionally following the sports car in the same way that the fugitive can determine whether she is being tailed: by moving the mouse around randomly to change the path of the sports car. Like the car that is tailing the fugitive, the car in the demonstration that is intentionally following the sports car will compensate for these disturbances and maintain a constant distance behind it. The following cars that are not following intentionally just continue on the path that the sports car would have taken if you had not changed its path by moving the mouse.

The Test for Controlled Variables (TCV)

The method used to deduce which of the three cars was intentionally following the sports car in the "Detection of Intention" demonstration is an example of the control theory-based "Test for the Controlled Variable" or TCV (Powers, 1979; Runkel, 2003). The TCV is a formalized version of the obstacle-based approach to detecting intention that was used by the fugitive to figure out whether she was being tailed and by William James to decide whether the iron filings or Romeo was behaving intentionally.

The TCV tests for intentionality under the assumption that intentional behavior is a process of control; evidence of control is considered to be evidence of intention. The evidence of control sought by the TCV is the existence of a controlled variable. The TCV is a quantitatively precise method for determining whether some variable is under control and, if so, exactly what it is.

The TCV starts with a hypothesis about an aspect of the environment that is being controlled: a hypothesis about the controlled variable. In the "Detection of Intention" demonstration, three hypotheses about the controlled variable can be tested simultaneously: that the controlled variable is either q_{i1}, q_{i2}, or q_{i3}, the distances between the sports car and each of the three following cars, respectively. The next step in the TCV is to apply disturbances that would have an effect on the hypothesized controlled variable if it were *not* under control but would have little or no effect if it were. In the "Detection of Intention" demonstration, disturbances were applied to all three possible controlled variables simultaneously by moving the sports car with the mouse. These disturbances will increase the distance between a following car and the sports car if this distance is not controlled, but they will have little or no effect on this distance if it is under control.

The next step in the TCV is to monitor the possible controlled variable while it is being disturbed, to see whether or not the disturbance does have an effect. If it does, then the variable can be ruled out as a possible controlled variable; it is not under control. In the "Detection of Intention" demonstration this step is done by monitoring each of the three possible controlled variables (the distance between each of the following cars and the sports car, q_{i1}, q_{i2}, or q_{i3}) until one is found that is not affected by the disturbance. If, for example, the first hypothesis is that the distance between the gray sedan and the sports car q_{i1} is under control, but it changes as the sports car is moved with the mouse, then the disturbance to this variable is effective and q_{i1} is not under control. In this case, one returns to the first step of the TCV and formulates a new hypothesis about what variable is under control.

The next hypothesis might be that the distance between the white roadster and the sports car (q_{i2}) is under control. If the disturbance has little or no effect on the distance between these cars then this variable is likely to be under control. One can continue to apply a disturbance (keep moving the sports car around with the mouse) until one is convinced that it is having very little effect on q_{i2}, at which point it is safe to conclude that the distance between the light grey roadster and the sports car is the controlled variable, which is equivalent to saying that the light grey roadster is intentionally following the sports car.

The TCV can be repeated as often as desired in the "Detection of Intention" demonstration. Once the controlled variable (the car that is intentionally following the sports car) is identified, the mouse can be clicked and a new car (possibly the same one as before) is selected to be the one intentionally following the sports car. Again, it is impossible to tell which it is by just looking at the behavior of the three following cars. The only way to be sure which is the new, intentionally following car is to do the TCV once again. A more detailed description of the steps involved in doing the TCV can be found in Runkel (2003).

Perceptual Control Theory as a Model of the Intentional Behavior of Humans

The "Detection of Intention" demonstration shows how the TCV can be used to distinguish intentional from unintentional behavior when the intentional behavior is that of a Perceptual Control Theory model of a control system. But the question remains whether the TCV can distinguish intentional from unintentional behavior when the intentional behavior is that of a real organism, such as a human. It can, if the intentional behavior of a human is equivalent to the controlling done by the Perceptual Control Theory model.

Thus, Perceptual Control Theory can be tested as a model of the intentional behavior of organisms by seeing whether the TCV can be used to distinguish intentional from unintentional behavior in humans. Such tests have been done and they strongly suggest that the TCV can, indeed, be used to make this distinction and do it quite reliably (Marken, 1982; 1983). The reader can demonstrate this to himself using an Internet demonstration called "Mind Reading," a frame of which is shown in Fig 3.[15]

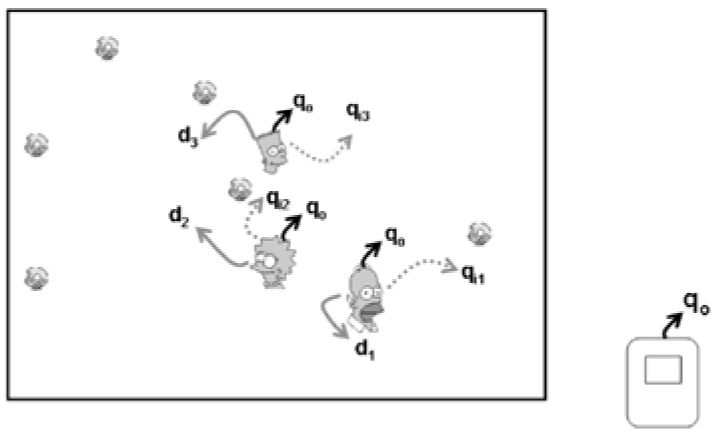

Fig. 3. One frame of animated "Mind Reading" demonstration.

The "Mind Reading" demonstration shows three familiar avatars that can be moved around the screen using the mouse controller. The mouse moves all three avatars, as indicated by the arrows labeled q_o. Each avatar is also moved by a different, slowly varying, computer-generated disturbance, as indicated by the arrows labeled d_1, d_2, and d_3. So the observed path of each avatar, indicated by the arrows labeled q_{i1}, q_{i2}, and q_{i3}, is the net result of mouse movements and disturbances: $q_{i1} = q_o + d_1$, $q_{i2} = q_o + d_2$, and $q_{i3} = q_o +$

15 Marken, R. S. (2008) Mind reading, http://www.mindreadings.com/ControlDemo/Mindread.html

d_3. The person doing the demonstration is asked to pick any one of the three avatars and move it around the screen intentionally while avoiding the obstacles (dodging the donuts) as best she can. When this is done, all three avatars move around the screen in different paths and, as in the "Detection of Intention" demonstration, it is impossible to tell which is being moved intentionally.

The computer, by carrying out the TCV, determines which of the three avatars is being moved intentionally. It does this by looking for lack of effect of the disturbances to the path of each of the three avatars, which are the three possible controlled variables. Lack of effect is indicated by a lack of correlation between the variations in a possible controlled variable and variations in the disturbance to that variable. So the computer performs the TCV by iteratively computing the correlation between d_1 and q_{i1}, d_2 and q_{i2}, and d_3 and q_{i3} on each frame of the animation from a continuously updated set of 200 values of these variables. When one of these three correlations is lower than the other two by a threshold amount, the computer reports that the path of the corresponding avatar is the controlled variable.

The "Mind Reading" and "Detection of Intention" demonstrations are essentially the inverse of each other. In the "Detection of Intention" demonstration, the TCV is used to determine which of three cars is intentionally following the sports car; in the "Mind Reading" demonstration, the computer uses the TCV to determine which of three avatars is being intentionally moved. In one case ("Detection of Intention"), the participant in the demonstration is using the TCV to infer intentions from "outside" the behaving system, which is a computer program; in the other ("Mind Reading"), a computer program is using the TCV to infer the intentions of the participant. So the "Mind Reading" demonstration allows the participant to know whether the TCV is correctly inferring intentions when it identifies controlled variables because the intentions being inferred are those of the participant herself.

After the viewer intentionally moves one of the avatars for a few seconds, the computer will indicate its inference regarding which one it is by changing its identity. If that avatar is the one intentionally being moved, then the computer, using the TCV, has correctly inferred intention. The computer's guesses are most likely to be correct once the participant is very skillful at moving the avatars. So, the computer infers intention best after the task has been practiced for a few minutes and the avatars can be controlled skillfully.

Using the TCV to Validate ToM

The results of the "Mind Reading" demonstration provide evidence that the TCV is a method of detecting real, human intentions, supporting the notion that Perceptual Control Theory does provide a valid model of intentional behavior. This means that the TCV can be used to validate the judgments of intentionality that are made in ToM research. This can be shown using the "Mind Reading" demonstration. In this case, the demonstration is used to determine whether a person watching the avatars move around the screen can accurately attribute intentionality. This was done in an experiment where an experimenter, the author, moved a selected avatar intentionally on different test trials while observers tried to identify which it was.

The experimenter made the intentionally moved avatar follow an arbitrary path (rather than a structured one, such as a circular path) so that the shape of the path would be similar to those of the unintentionally moved avatars. Each observer tried to identify the intentionally moved avatar before the computer did, which gave the observer about 20 seconds to make the identification on each trial. Trials were thrown out if the computer made the identification before the observer. Once the observer made the identification, the experimenter waited until the computer made its identification and then started intentionally moving a different avatar. On each trial, the experimenter recorded the avatar that was actually moved intentionally as well the attributions of intention made by the computer and the observer.

Six observers were tested over 20 trials each. The accuracy of attributions of intention was measured as the proportion of trials on which the observer correctly attributed intention to the avatar that the experimenter was moving intentionally. Since there were three avatars, the probability of a correct attribution by chance alone is .33. Four of the six observers correctly identified the intentionally moved avatar at no better than chance level (the proportion of trials on which intention was correctly attributed to the intentionally moved avatar was not significantly different from .33 for these 4 observers). Two observers did significantly better than chance, correctly attributing intention on about .65 of the trials ($p < .003$).

In this study the observers did attribute intentionality to the behavior of the avatars, as per ToM. But it also shows that these attributions are not particularly accurate; all observers attributed intentionality to the unintentionally moved avatars on a large proportion of the trials. This finding is consistent with the classic observation of Heider and Simmel (1944) that people will attribute intentions to even the unintentional movements of animated geometrical forms. Since the TCV makes it possible to discriminate truly intentional from truly unintentional behavior, future research on ToM could be aimed at determining the features these two kinds of behavior have in common that lead them to be seen as intentional.

Perceptual Control Theory as a ToM for Psychologists

To the extent that PCT is a valid model of intentionality, it can serve not only as a basis for validating attributions of intention in ToM research, but also as an empirically-based ToM that can be used by researchers and practitioners in all areas of psychology as a basis for understanding the intentional behavior of organisms. From a Perceptual Control Theory perspective, understanding intentional behavior is a matter of understanding what variables organisms control and how they control them, making the TCV the centerpiece of the Perceptual Control Theory approach to understanding behavior (Marken, 2009).

One example of the Perceptual Control Theory approach to understanding intentional behavior is found in the study of object interception, where the goal of research is to understand how a pursuer, such as a baseball outfielder, manages to intercept a moving object such as a fly ball. Object interception is clearly an intentional behavior; the pursuer reaches the target object by moving as necessary to counter variations in its path. Based on early theoretical guesses about how outfielders intercept fly balls (Chapman, 1968), there is general agreement that a pursuer intends to keep certain aspects of the optical projection of the pursued object in a goal state. Therefore, research on object interception has been aimed at identifying what aspects of the optical projection these might be. From the perspective of Perceptual Control Theory, this research is aimed at identifying the optical variables that are controlled by the movements of the pursuer; the controlled variables that are the basis of object-interception behavior.

Object-interception researchers have proposed three different hypotheses regarding the variables controlled in object interception: linear optical trajectory or LOT (McBeath, Shaffer, & Kaiser, 1995), optical acceleration cancellation or OAC (McLeod, Reed,

& Dienes, 2001) and control of optical velocity or COV (Marken, 2001). The LOT hypothesis proposes that pursuers move so as to keep the ratio of vertical to horizontal optical movement of the pursued object constant. When they do this, the pursued object will trace out a linear optical trajectory on the eye. The OAC hypothesis proposes that pursuers move so as to cancel the vertical and horizontal optical acceleration of the pursued object, bringing these variables to zero. The COV hypothesis proposes that it is the vertical and horizontal optical velocity (rather than acceleration) of the pursued object that pursuers are trying to bring to zero.

Various versions of the TCV have been used to test these different hypotheses. A particularly ingenious test of the LOT hypothesis was done by Shaffer, Krauchunas, Eddy, and McBeath (2004) using Frisbees as the objects to be intercepted. If LOT is the controlled variable in object interception, then the highly irregular trajectory of the Frisbee should have had little or no effect on the linearity of optical trajectory seen when pursuers (who happened to be dogs in this case) tried to intercept it. In fact, the observed optical trajectories were quite non-linear, ruling out LOT a possible controlled variable (Marken, 2005).

Another version of the TCV was used to test the OAC and COV hypotheses about the controlled variable in object interception (Shaffer, Marken, Dolgov, & Maynor, in press). Since it is difficult to apply disturbances only to optical acceleration or velocity, the approach to testing these hypotheses involved the use of computer simulations of control models of object interception. Models that used either optical acceleration or velocity as the controlled variables were compared in terms of their ability to account for the movements of pursuers trying to intercept toy helicopters that flew in highly irregular trajectories. The model that controlled optical velocity accounted for 93% of the variance in actual pursuer movements, while the model that controlled optical acceleration accounted for only 75% of the variance in these movements. Although more tests using different disturbances to the hypothetical controlled variables are needed, the results of the modeling version of the TCV strongly suggest that optical velocity is the variable controlled in object interception.

Other applications of Perceptual Control Theory to understanding the intentional behavior of organisms can be found in the study of motor behavior (Marken, 1986; 1991), animal behavior (Berkenblit, Feldman, & Fucson, 1986; Pellis, Gray, Gray, & Cade, 2009; Bell & Pellis, 2011), developmental psychology (Plooij, 1984) and psychopathology (Carey, 2008; Higginson, Mansell, & Wood, 2011). The basic assumption of all research based on Perceptual Control Theory is that intentional behavior is organized around the control of perceptual input variables. Therefore, a central feature of this research is the TCV, which identifies the input variables an organism is controlling. Once it is known what variables an organism controls—equivalent to determining its intentions—research can be designed to assess how these variables are controlled, and why, questions that can also be addressed using versions of the TCV.

Potential Difficulties When Using the TCV

The demonstrations of the TCV described in this paper represent idealized applications of the methodology in highly constrained situations. Perhaps the most obvious constraint has been on the nature of the possible controlled variable itself; in both the "Detection of Intention" and "Mind Reading" versions of the TCV it was possible to represent the hypothetical controlled variable as a simple quantitative function of physical variables, such as distance (between cars) or position (of an avatar). But the intentional behavior that occurs in real life often involves the control of variables that are impossible to represent as a simple function of physical variables, e.g., the honesty of a communication or the intimacy of a relationship. A quantitative approach to the TCV will not work when trying to study such abstract variables, but the basic principle of the TCV still applies: disturb a hypothetical controlled variable and look for lack of effect.

The problem is how to measure the state of an abstract variable, like honesty, to decide whether or not it has been affected by a disturbance (such as yelling "liar" after a person makes a statement). There are many possible ways to approach the measure of abstract controlled variables using "subjective" methods such as rating responses. For example, Robertson, Goldstein, Mermel, and Musgrave (1999) described one innovative approach using collections of 3 x 5 cards with self-descriptive adjectives to represent the state of an abstract controlled variable – the state of one's self-concept– and non-self-descriptive adjectives to serve as possible disturbances to this variable.

Another important consideration when using the TCV to analyze more natural examples of behavior is that organisms control many perceptual variables at a time and the reference specifications (goals) for the state of some of these perceptions are varied as the means of controlling others (Powers, 2005). For example, one's specific goal for intimacy with another person will vary, depending on whether a higher level intention is to get a job from or to marry that person. The implications of this for the TCV are that a single failure to compensate for a disturbance to a hypothetical controlled variable is not enough to rule out that variable as being under control. For example, a person may fail to compensate for the stand-offish behavior in another person, not because the person is not controlling for intimacy, but because his or her desired intimacy with the stand-offish person is very low, so there is no need to compensate for the stand-offishness. Changing the disturbance from stand-offish to enticing might lead to compensatory actions that would suggest that something like "intimacy" is, indeed, under control.

The TCV described in this paper is not a recipe to be followed by rote but, rather, a set of principles that can serve as the basis for various approaches to identifying the intentions underlying behavior. Different methodologies can be used to carry out the TCV, including controlled experimentation (Marken, 1989), simulation modeling (Marken, 2005) and clinical interview techniques (Carey, 2008). Which methodologies are used in a particular circumstance will depend on the nature of the controlled variable(s) under study, practical and ethical considerations and, of course, the ingenuity of the researcher.

Conclusion

The demonstrations described in this paper suggest that inferences about intention based on the TCV can reflect the true intentions of the organism far more accurately than those based on observation alone. This means that the TCV can be used in ToM research to validate inferences about intention. But, more importantly, the TCV (and the Perceptual Control Theory model of intentional behavior on which it is based) provide an empirical and theoretical basis for the study of the intentional behavior of organisms. Perceptual Control Theory can be viewed as a somewhat revolutionary ToM for scientific psychology (Marken, 2009), one where behavior is understood in terms of inferences about intention that can be tested and, if necessary, rejected using the TCV.

4 · Testing for Controlled Variables: A Model-Based Approach to Determining the Perceptual Basis of Behavior[16]

Abstract — Perceptual Control Theory (PCT) views behavior as organized around the control of perceptual variables. Thus, from a PCT perspective, understanding behavior is largely a matter of determining the perceptions that organisms control – the perceptions that are the basis of the observed behavior. This task is complicated by the fact that very often the perceptions that seem to be the obvious basis of some behavior are not. This problem is illustrated using a simple pursuit tracking task where the goal was to keep a cursor vertically aligned with a target set at various horizontal distances from the cursor. The "obvious" perceptual basis of the behavior in this task is the vertical distance between cursor and target. But a control model suggests that a better description of the perceptual basis of the behavior is the angle between cursor and target. The experiment shows how a control model can be used to do the Test for the Controlled Variable (TCV), a control theory- based approach to distinguishing the actual from the apparent perceptual basis of any behavior.

Perceptual Control Theory (PCT) assumes that the behavior of organisms is organized around the control of perceptual variables (Powers, 1973; Marken, 1982). Thus, from a PCT perspective, understanding behavior is largely a matter of discovering

16 Reprinted from Marken, R. S. (2013) Testing for Controlled Variables: A Model-Based Approach to Determining the Perceptual Basis of Behavior, *Attention, Perception and Psychophysics*, with permission of the Psychonomic Society.

the perceptions that an organism controls, which is equivalent to determining the perceptual basis of the organism's behavior. The perceptions that an organism controls are called *controlled variables*. So understanding the perceptual basis of behavior is a matter of identifying the controlled variables around which behavior is organized.

What Are You Doing?

The idea of trying to understand behavior in terms of the perceptions an organism controls may seem somewhat strange but it is actually something we do quite often in everyday life. In particular, we are doing it when we see people doing something and ask ourselves what they are doing. When you think about it, this is an odd question to ask when the behavior we are asking about is happening right before our eyes. But the question rarely strikes us as odd because we know we are asking, not about the behavior we can see but, rather, about the purpose of that behavior – what these people are trying to accomplish – which is not easy to see at all. The reason for this, according to PCT, is that purpose is a perception in the brains of those doing the behavior.

The concept of purpose as perception can be illustrated by considering the purpose of your opponent's behavior in a game such as chess. The behavior that is easy to see is each of the opponent's moves. The behavior that is hard to see is the purpose of these moves. It is difficult to see the opponent's purpose because it is a perception that the opponent is producing for him or herself. In the chess game it is a perception of the relationship between the pieces on the board.

The problem of determining the opponent's purpose results from the fact that there are many different ways to perceive the same set of relationships. For example, the relationship between pieces on the board that results from the opponent's move could be seen as a threat of capture, as solidifying the opponent's "control of the center" or as setting a trap. The purpose of the opponent's move is to produce one (or more) of these perceptions, you just don't know which.

The process of acting to produce a particular perception – such as a particular relationship between pieces on the chess board – is called *control* (Marken, 1990). Like purpose, control involves the production of pre-selected perceptions and doing so in the face of unpredictable disturbances, such as the moves you make in response to those of your opponent. So determining the purpose of behavior is equivalent to determining the perceptions that the person is controlling. It is difficult to determine what these perceptions are because they exist only in the brain of the person doing the controlling.

Jumping to Conclusions

The difficulty of determining a person's purposes – the perceptions they control – does not stop us from jumping to conclusions about what those purposes are. This may result from the apparently innate inclination of humans (and, possibly, some non-human primates) to understand behavior in terms of inferences about its purpose (Heider & Simmel, 1944; Premack & Woodruff, 1978). The tendency to jump to conclusions about the purpose of behavior can be a particular problem for psychologists who are trying to understand the nature of purposeful behavior (Marken, 1992). This is because a correct understanding of any particular example of purposeful behavior requires that the actual purpose of that behavior be accurately identified (Marken, 2002).

The problem of jumping to conclusions about the purpose of behavior can be illustrated using a simple pursuit tracking task, like that shown in Figure 1. In this task the participant is asked to keep a cursor, c, aligned with a moving target, t. The subject sees just a purple oval target and green oval cursor, both moving in a vertical path on the computer screen. The cursor moves as a result of the participant's mouse movements, q.o; the target moves as a result of time variations in a computer generated disturbance, d.

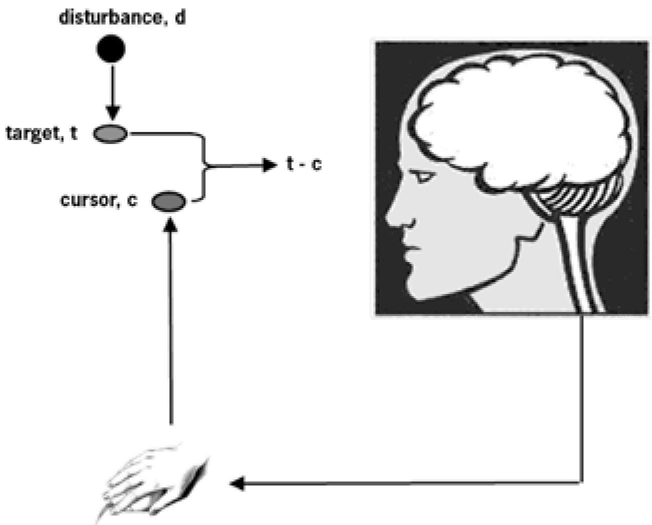

Figure 1. Pursuit tracking task where the participant is to keep a cursor aligned with a target that moves in a randomly varying vertical path caused by a computer generated disturbance.

This is a control task where the participant's purpose – the perception to be controlled – seems obvious. It is a perception of zero distance between cursor and target: t-c = 0. This is certainly the assumption made in most studies of tracking (Jagacinski & Flach, 2002). However, this assumption may be wrong; there are other aspects of the relationship between target and cursor that could be the perception being controlled in this task. In order to see why this might be the case it is necessary to look at a model of the behavior in this tracking task.

PCT Model of Purposeful Behavior

Figure 2 is a diagram of the basic PCT model of the behavior in a pursuit tracking task. The participant in this task is viewed as a control system controlling a perceptual representation of the distance between target and cursor (t-c). This distance, called q.i in the diagram, is the input to the control system. A perceptual input function, I, transforms q.i into a perceptual signal, p, which is compared to a reference signal, r, that specifies the desired state of that perception. The comparison is performed by a comparator, C, which continuously computes the difference between p and r, r-p. This difference is a time varying error signal, e, that drives the participant's outputs, q.o, via the output function, O. These outputs have a *feedback* effect, via q.i and p, on the error signal that is the cause of those outputs.

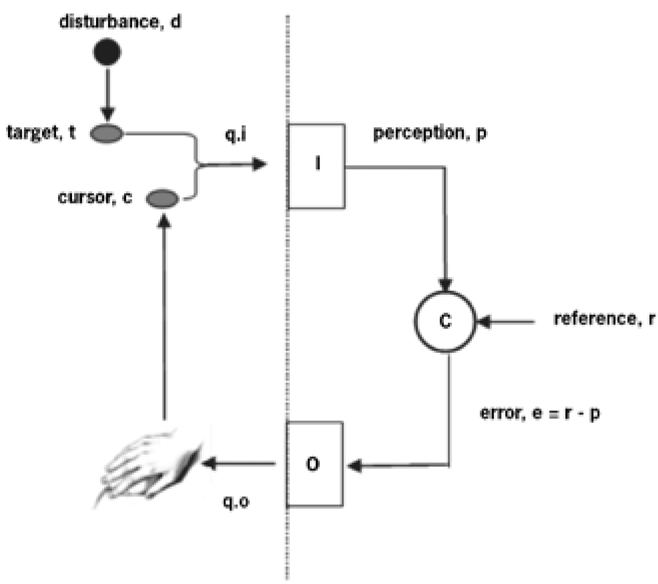

Figure 2. Perceptual Control Theory (PCT) model is the behavior in the pursuit tracking task.

The behavioral organization diagrammed in Figure 2 represents a closed-loop system where inputs cause outputs while, at the same time, outputs cause inputs. When the effect of outputs is to reduce the error that is causing those outputs, the system in Figure 2 is a negative feedback control system. Such a system controls in the sense that it keeps a perception, p, close to the reference signal, r, protected from disturbance, d (Powers, 1973). In the pursuit tracking task, this system will keep its perception of the difference between target and cursor close to the reference signal value (assumed to be zero), protected from disturbance, which is the changing position of the target.

Control of Perception

The fact that a control system, like that shown in Figure 2, controls a perception means that you can't really tell what it is doing – its purpose – by looking at its visible behavior[17]. In a pursuit tracking task the visible behavior of the participant consists of the movements of the mouse, q.o, as well as a measure of the average deviation of cursor from target. If mouse movements keep the cursor near the target, so that the average deviation between cursor and target is small, an observer is likely to conclude that the subject's purpose is to control t-c. But since it is actually a perception that is being controlled, there are other possibilities, as illustrated in Figure 3.

Figure 3 shows two possible perceptions that might be under control in the pursuit tracking task. The upper diagram in Figure 3

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17 Human behavior presumably involves the control of many perceptions simultaneously. But it should be noted that not everything a person perceives can be (or is being) controlled. Figure 2 shows that only those perceptions that are affected by the system's output can be controlled; so only these perceptions can be the basis of observed behavior.

shows the perceptual function, I, computing a perception, p_1, which is proportional to the difference between t and c:

1) $p_1 = k\,(t - c)$

This is the perception that an observer is likely to conclude is the one being controlled in the pursuit tracking task.

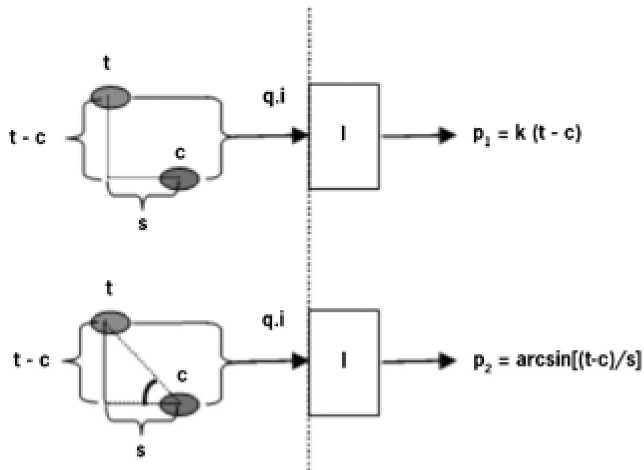

Figure 3. Possible perceptions controlled in the pursuit tracking task: 1) vertical distance between target and cursor, t – c, and 2) angular separation between target and cursor, arcsine (t–c)/s.

The lower diagram in Figure 3 shows another possibility. In this case the perceptual function, I, is computing a perception, p_2, which is proportional to the angular separation between t and c. This angle depends on both the vertical distance between target and cursor, t – c, as well as the horizontal distance between target and cursor, s. The perceptual function is assumed to carry out the equivalent of computing the arcsine of the tangent of the triangle connecting target and cursor:

2) $p_2 = \text{arcsine}\,[(t-c)/s]$

Testing for the Controlled Variable

The two perceptions, p_1 and p_2, that might be the basis of the purposeful behavior in the pursuit tracking task are possible controlled variables. According to PCT, understanding the purposeful behavior in this (or any) task is largely a matter of determining which perception is actually under control: that is, determining the controlled variable. This can be done using a control-theory based methodology called the Test for the Controlled Variable or TCV (Marken, 2009; Powers, 1979; Runkel, 2003).

The TCV is based on the fact that a variable that is under control – a controlled variable – will be protected from disturbance by the actions of a control system. In the pursuit tracking task the variation in target position is a disturbance to both target - cursor distance (p_1) and target-cursor angle (p_2). Typically, the only variable thought to be under control in pursuit tracking is target-cursor distance. The effect of target movement on target- cursor distance is measured in terms of RMS error – the square root of the average distance between cursor from target. To the extent that RMS error is close to zero, the perception of target-cursor distance is considered to be under control. However, this result is also consistent with the possibility that the variable that is actually under control is target - cursor angle. This is because disturbances created by target movement have the same effect on target - cursor angle – arcsine [(t-c)/s] – as they do on target-cursor distance – k (t-c).

The TCV starts with a hypothesis regarding the perceptual basis of a particular behavior. In the case of this pursuit tracking task there are two hypotheses that can be tested simultaneously: the perceptual basis of tracking behavior – the controlled variable – is either 1) target-cursor distance or 2) target-cursor angle. These two hypotheses can be tested by applying a disturbance that would be expected to have an effect on one of these perceptions but not the other. Since, according to equations 1 and 2, the horizontal separation between target and cursor, s, affects only target - cursor angle, and not target-cursor distance, variations in s should be a disturbance to target-cursor angle but not distance.

In most applications of the TCV, the controlled variable is revealed *by lack of effect* of disturbances to the hypothetical controlled variable due to the compensatory actions of the participant (Runkel, 2003). Thus, it would be concluded that the participant is controlling target-cursor angle if variations in s had less than the expected effect on this variable. However, in the present case the participant cannot compensate for the effect of variations of s on target – cursor angle. Therefore, a version of the TCV that uses computer simulation (Marken, 2005) must be used to determine the nature of the expected effect of variations in s on tracking performance depending on whether the participant is controlling target - cursor distance or angle. The behavior of the computer simulation can then be compared to that of the human participant to see which hypothesis about the variable under control produces simulation data that gives the best fit to the human data.

Mathematical Basis of the Computer Simulation

A computer simulation of the behavior in the pursuit tracking task is based on the PCT model diagrammed in Figures 2 and 3. The model can be represented by a set of three equations that can be turned into computer program statements. The first equation, called the *system function*, describes the behavior of the system (a human in this case) doing the tracking:

3) $q.o = k.o\ (r - p)$

This equation says that variations in output (q.o, the mouse movements in a tracking task) are proportional to variations in an error signal, r - p, which is the difference between a reference specification, r, and a perception, p, of the relationship between target and cursor. The constant of proportionality, k.o, is the output *gain*; the amount of output produced per unit error.

The second equation, called the *environment function*, describes the physical relationships between system outputs and inputs:

4) q.i = k.e(q.o) +k.d(d)

This equation says that variations in the input to the system, q.i, are proportional to the sum of effects of variations in output, q.o, and disturbance, d. In the pursuit tracking task q.i is the time varying difference between target and cursor. Equation 4 says that this difference depends on mouse movement, q.o, which determines the state of the cursor, and a time varying disturbance, d, which determines the state of the target. The constant k.e in equation 4 is the *feedback function* that relates system output, q.o, to input, q.i, while k.d is the *disturbance function* that determines the effect of the disturbance on target movements. In the present pursuit tracking task both k.e and k.d are equal to 1.

Finally, the third equation defines the *perceptual function* that transforms the input variable, q.i, defined in the system function equation (4), into the perceptual variable, p, defined in the environment function equation (3):

5) p = k.i (q.i)

In this equation k.i represents either of the two perceptual functions described by equations 1 and 2. The computer simulation can be run with each of these different functions to see which gives the best fit to the behavior observed in a pursuit tracking task.

Computer Simulation

A computer implementation of the equations that define the PCT model of pursuit tracking is described in the following set of pseudo-code program statements:

```
6)    6.1  For i  = 1 to NSamples

      6.2  t : = d[i]

      6.3  c : = q.o

      6.4  q.i : = t – c

      6.5  p : = k.i (q.i)

      6.6  q.o : =  q.o + (k.o (r - p) - q.o))/slow

      6.7  Next i
```

This code assumes that one trial of a pursuit tracking task consists of NSamples of a time varying disturbance that determines the position of the target over the course of the trial. The code in equation 6 loops through the NSamples, setting the target position, t, to the current value of the disturbance, d[i], and setting the cursor position, c, to the current value of the output, q.o, produced by the simulated tracker. The difference between t and c in each sample interval is the input variable, q.i. The input is then transformed into a perception by a perceptual function, k.i(q.i), that produces perception p_1 or p_2 as defined by equations 1 and 2, respectively. Finally, a new value of the output, q.o, is calculated as an increment to the current value, the size of the increment being proportional, by the gain factor k.o and a slowing factor, slow, to the difference between a reference specification, r, and the perception, p.

Program statements 6.1 through 6.4 implement the environment function described by equation 4; statement 6.5 carries out the perceptual function implied by equations 1 and 2; and statement 6.6 implements the system function described by equation 3. The system function in statement 6.6 is implemented as a "leaky integration" in order to take into account the fact that the variables in the tracking task are changing over time.

Pursuit Tracking Experiment

Two participants, RM and MT, were tested in a computer-based pursuit tracking task. The target and cursor appeared on the screen as shown in Figure 1. The target moved vertically driven by a computer-generated filtered random noise disturbance. The participant kept the cursor as closely aligned with the target as possible by moving the mouse forward or back to move the cursor up or down. The horizontal separation between target and cursor, s, was different on different trials, the distance ranging from 0 to 980 pixels.

The center frequency of the noise disturbance determined task difficulty in terms of the speed of the oscillatory movements of the target; a disturbance with a low center frequency resulted in a slowly moving target and, thus, an easier task than one with a high center frequency. After several practice trials, the participants performed two tracking trials, one with an easy and one with a difficult disturbance, at five different horizontal separations between target and cursor, for a total of ten trials. Each trial lasted 1 minute and the trials were presented in a random order.

Comparing the Control Model to Human Behavior

Figure 4 shows how well the behavior of the PCT model compares to that of a human participant during a segment of one trial in a compensatory tracking task. The figure shows the cursor movements made by a human participant (labeled Human) and the PCT model controlling p_1 (the cursor-target distance, labeled Distance Control) and p_2 (cursor-target angle, labeled Angle Control) during a 15 second segment of a pursuit tracking task. The horizontal distance between target and cursor (s) during this trial was 980 pixels (20 cm). The figure also shows movements of the target (labeled Target) during this segment of the task.

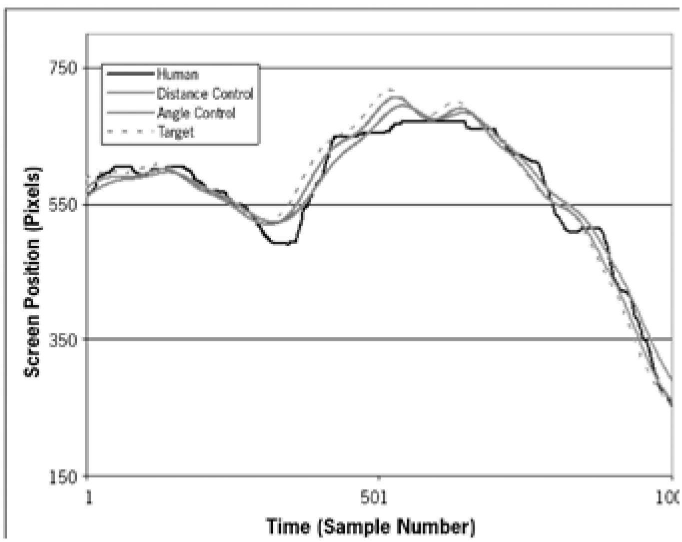

Figure 4. Human and model cursor movement and target movement during a 15 second period of a pursuit tracking task with horizontal separation of 980 pixels (20 cm) between target and cursor.

It is clear from Figure 4 that the behavior (cursor movements) of both the Distance Control and Angle Control models closely approximates that of the Human. The next step in the TCV is to determine which model provides a better fit to the Human data. Because the models make different predictions about the effect of variations in horizontal target-cursor separation, s, on behavior, it is possible to determine which model is best by comparing the behavior of the models to that of the Human at different values of

s. Since the models control different perceptions, the model that gives the best account of the data can be considered to be controlling a perceptual variable that is most like the one controlled by the Humans.

The models were tested by having the computer version of each model (the code in equation 6) perform the same tracking task as the Human participants; the computer tracked the same target movements at the same horizontal separations between target and cursor, s, as did the Human participants. The performance of both Human participants and the models was measured as the ability to control the vertical distance between cursor and target, keeping it close to zero. The measure of control used was the ratio of the observed variance in target-cursor deviation, var(t-c), to the variance of the target, var(t), which can be considered the expected variance of t-c if the participant did nothing (so that c is a constant). If control is good, var(t-c) will be very small relative to var(t) so the ratio var(t-c)/var(t) will be very small. The negative log of this ratio is taken so that the better the control (the smaller the ratio var(t-c)/var(t)), the larger the number representing the quality of control.

Tests Based on Performance Measures. The behavior of the Distance and Angle Control models was fit to the Human performance data by adjusting the slowing and gain parameters to get the closest fit of model to Human performance at each separation. Figure 5 shows measures of performance at different horizontal separations, s, of cursor and target for two Human participants (RM, MT) as well as for the best-fitting versions of the Distance and Angle Control models.

The Human performance results are shown as solid black diamonds. The performance of both Humans declines as s increases. This decline is captured by the Angle Control model (solid dark grey triangles) but not for the Distance Control model (solid light grey squares). Indeed, the performance of the Distance Control model is nearly the same at all values of s for both participants. The performance of the Distance Control model even increases slightly for the trails performed by participant RM.

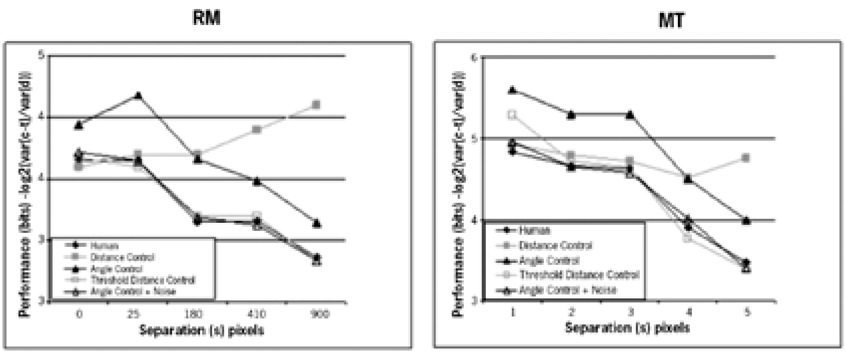

Figure 5. Measures of performance of two Human participants and for the Distance, Angle, Threshold Distance and Angle Control + Noise models.

The fit of the models to the Human performance data can be measured in terms of the squared correlation, R^2, between Human and model performance at each separation, s. The R^2 for the fit of the Distance Control model to the Human performance, averaged over MT and RM, was .51. The average R^2 for the fit of the Angle Control model to the Human performance was .99. Clearly, the Angle Control model fits the Human performance data much better than does the Distance Control model in terms of the decline in tracking performance with increasing s.

The decline in performance for the Angle Control model results from the fact that s is included in the calculation of the controlled variable, arctan((t-c)/s). Increases in s affect the controlled Angle variable in a way that reduces the loop gain of the control system. Loop gain is the product of all gain factors around the control loop.

In the model described by equations 3 through 5 the gain factors are k.i (input function), k.o (output function) and k.e (feedback function). So loop gain is proportional to the product k.i*k.o*k.e. The higher the loop gain in a control loop the better the control (in terms of keeping the controlled variable close to the reference, r). If Angle is the controlled variable then k.i is proportional to the derivative of arctan(t-c)/s. So

7) $k.i = s/(s^2+(t-c)^2)$

Since the distance between target and cursor (t-c) during a tracking trial is typically being kept relatively small, k.i will decrease exponentially as s increases, resulting in the decrease in performance of the Angle Control model.

Improving the Fit of the Models to the Human Performance Data.

It is possible that the poor fit of the Distance Control model to the Human performance data results from the fact that the perception of vertical target-cursor distance degrades with increasing horizontal separation, s. So it should be possible to improve the fit of the Distance Control model by degrading the perception of Distance with a "threshold" band. This band was placed around the value of the Distance perception, t-c, such that only variations in this variable that are outside of the band are perceived. The width of this threshold band increased with increasing s. By appropriate selection of a threshold width for each value of s it was possible to match the performance of the Distance Control model to that of the Human participants quite well, as can be seen in the plots of the Threshold Distance model (the open light grey squares in Figure 5).

In order to capture the decline in Human performance with increasing s four parameters, representing the width of the threshold band, must be estimated for the Threshold Distance model. This decline is captured "automatically" by the Angle Control model through inclusion of a number proportional to the value of s – the psychological value of s – in the calculation of the controlled Angle perception, which reduces the loop gain with increasing s. However, the performance of the Angle Control model is much better than that of the humans at all values of s, as can be seen by the fact that, for both RM and MT, the plot of the performance of that model as a function of s (solid dark grey triangles in Figure 5) runs parallel to but is much higher on the graph than that for the Human.

The Angle Control model can be made to more closely approximate the human performance by adding low pass filtered random noise to the output of the model. The noise amplitude that produced the best fit for both models was 3% of the output range. This level of noise seems to be of the correct order of magnitude based on estimates of the magnitude of neural noise levels derived from neurophysiologic measures (Nakajima, Fukamachi, Isobe, Miyazaki, Shibazaki, & Ohye, 1978; Miller & Troyer, 2002). The performance of the Angle Control model with added noise (the open dark grey triangles in Figure 5; Angle Control + Noise) can be seen to fit the Human performance data as well as the Threshold Distance model.

Since the noise level added to the Angle Control model was the same for all values of s, only one parameter (noise amplitude) was estimated to achieve the fit of the Angle control model to the Human data while four parameters – the threshold widths at the different horizontal separations, s – were required to get the same fit for the Threshold Distance model. Also, The Distance Control model includes no mechanism that explains the increase in threshold width with the increase in s. Therefore, parsimony would seem to recommend a model that controls Angle over one that controls Distance as giving the best account of the Human data in this task.

However, before concluding that Angle is the controlled variable in this task it is possible to make a more detailed comparison of the models by measuring how well they fit the detailed cursor movements made by the Human participants on each trial. If the two models are equally good predictors of overall tracking performance they would be expected to do equally well at accounting for the detailed time variations in Human cursor movements (as shown in Figure 4).

Tests Based on Model Fit to Detailed Cursor Movements. Figure 6 shows the average RMS deviation of model from Human cursor movements for the two models that gave equally good fits to the Human performance data – the Threshold Distance and Angle Control + Noise models. The fit of the models is shown as a function of the horizontal separation of target from cursor, s. The difference in average RMS deviation of the two models from the time variations in Human cursor movements is significant for both MT ($t(4)=3.37$, $p < 0.011$) and RM ($t(4) = 2.76$, $p < 0.025$). The results in Figure 6 show that the Angle Control + Noise model gives a much better fit to the Human data than the Threshold Distance model at all values of s, but particularly at larger values of s. This is strong evidence that Angle rather than Distance is the perception controlled in this tracking task: the hypothesis that Distance is the perceptual basis of tracking can be rejected.

A close look at the time traces of Human and model cursor movements suggests why the Angle Control + Noise and Threshold Distance models account for the performance data equally well

(Figure 5) while the Angle Control + Noise model accounts for the detailed Human cursor variation data much better than does the Threshold Distance model (Figure 6). The observed decrease in the performance of the two models with increasing s, as seen in Figure 5, results from different characteristics of the detailed behavior of each model. The poorer performance of the Angle Control + Noise model with increasing s results from the fact that, like the Human, the variation of model cursor movements around the target increased as s increased, a reflection of the decreased gain of the control model with increasing s. On the other hand, the poorer performance of the Threshold Distance model with increasing s resulted from the fact that, unlike the human cursor movements, model cursor movements remained a constant distance from the target, a distance that increased with increasing s.

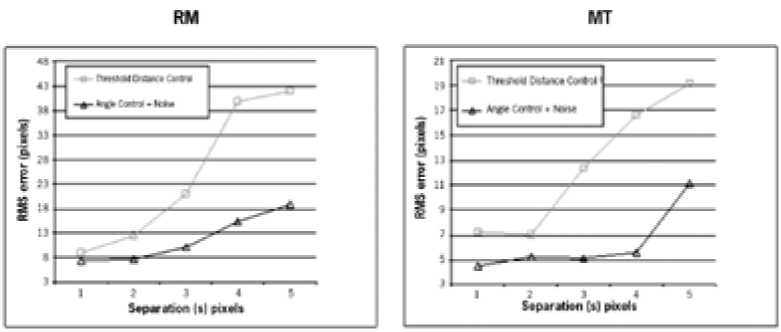

Figure 6. Fit of Angle Control + Noise and Distance Threshold models to human data.

Understanding Behavior in Terms of Controlled Variables

The comparison of the models controlling different perceptions suggests that Angle rather than Distance is likely to be the perceptual basis of behavior in the pursuit tracking task. The purpose of the participants' behavior – mouse movements – in this task is to keep the target-cursor angle rather than distance close to 0.0. While this is an interesting and counterintuitive finding – since, as mentioned above, causal observation would suggest that the participant's purpose in this task is to control the distance between cursor and target – it may not be considered particularly significant since tracking is not a particularly significant behavior. But this research demonstrates a methodology – the TCV – that can serve as the basis for understanding *any* example of purposeful behavior in terms of the perceptions that are under control. It is a methodology that differs from more familiar, traditional methodologies that do not take the purpose of behavior into account (Marken, 2013).

The approach to understanding purposeful behavior demonstrated in this research has been used to understand "real world" examples of purposeful behavior including the hording behavior of rats (Bell and Pellis, 2011), the posture control of crickets (Pellis, et al., 2009), the parenting behavior of chimps (Plooij, 1984), the shock avoidance behavior of rats (Powers, 1971), the object interception behavior of humans and canines (Marken, 2005; Shaffer et al., 2004) and the self-image control behavior of college freshmen (Robertson et al., 1999). Clearly, the TCV can be used to understand purposeful behaviors that involve the control of perceptions that are more complex than Distances and Angles.

Acknowledgements

I would like to acknowledge the assistance of Martin M. Taylor, who wrote the pursuit tracking program and participated in the experiment as participant MT.

5 · Optical Trajectories and the Informational Basis of Fly Ball Catching[18]

Abstract – D. M. Shaffer and M. K. McBeath (2002) plotted the optical trajectories of uncatchable fly balls and concluded that linear optical trajectory is the informational basis of the actions taken to catch these balls. P. McLeod, N. Reed, and Z. Dienes (2002) re-plotted these trajectories in terms of changes in the tangent of optical angle over time and concluded that optical acceleration is the informational basis of fielder actions. Neither of these conclusions is warranted, however, because the optical trajectories of even uncatchable balls confound the information that is the basis of fielder action with the effects of those same actions on these trajectories. To determine the informational basis of fielder action, it is necessary to do the control-theory-based Test for the Controlled Variable, in which the informational basis of catching is found by looking for features of optical trajectories that are protected from experimentally or naturally applied disturbances.

Shaffer and McBeath (2002) tried to determine the informational basis of fly ball catching by observing the optical trajectories of uncatchable fly balls as seen by fielders running to catch these balls. They reasoned that the information fielders use to catch fly balls should be apparent in the optical trajectories of uncatchable balls in terms of how long a potential cue, such as spatial linearity, is maintained relative to other cues, such as optical acceleration.

18 Reprinted from Marken, R. S. (2005) Optical Trajectories and the Informational Basis of Fly Ball Catching, *Journal of Experimental Psychology: Human Perception & Performance*, 31 (3), 630 – 634 with permission of the American Psychological Association.

Because the linearity of optical trajectory was maintained longer than the constancy of optical acceleration, Shaffer and McBeath concluded that the information fielders use as the basis of action is the linear optical trajectory (LOT) of the balls, which is consistent with LOT theory (McBeath, Shaffer, & Kaiser, 1995).

In reviewing the results of Shaffer and McBeath (2002), McLeod, Reed, and Dienes (2002) noted that there is a consistent and pronounced downward curvature in the trajectories of balls that go over the fielder's head, which incorrectly indicates that the ball is going to fall short. McLeod et al. re-plotted these trajectories in terms of the tangent of the vertical optical angle of the ball (tanα) over time and found that tanα increases at an accelerating rate, which correctly indicates that the ball is going to go over the fielder's head. McLeod et al. concluded, therefore, that acceleration of tanα is the information that fielders use as the basis of their actions, which is consistent with optical acceleration cancellation (OAC) theory (Dienes & McLeod, 1993; Michaels & Oudejans, 1992).

The Shape of Optical Trajectories

Although Shaffer and McBeath (2002) and McLeod et al. (2002) disagreed about the informational basis of fly ball catching, they agreed that clues to what this information is can be found in the optical trajectories seen by fielders when they try to catch uncatchable fly balls. Indeed, in their reply to McLeod et al. (2002), Shaffer, McBeath, Roy, and Krauchunas (2003) pointed to the linearity of optical trajectories during all but the last moments of attempted catches as evidence that this information provides a viable basis for catching fly balls. This argument shows that the shape of optical trajectories remains the basic evidence in the debate about the informational basis of catching.

One argument for using the trajectories of uncatchable fly balls to determine the informational basis of catching is that the information in these trajectories is more readily apparent because it is not entirely nulled by the fielder's own actions (McLeod et al., 2002). However, this argument ignores the fact that the feedback effects of fielder actions on the trajectories of even uncatchable fly balls are still present, and they are strong. The shapes of the optical trajectories that are observed when fielders run to catch even uncatchable fly balls depend as much on the fielders' actions relative to the balls as they do on each ball's actual trajectory. Therefore, the information that is the basis of a fielder's actions cannot be seen in the shape of these trajectories, because this information is confounded with the effects of those same actions on the trajectories.

Looks Can Be Deceiving

The problem of determining the informational basis of catching by looking at the optical trajectories of uncatchable fly balls can be illustrated using a computer model of a fielder trying to catch such balls. Several such models have been developed (e.g., Marken, 2001; Tresilian, 1995). These are closed-loop control models, which automatically take into account the feedback effects of fielder actions on the optical trajectories seen by the fielder model. Such models can be used to show what the optical trajectories of uncatchable fly balls would look like if fielders were using particular kinds of information as the basis of catching.

The plots in Figures 1 and 2 show the optical trajectories that are seen by a fielder model trying to catch fly balls on the basis of information about the balls' vertical optical velocity and lateral displacement. Vertical optical velocity is the rate of change in angle α over time, and lateral displacement (γ) is the angular deviation of the ball from the line of gaze, which is always straight ahead. All trajectories in Figures 1 and 2 are for uncatchable balls that go over the head of the fielder model. The trajectories in Figure 1 are plotted in terms of the vertical (α) and lateral (β) optical angle of the ball relative to a fixed point in the visual scene, which is typically taken to be home plate (McLeod et al., 2002, Appendix, p. 1501). The trajectories are linear but slightly downward sloping. The shape of these trajectories is very similar to that of the trajectories reported by Shaffer and McBeath (2002, Figure 8B, p. 344). Note that angle β in Figure 1 is not the same as the variable γ, which is the one controlled by the fielder model.

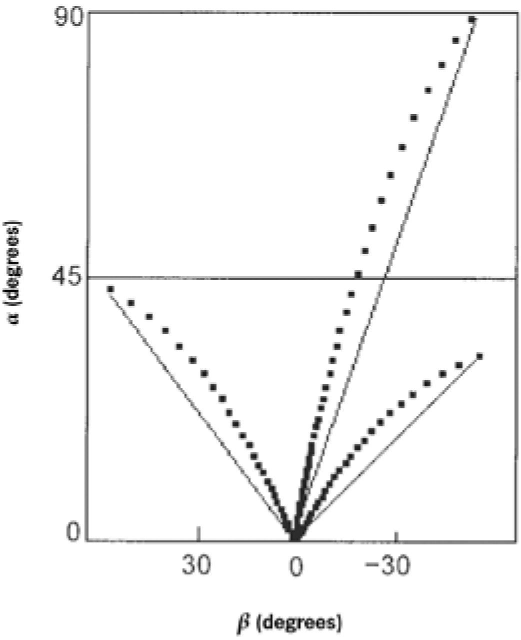

Figure 1. Optical trajectories of uncatchable balls that go over the head of a fielder model controlling both vertical optical velocity and lateral optical displacement. α *is the vertical angle above horizontal from the fielder to the ball.* β *is the horizontal angle between a line from the fielder to home plate and a line from the fielder to the point where the vertical projection of the ball hits the ground.*

Shaffer and McBeath (2002) have noted that a model that acts to match the rates of change in α and β could produce linear trajectories like those in Figure 1. The fielder model that produced the linear trajectories in Figure 1 was, indeed, controlling the rate of change in α, but it was not controlling the rate of change in β, and more important, it was not controlling these two variables relative to each other. So the linear trajectories in Figure 1 were produced by a model that was using neither LOT nor the relative rates of change in α and β as the informational basis of catching. Moreover, the nonlinearities in the plots do not depend on changes in where the fielder is looking in rotational space. Such changes have been suggested as one reason why the otherwise linear trajectories for uncatchable balls curve downward near the end of the catch (Shaffer et al., 2003). The model that produced the trajectories in Figure 1 always looked straight ahead at the ball, even as it moved laterally to catch the ball.

Figure 2 shows the optical trajectories in Figure l re-plotted in terms of $\tan\alpha$ over time. The trajectories show that $\tan\alpha$ increases at an accelerating rate when the ball is hit over the fielder's head. These plots are equivalent to the re-plots of the Shaffer and McBeath (2002) trajectories that were made by McLeod et al. (2002). Again, the shape of the trajectories in Figure 2 is very similar to that of the trajectories reported by McLeod et al. (2002, Figure 1, bottom panel, p. 1500).

The results in Figures 1 and 2 show that the shapes of optical trajectories can be deceiving. The trajectories in Figure 1 appear to be consistent with LOT theory because they remain linear throughout most of an attempted catch. But the observed linearity of these trajectories is produced by a model that does not use LOT (or constancy of the ratio of rate of change in α to rate of change in β) as the basis of its actions. Similarly, the trajectories in Figure

2 appear to be consistent with OAC theory because the observed acceleration of tan α correctly indicates that the ball is going to go over the fielder's head. But, again, the observed acceleration of tan α is produced by a model that does not use acceleration of tan α as the basis of its actions.

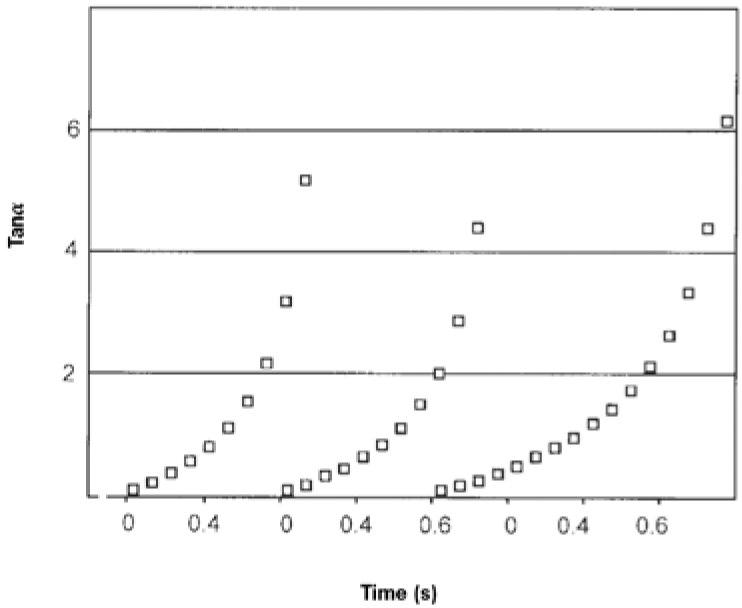

Figure 2. Optical trajectories from Figure 1 plotted in terms of the tangent of the vertical optical angle of the ball (tan α) over time.

Closed-Loop Analysis of Catching

Researchers have looked at optical trajectories to determine the information that fielders use as the basis of their actions under the assumption that this information is a cue for fielder actions. In fact, the information that fielders use as the basis of action is simultaneously a cue for and a result of action. There is a closed-loop relationship between what the fielder sees—the optical trajectory of the ball—and what the fielder does on the basis of what is seen—the fielder's actions. When this closed-loop situation is correctly analyzed using control theory, we find that the informational basis of catching is not a cue but rather a controlled result of action. In the jargon of control theory, the informational basis of catching is a controlled variable (Marken, 2001). To determine the informational basis of catching, it is therefore necessary to determine what optical variables fielders control when catching fly balls. The method used to do this is the control-theory-based Test for the Controlled Variable (TCV; Marken, 1997; Powers, 1973, pp. 232–234).

Testing for Controlled Variables

The TCV starts with a hypothesis about the variable that is being controlled by the behaving system. For example, in the case of catching fly balls, the starting hypothesis might be that the controlled variable—the one controlled by the fielder—is acceleration of tanα. One then applies disturbances to the hypothetical controlled variable and looks to see if these disturbances have the expected effects on the variable. In the case of acceleration of tanα, one could perturb the path of the fly ball in a way that would cause known variations in the acceleration of tan α if the fielder were not acting to keep that variable under control.

One evaluates the effects of disturbances by monitoring the state of the hypothetical controlled variable while known disturbances are being applied. The effects of these disturbances can be measured in terms of the correlation between time variations in the disturbance and concomitant time variations in the hypothetical controlled variable. For example, one can measure the correlation between variations in the disturbance applied to the trajectory of the ball and variations in the acceleration of tanα over time. A high correlation indicates that the disturbance is having the expected effect on the hypothetical controlled variable, because the behaving system is doing nothing to protect the variable from disturbance. A correlation close to zero indicates that the disturbance is not having the expected effect, because the behaving system is acting to protect the variable from the disturbance.

If disturbances do have the expected effects on the hypothesized controlled variable, then that variable is not under control in the sense that it is not being protected from the effects of the disturbances by the actions of the behaving system. If, for example, disturbances applied during a catch have the expected (or something close to the expected) effects on the acceleration of tanα, the hypothesis that acceleration of tan α is the controlled variable can be rejected. In this case, the next step in the TCV is to develop a new hypothesis regarding the controlled variable and to test again by applying disturbances to determine whether this new variable is under control.

If disturbances do not have the expected effects on a hypothesized controlled variable, then that variable is very likely under control in the sense that it is being protected from the effects of the disturbances by the actions of the behaving system. If, for example, disturbances applied during a catch have little or no effect on the acceleration of tanα —acceleration of tanα remains nearly constant—the hypothesis that acceleration of tanα is the controlled variable can be accepted, at least tentatively. The TCV continues until one comes up with a definition of the controlled variable that passes the test in the sense that it is protected from all disturbances that should have an effect on the variable.

Doing the TCV

We can use the fielder model to demonstrate the TCV. We start by imagining that we do not know what information the model is using as the basis of fly ball catching. That is, we place ourselves in the situation we are in when we test to determine the variable controlled by real fielders. We assume that what we know about the behavior of the model is what we know about the behavior of a real fielder. For example, we know that a fly ball traces out a nearly linear optical trajectory, like that in Figure 1, when the fielder runs to catch the ball. So we can start the TCV with the hypothesis that the fielder model is controlling for production of this LOT, which is equivalent to hypothesizing that LOT is a controlled variable.

If LOT is a controlled variable, then disturbances that change the trajectory of the ball while the ball is in flight should have little or no effect on the linearity of the optical trajectory. So we can test the hypothesis that LOT is a controlled variable by applying a disturbance to the trajectory of the ball that would make the LOT nonlinear if LOT were not controlled. We can select such a disturbance and easily apply it to the computer-generated trajectories of the balls caught by the fielder model—in this case, a sinusoidal change in the lateral position of the ball, which acts like a strong wind pushing the ball to the left and to the right during its flight.

Figure 3A shows the optical trajectories of two fly balls, one that was not affected by the lateral disturbance and one that was. The trajectories of the two fly balls would have been exactly the same had the lateral disturbance not been applied to one of them. The effect of the disturbance is clearly visible in the optical trajectory traced out during the catch, particularly in comparison with the nearly linear trajectory produced when no lateral disturbance was present. The effect of the disturbance on the hypothetical controlled variable can be quantified by measuring the correlation between lateral variations of the optical path (variations in β and variations in the disturbance to that path). This correlation is .98, showing that the disturbance to LOT was almost completely effective. The conclusion of the TCV is that the fielder model does not control LOT. And, indeed, it does not.

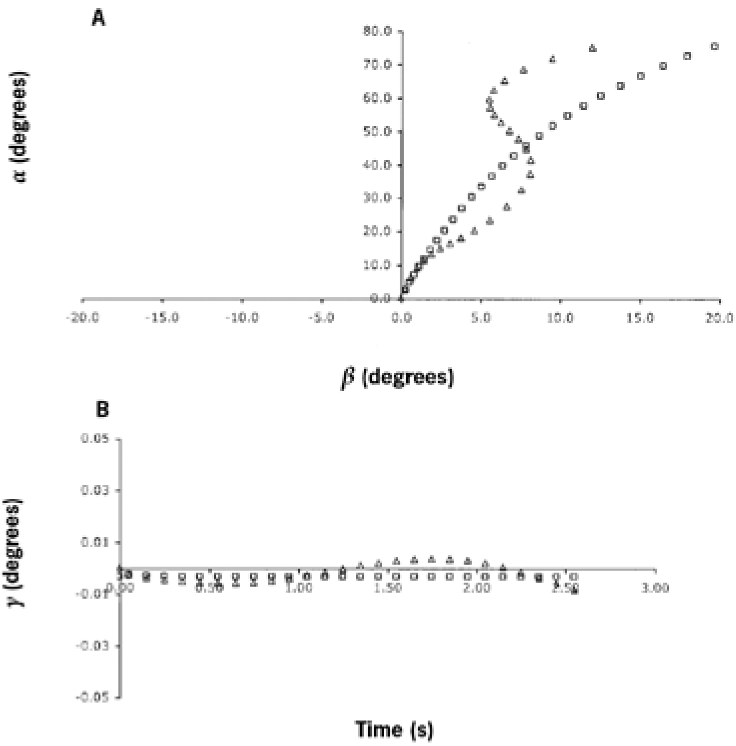

Figure 3. A: Optical trajectory with (triangles) and without (squares) sinusoidal disturbance to the lateral path of the ball. B: Lateral displacement (γ) of the ball image from the line of gaze plotted over time for the trajectories in Panel A.

The next step in the TCV is to continue looking for the variable controlled by the fielder model. Figure 3B shows the results of testing to see whether lateral displacement from the line of gaze (the variable γ) is a controlled variable. The two traces show lateral displacement over the course of the same two catches shown in Figure 3A. The disturbance appears to have some effect on lateral displacement, but that effect is quite small. The correlation between disturbance and lateral displacement is -.01. So the disturbance has very little effect on lateral displacement, which would lead one to conclude that lateral displacement (γ) is a controlled variable. And, indeed, lateral displacement is one of the variables controlled by the fielder model.

The results in Figure 3 show that a disturbance has a large effect on one possible controlled variable, LOT, but little or no effect on another, lateral displacement angle (γ). In this case, after testing only two hypotheses about the variable controlled by the fielder model, we hit on what we know to be one of the variables that is actually controlled by the model, lateral displacement angle (γ). The same type of testing could be done to determine that the other variable controlled by the model is rate of change in α. Control of this variable could be detected by applying disturbances to the vertical component of the ball's trajectory.

It should be noted that the disturbances used in this demonstration of the TCV produce ball movements that would be unrealistically large for a real ball moving through the air. These disturbances were selected for this simulation of the TCV to make their effect on an uncontrolled variable, such as β in Figure 3A, relative to their effect on a controlled variable, such as γ in Figure 3B, visually obvious.

Shaffer, Krauchunas, Eddy, and McBeath (2004) did something very much like the TCV using Frisbees as a means of producing nonparabolic trajectories. The optical trajectories of catches made when there was a large lateral change in the trajectory of the Frisbee (Shaffer et al., 2004, Figure 4, p. 440) resemble the optical trajectories of laterally disturbed balls caught by the fielder model, like the one shown by the triangle plot in Figure 3A. Shaffer et al. (2004) showed that a double (and, in one case, a triple) LOT could be fit to the optical trajectories observed when there were large midair perturbations, as there were with the Frisbee. A triple LOT would fit the laterally disturbed trajectory shown in Figure

3A rather well, even though these LOTs are not the informational basis of the catching done by the model. This shows again that one cannot determine the informational basis of catching by looking only at aspects of the optical trajectory alone. To determine the informational basis of catching, one must test for the lack of expected effects of disturbances to the aspects of the trajectory that are thought to be under control. That is, one must do some version of the TCV.

Methodological Considerations

When doing the TCV, it is important to apply disturbances that the system is capable of resisting. In other words, the system must be able to successfully control the hypothesized controlled variable. In the case of fly ball catching, this means that the hypothetical controlled variable should be disturbed in a way that does not make it impossible for the fielder to catch the ball. Disturbances that produce uncatchable balls will have a strong effect on the hypothetical controlled variable, but it will be impossible to tell whether this effect occurs because the fielder is not controlling the variable or because the fielder could not control it. In the example TCV shown in Figure 3, both the disturbed and the undisturbed fly ball were caught by the fielder model.

It is also important when doing the TCV, as it is in all experimentation, to be wary of the possibility of confounding. The potential confound of most concern in the TCV comes from the fact that the disturbances can affect the state of more than one possible controlled variable. In the case of catching, for example, disturbances that affect the acceleration of $\tan\alpha$ will also affect the velocity of $\tan\alpha$. To the extent that the actions that protect the acceleration of $\tan\alpha$ from disturbance also protect the velocity of $\tan\alpha$ from the same disturbance, it will be impossible to tell whether the variable under control is the acceleration of tanα or the velocity of tanα.

Removing confounds from the TCV requires ingenuity, as does removing confounds in any experimental testing situation. To remove such confounds, the experimenter must, of course, be aware of them and then be able to produce disturbances that will be resisted only if one variable rather than another is actually under control. In the case of fly ball catching, this will require the ability to generate very specialized disturbances to the trajectory of the ball. One way to produce such disturbances would be to use CAVE virtual reality technology (Zaal & Michaels, 2003), whereby a computer is used to add precisely calculated disturbances that affect only one hypothetical controlled variable at a time.

It is also important to note that the TCV is done on a person-by-person basis. The TCV does not assume that every person controls the same variables when performing a particular behavior. In the study of catching, for example, the TCV does not assume that all fielders control the same variables. Indeed, one goal of the TCV would be to see whether there is evidence that different fielders control different variables when they catch fly balls. The TCV should be able to detect any individual differences in the informational basis of catching. Indeed, the test could be used to determine whether there are differences across species in the variables controlled when catching (Shaffer et al., 2004). If there are such differences, it would be interesting to see whether catching is accomplished more effectively by controlling some variables rather than others.

Conclusion

McBeath et al. (1995) introduced an important innovation in the study of how fielders catch fly balls by using cameras to capture the optical trajectories of fly balls as seen from the fielder's perspective during catches. These optical trajectories show what fielders see when they run to catch a ball, but they do not show what fielders control while catching. To determine the informational basis of catching, it is necessary to determine the optical variable(s) that fielders control. This can only be done using some variant of the TCV, in which one looks for lack of effects of disturbances to hypothetical controlled variables.

The TCV still requires that one monitor what the fielder sees when catching balls: optical trajectories. But the TCV also requires that one look at the relationship between what the fielder sees—the possible controlled variables—and disturbances that should have an effect on what is seen. Aspects of optical trajectories that should be affected by these disturbances but are not are the informational basis of catching.

Illusions and Confusions

6 • The Illusion of No Control: A Perceptual Bias in Psychological Research

Abstract — The *Illusion of Control* is that people are in control when they are not (Langer, 1975); the *Illusion of No Control* is that people are not in control when they are (Powers. 1978). The present paper shows how the less familiar Illusion of No Control has influenced the way psychologists interpret the results of their research. The illusion results from a perceptual bias that inclines people to see behavior as controlled by external events (such as the independent variables in experimental research) rather than as a process of controlling aspects of the world that are affected by those events. This bias is an understandable consequence of the nature of control and can be exposed using the control theory-based Test for the Controlled Variable (TCV). The TCV provides a new approach to psychological research that focuses on the search for the variables that are controlled by rather than those that control behavior.

In a now classic paper, Ellen Langer (1975) showed that people often perceive themselves as having control in situations where they actually have none, a phenomenon that has been dubbed the *Illusion of Control*. At nearly the same time, William T. Powers (1978) showed that people often perceive others as having no control in situations where they actually do, a phenomenon that could be called the *Illusion of No Control*. Both of these illusions have important implications for how psychologists understand human behavior and cognition. But psychologists have devoted most of their attention to the *Illusion of Control*, perhaps because it has obvious practical implications, being clearly relevant to the treatment of dysfunctional behaviors such as compulsive gambling (eg. Langer & Roth, 1975; Toneatto, Blitz-Miller, Calderwood, Dragonetti & Tsanos, 1997). The present paper focuses on the less familiar but no less important *Illusion of No Control*, which has significant implications for scientific psychology, being relevant to how psychologists interpret the results of their research (Marken, 2002; Powers, 2005).

The Illusion of No Control

The difference between behavior that involves control and that which does not mirrors the distinction made in neurobiology between voluntary and involuntary behavior (Alters & Alters, 2005). Behavior that involves control is equivalent to voluntary behavior; it is behavior that is done intentionally, "on purpose". Behavior that involves no control is equivalent to involuntary behavior; there is no control over this behavior because what is done is caused by external events. The *Illusion of No Control* is seen when behavior that is actually voluntary appears to be involuntary. For example, the illusion is seen when a person abruptly turns to see an attractive passer-by. The appearance is that the turning is elicited by the sight of the passer-by when, in fact, the turning is done intentionally in order to keep the passerby in view (Marken, 1997).

The *Illusion of No Control* is particularly compelling in psychological experiments. The illusion is that the behavior of the participants in these experiments is involuntary (elicited by the independent variable) when it is not. For example, the illusion can be seen in the classic "conformity" experiments in social psychology where the conforming judgments of some participants seem to be elicited by the judgments of the other "stooge" participants (Asch, 1951). In fact, the conforming behavior of the participants is voluntary; those who go along with the stooge participants are doing so on purpose.

Is It Real or Is It Illusory

In order to determine whether or not an appearance is an illusion you have to develop tests that allow you to see what is actually happening. For example, in the classic Mueller-Lyer illusion (Fig. 1) the appearance is that the two horizontal lines are of unequal length; the line with tails that point out appears longer than the one with tails that point in. You can test to determine whether or not this appearance is illusory by measuring the length of each line with a ruler. When you do this you will find that the lines are of equal length; the appearance of unequal lines is an illusion.

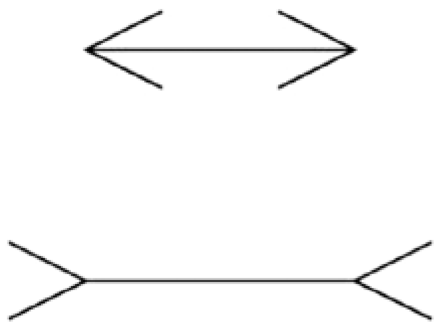

Figure 1. The Muller-Lyer, a classic visual illusion.

As with the Mueller-Lyer, the *Illusion of No Control* can be seen to be an illusion only by determining whether what appears to be happening actually is. The appearance of voluntary behavior being involuntary – the *Illusion of No Control* – is equivalent to the appearance of equal length lines being unequal (the Mueller-Lyer illusion). Thus, in order to determine whether the appearance of involuntary behavior is an illusion we need something equivalent to the ruler that is used to determine that the appearance of unequal lines in the Mueller-Lyer is an illusion.

The "ruler" that can be used to tell whether or not the appearance of involuntary behavior is an illusion is a set of research tools known collectively as the Test for the Controlled Variable or TCV (Powers, 1979; Marken, 2009). Like the ruler in the Muller-Lyer illusion, the TCV can be "held up" to behavior to see whether it is voluntary or not. The tools that make up the TCV are based on the assumption that voluntary behavior is a process of control. Therefore, in order to understand how the TCV works it is first necessary to understand the nature of the phenomenon that it measures: the phenomenon of control.

The Phenomenon of Control

Control is an objectively observable phenomenon that can be seen in the behavior of certain devices, called control systems (Bennett, 1979), as well as in that of living organisms, such as people (Marken, 1988). Control is the process of producing preselected results in the face of environmental disturbances that would otherwise prevent these results from occurring. For example, control can be seen in the behavior of the home thermostat, a control system that produces a pre-selected result – a room temperature of, say, 68° – in the face of disturbances – such as variations in outdoor air temperature and the number of people in the room – that would otherwise prevent this result from occurring. Control can also be seen in the behavior of the driver of a car, who produces preselected results – such as maintaining a safe distance from other cars – in the face of disturbances – such as variations in the speed and direction of the other cars – that would otherwise prevent this result from occurring.

The preselected results produced by devices such as the thermostat and by living organisms, like the driver, are the states of variables. A room temperature of 68° is clearly the state of a variable: room temperature. A safe distance is also the state of a variable:

distance. So another way to define control is as a process of keeping variable aspects of the world in predetermined states, protected from the effects of disturbances that would otherwise cause these variables to deviate from these states. The variables that are being kept in predetermined states, protected from disturbances, are called *controlled variables*.

The existence of controlled variables is evidence that control is happening. A controlled variable is an aspect of the world that remains stable when it is clear that it should be varying due to changing circumstances. For example, room temperature can be seen to be a controlled variable if it stays at 68° despite the fact that outside temperature is rising or plummeting. Room temperature should be varying along with these changes in outside temperature. The fact that the room temperature remains constant means that it is probably under control; room temperature is probably a controlled variable.

The same is true with cars that follow at a safe distance from the cars in front. Since the cars being followed are constantly changing their speed the distance between cars should be varying considerably with the following car often bumping the car in front. But cars very rarely bump the car in front. A safe distance is maintained despite the disturbances created by variations in the speed of the cars in front; the distance between cars is clearly a controlled variable.

How Control Works

Controlled variables, like room temperature and the distance between cars, do not remain in predetermined states by accident. There must be active opposition to the disturbances that would otherwise move these variables from their predetermined states. And this opposition must be quantitatively precise. The thermostat system must produce just the right heating or cooling needed to offset the changes in outdoor temperature and keep the room temperature at 68°; the driver of the following car must produce just the right acceleration or deceleration needed to offset the changes in speed of the car in front and maintain a safe following distance. The behavioral organization that does this – that keeps controlled variables under control – is a closed-loop negative feedback system like that shown in Figure 2.

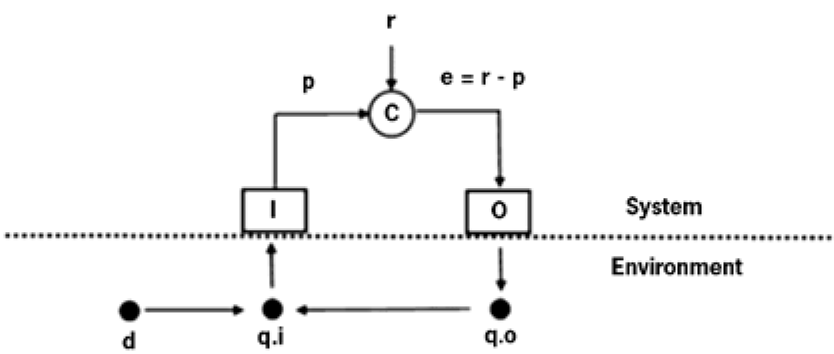

Figure 2. Functional diagram of a negative feedback control system.

Figure 2 represents a model of how control works based on control theory (Powers, 2005); it is a functional diagram of a control system (System), such as a thermostat or driver, acting to control a variable aspect of the environment, such as temperature or distance, which exists outside of the system (Environment). The aspect of the environment that is under control is the input variable, q.i, which is the controlled variable. The value of q.i at any instant depends on what the system does (the output variable, q.o) as well on environmental disturbances, (the disturbance variable, d). In the case of the thermostat, q.i is room temperature, q.o is the output of the heater/air conditioner and d is variations in outdoor air temperature; in the case of the driver, q.i is the distance between cars, q.o is the speed of the following car and d is the speed of the lead car.

The System in Fig. 2 must precisely vary its outputs, q.o, so as to compensate for disturbances, d, and keep the controlled variable, q.i, in a predetermined state. It does this by comparing a perceptual representation of the controlled variable, p, to a reference signal, r, that specifies the desired state of p. The reference signal represents the "predetermined" state of q.i. Any difference between r and p is an error signal, e, that drives variations in system output, q.o, which affect the state of the controlled variable, q.i, and the corresponding perception, p. The effect of system output, q.o, on the perception of the controlled variable, p, is called *feedback*. Feedback completes a closed loop of causality that runs from q.i to p to e to q.o and back to q.i. When variations in q.o reduce the difference between r and p there is *negative feedback*; the feedback is negative because variations in q.o are *reducing* error (r-p) which is the cause of those variations.

When there is negative feedback in the relationship between a system and the perception of an environmental variable, q.i, then the environmental variable is under control. The system is varying its output, q.o, to compensate for disturbances to q.i and keep it in a predetermined state, which is defined by the system itself in terms of its setting of the value of the reference signal, r. By changing the value of r the system changes the state in which the variable q.i is maintained. For example, if Fig. 2 represents a driver controlling for a safe distance, then q.i is the distance between cars and r defines the distance that the driver considers safe. The driver produces outputs, q.o, in the form of variations in the speed of the car that compensate for disturbances to q.i and keep the perception of the distance between cars equal to r. If the cars are moving slowly r may be set at a value that represents a closer distance than when the cars are moving fast. But regardless of the setting of r the driver will keep the perception of q.i close to r while protecting it from disturbances.

The Test for Controlled Variables

The control theory model in Fig. 2 provides a basis for determining whether or not any particular behavior involves control. The first step is to recognize that the term "behavior" refers to system outputs, q.o, as well as the results of these outputs, q.i. The model shows that there is control involved in behavior if system outputs vary in such a way as to protect q.i from the effects of disturbances. That is, control exists if some result of a system's outputs, q.i, is a controlled variable. Thus, the way to test to see if some behavior involves control is to apply disturbances to a possible controlled variable, q.i, and measure their effect on that variable. If disturbances have far less effect than would be expected and this lack of effect can be traced to the outputs of the system then the behavior of the system can be considered to involve control; q.i is a controlled variable. This is the basic procedure used in the Test for the Controlled Variable or TCV.

A simple example of the use of the TCV is determining whether the behavior of "following" involves control. Suppose you are driving down the street and notice that a car has been following you. To determine whether this following behavior involves control you start by guessing that the driver of the car behind you is controlling the distance between cars; this distance is the possible controlled variable, q.i. This variable is affected by the speed and direction of the following car, which are the outputs of the driver of that car. Disturbances to this variable are the direction and speed of your own car. If the car behind is controlling for following then these disturbances will have little or no effect on the car's distance behind you.

So you can test to see if following involves control by randomly varying your speed and direction and watching to see if these disturbances have any effect on the distance between yours and the following car. If they do have an effect – if, for example, the distance increases substantially as the following car goes off in a different direction after you make a turn – then the following is not under control. If, however, the distance between cars stays nearly constant (the following car stays behind) after several random changes in speed and direction, then you are being tailed; the following involves control inasmuch as the distance between cars is a controlled variable. A demonstration of testing for "following" is available on the Internet (Marken, 2012).

Illusions of No Control

With the TCV in hand it is possible to determine whether or not control is involved in some well-known examples of behavior that appear to involve no control. That is, we can use the TCV to see whether or not these behaviors are examples of the *Illusion of No Control*.

Reflexes. The prototypical example of behavior that involves no control – involuntary behavior – is the reflex. A familiar example is the patellar or "knee-jerk" reflex that occurs when the patellar tendon (just below the kneecap) is hit with a hammer (Weiner, 2010). The knee-jerk seems to be an involuntary response to the hammer tap; it is a behavior that seems to involve no control. In fact the patellar reflex is part of a control system that is aimed at controlling the perceived angle of the knee or a variable, such as muscle length, that is related to this angle. The normal disturbance to this variable is changes in the forces on the knee that are produced while walking, running or lifting. The hammer tap is an artificial disturbance that is equivalent to a sudden force, such as landing on the foot while running, that would buckle the leg. The knee jerk results from the muscle contraction that counters this disturbance and prevents buckling.

The *Illusion of No Control* occurs in reflex behavior when the disturbance to the controlled variable is abrupt, as it is in the case of the patellar reflex. The abrupt tap disturbance to knee angle, which makes it seem like the knee has buckled, is removed just as the control system is causing upward muscle forces that would maintain the current angle. But the knee angle never really changed so the upward restoring forces lift the foreleg unnecessarily and what is seen is a kick in response to the tap stimulus.

The fact that control is going on in the patellar can be seen more clearly by holding the TCV up to this behavior. This is done by observing the effect on the presumed controlled variable, knee angle, of disturbances that vary fairly smoothly over time, as they do during running and walking. In this case control can be seen in the fact that the controlled variable remains the same each time the leg hits the ground; the knees never buckle because knee angle is protected from disturbances by the forces exerted by the leg muscles – the muscles that produce the apparently involuntary "knee jerk" in response to the abrupt tap on the tendon.

Selection by Consequences. Another well-known example of behavior that involves no control is that seen in operant conditioning experiments. Rather than being in control, the animals in these experiments appear to be under control. Indeed, their behavior appears to be controlled (selected) by its consequences (Skinner, 1981). Some consequences, called positive reinforcement, select behavior by increasing the strength of the behavior that produced them; other consequences, called negative reinforcement, "deselect" behavior by decreasing the strength of the behavior that produced them. The organism appears to have no control; it's the consequences that are in control.

But the behavior in operant conditioning experiments that appears to involve no control might actually involve control. Again we can test this by holding the TCV "ruler" up to operant behavior to see if we are seeing an *Illusion of No Control.* The first step in using the TCV is to guess what might be under control in these experiments. One possibility is that a controlled variable is the rate at which reinforcements occur (Powers, 1971). Evidence for this comes from studies in which the number of responses required to produce a reinforcement – the so-called "schedule of reinforcement" – is varied. If the rate of reinforcement is under control then varying the number of responses needed to produce a reinforcement will act like a disturbance to the rate at which reinforcements arrive; as the number of required responses increases, the rate of responding should also increase in order to compensate for this disturbance and keep the reinforcements coming at the same rate. And this seems to be what happens (Timberlake, 1984; Yin, 2013). The rate at which reinforcements are delivered is apparently a controlled variable, protected from disturbances, such as variations in the schedule of reinforcement delivery, by variations in response rate. The organisms in operant experiments appear to be controlled rather than in control but the TCV suggests that this is an example of the *Illusion of No Control.*

Causation in Psychological Experiments. Experiments in psychology are aimed at finding causal relationships between environmental (independent) and behavioral (dependent) variables (eg., Levitan, 2002). And these relationships, though somewhat noisy due to the high level of variability of behavior, are regularly found. These results are taken to mean that the behavior of the participants in these experiments involves no control; it is the independent variables that are in control, not the participants themselves. But there is reason to believe that this is another example of the *Illusion of No Control* (Powers, 1978). Again, this can be tested by holding the "ruler" of the TCV up to the behavior seen in psychology experiments.

A simple example of a psychology experiment is the choice reaction time task where a participant makes one of two different responses based on a signal. For example, the participant might be asked to move a switch one way if a light signal is red and the opposite way if it is green. The color of the light is the independent variable and the switch movement is the dependent variable. Marken (2013) used the TCV to determine whether or not control is involved in this type of experiment. The hypothesis was that there was control and that a perception of the relationship between signal color and the switch response is the controlled variable. This was tested by seeing whether the hypothetical controlled variable was protected from disturbance. The disturbance was applied to the switch response component of the hypothetical controlled variable and it was found that participants kept the relationship between signal light and switch movement under control by varying the direction of switch movement appropriately.

The TCV can also be done using mathematical or computer modeling. This approach to the TCV was used to determine whether or not control was involved in a particular kind of experiment known as magnitude estimation (Stevens, 1957). In the simplest magnitude estimate experiment the participant produces a number whose size is proportional to the magnitude of a stimulus. The different values of the stimulus are the independent variable and the numerical magnitude estimates are the dependent variable. The appearance is that there is no control involved in this experiment; the magnitude estimates appear to be made in response to the stimulus magnitudes. However, another possibility is the participants are controlling the relationship between their perception of the magnitude of the stimuli and the magnitude estimates themselves. Again, the hypothesis is that a perceived relationship is the controlled variable in this experiment.

Marken (2008) tested this hypothesis using a mathematical modeling version of the TCV. The observed relationship between stimulus and response in a magnitude estimation task is a power function (Stevens, 1957). But such a relationship will be found if participants are controlling the relationship between perceptions that are a log function of the stimulus and response. While it has been known for some time that the power relationship observed in magnitude estimation studies could be derived from the assumption that the perception of stimulus and response are logarithmic (MacKay, 1963), this fact has only recently been seen as a method of testing to determine whether control is involved in the magnitude estimation task.

The Behavioral Illusion. The difference between the observed power relationship and the presumed actual log relationship between stimulus and response in the magnitude estimation experiment is a version what has been called the *behavioral illusion* (Powers, 1978). The behavioral illusion, illustrated in Figure 3, is that the relationship between stimulus (independent) variables and response (dependent) variables in a psychological experiment reflects characteristics of the behaving system when, in fact, it reflects characteristics of the environmental feedback function that connects the system's outputs (O) to a controlled perceptual input (I): the controlled variable.

The behavioral illusion is a direct consequence of succumbing to the *Illusion of No Control*. Figure 3 shows an experimenter trying to determine whether the observed relationship between a stimulus

(IV) and response (DV) in an experiment reflects characteristics of the participants in the experiment (upper thought cloud) or of the feedback connection between the participants outputs (O) and a controlled input variable (I).

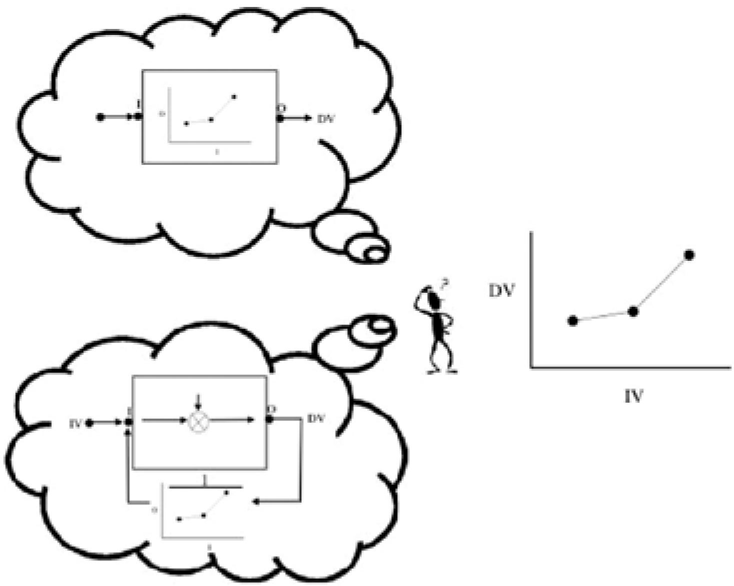

Figure 3. The "Behavioral Illusion".

If the experimenter sees the behavior in the experiment as involving no control when it actually does involve control (that is, if the experimenter succumbs to the *Illusion of No Control*) then the observed relationship between IV and DV will be taken to reflect psychological characteristics of the participants when, in fact, this relationship actually reflects characteristics of the feedback path in a control loop.

The *Illusion of No Control* can, thus, lead to a serious misinterpretation of the results of psychological experiments. The way to avoid this problem is to test, using some version of the TCV, to determine whether or not the behavior under study involves control before jumping to conclusions about what the results of an experiment say about the psychological processes underlying the observed behavior.

How Illusory is the Illusion of Control?

If people are in control when it appears that they are not then it is possible that people are not always mistaken when they say they are in control when it appears that they are not. That is, the *Illusion of Control* may sometimes be no illusion at all but, rather, another instance of the *Illusion of No Control*, with the observers of the people doing the controlling who are subject to the illusion (Gino, Sharek, & Moore, 2011). The *Illusion of Control* is typically demonstrated by having people estimate how much control they believe they have over completely random events (Presson & Benassi, 1996, Taylor & Brown, 1988; Tennen & Sharp, 1983; Thompson et al., 1998; 2004; Biner, Johnston, Summers,& Chudzynski,, 2009). People are said to be experiencing the *Illusion of Control* when they overestimate the amount of control they have over these events.

Asking people whether or not they are in control of some event is tantamount to asking whether that event is a controlled variable. It is well known that people are not particularly good at describing the cognitive basis of their own behavior (Nisbett & Wilson, 1977) so it should be no surprise that people find it difficult to identify the variables they control. For example, it is unlikely that people would identify vertical optical velocity as the variable controlled when catching a fly ball but research suggests that it is (Marken, 2001).

So when people say that they are in control of some event over which they actually have no control they may be referring to the control they have over some variable that involves that event and not necessarily to the event itself. For example, when asked whether they have control over the results of a coin toss, some people might say "yes", not because of some imagined control they have over how the coin will come up but because of some real control they have over the relationship between the frequency with which they say "heads" and "tails" and the actual frequency with which these events have occurred. And studies show that people do control for matching the frequency of their guesses to the frequency of random outcomes even though this is not the "optimal" strategy when one outcome occurs more frequently than another (Duda, Hart & Stork, 2001).

So people who seem to be succumbing to the illusion that they are in control when it looks like they are not – the *Illusion of Control* – may actually be in control. It just may be that the variable they are controlling – the controlled variable – may not be the one they say they are controlling. Again, when there is a question of whether or not control is involved in any instance of behavior, it is better to answer this question using some version of the TCV rather than by simply asking people whether or not they are in control.

Conscious and Unconscious Control

The fact that people are often controlling variables that they are not aware of controlling is strong evidence that controlling can occur unconsciously. Of course, people are also able to control consciously, as they do when asked, for example, to control the position of a cursor in a tracking task (Marken, 1982). So it is clear that the question of whether any example of behavior involves control or not is orthogonal to the question of whether control is conscious or not (Bargh & Marsella, 2008; Schlosser, 2012; Wegner & Wheatley, 1999).

The TCV can be used to determine whether or not any particular example of behavior involves control but it cannot be used to determine whether or not control is occurring consciously or unconsciously. The *Illusion of No Control* can occur whether control is occurring consciously or unconsciously. All that is needed is that the behavior involves control and that the observer of the behavior notices only the side effects of control – the actions that protect a controlled variable from disturbance and appear to be a reaction to the disturbance – while failing to notice the existence of the controlled variable itself.

Conclusion

This paper described the *Illusion of No Control*, which could be considered the mirror image of the well-known *Illusion of Control*. The *Illusion of No Control* occurs when behavior that involves control is seen as being caused or controlled by external events. In order to see that this is an illusion it is necessary to be able to "hold a ruler" up to the behavior under question to determine whether or not it actually involves control. This can be done using the control-theory based Test for the Controlled Variable (TCV). Different versions of the TCV were used to show how several well-known examples of behavior that appear to involve no control actually do involve control; these behaviors are examples of the *Illusion of No Control*. Recognizing the difference between behaviors that do and do not involve control requires an understanding of what control is and how it works. This paper gives a brief introduction to both of these topics; control is described as the process of keeping variable aspects of the environment – controlled variables – in predetermined states, protected from disturbances and this control is accomplished by the operation of a closed-loop negative feedback control system. The examples of the *Illusion of No Control* described in the paper show that failure to recognize control when it is happening – succumbing to the *Illusion of No Control* – can lead to serious misinterpretations of the psychological processes that underlie the observed behavior.

7 • The Power Law: An Example of a Behavioral Illusion

Abstract – Perceptual Control Theory (PCT) shows that a "behavioral illusion" can occur when studying closed-loop control systems. The illusion is that an observed relationship between environmental inputs and behavioral outputs reflect characteristics of the system itself when it actually reflects properties of the feedback connection between the system's output and a controlled perceptual input. A possible example of such an illusion is Stevens' Power Law, which says that the observed relationship between input and output in magnitude estimation experiments represents perceptual characteristics of the person under study. A PCT analysis shows that the Power Law is more likely to represent the inverse of a logarithmic feedback function connecting magnitude estimates to the perceived difference between numerical and stimulus magnitude. The possible existence of this behavioral illusion suggests that the first step in psychological research should be to test whether the behavior under study is that of a closed-loop system.

According to the Perceptual Control Theory (PCT) model of behavioral organization, living organisms are closed-loop systems that act to keep perceptual variables in pre-specified states, protected from disturbances caused by variations in environmental circumstances (Powers, 1973b). This process is called *control* and the perceptual variables that are maintained in pre-specified states are called *controlled variables* (Marken, 2001, page 101). To an outside observer, the actions that protect a controlled variable from disturbance will appear to be outputs that are caused by those disturbances. This is especially true if the existence of the controlled variable itself goes unnoticed (Cziko, 2000, page 88).

The causal path from disturbance to output will appear to run in one direction, starting with the disturbance, going through the behaving system and ending with the output action. The relationship between disturbance and output variations will, therefore, appear to represent the transfer function that characterizes the internal organization of the behaving system. However, in a closed-loop control system this relationship actually reflects characteristics of the feedback connection between system output and controlled variables.

Thus, when one deals with a closed-loop control system, observed relationships between environmental disturbance and behavioral output variables can create a "behavioral illusion" (Powers, 1978, page 421). The illusion is that the relationship between environmental and behavioral variables reflects characteristics of the system under study when, in fact, it reflects characteristics of the environmental feedback function that connects system output to a controlled perceptual input: the controlled variable.

An Example of a Behavioral Illusion

An example of a behavioral illusion can be seen in a simple tracking type experiment. Suppose that a participant is asked to operate a control lever to place a pointer next to a vertically movable target. As the target is moved up and down, from one position to another, the participant moves the lever to bring the pointer to each new position. For simplicity we will consider only one-dimensional tracking. If the target is moved 10 cm in one direction it is observed that the participant moves the hand on the lever through an arc of, say, 20 degrees in the opposite direction, and this relationship holds for all movements of the target. So it seems that there is a simple cause-effect relationship such that each centimeter of target movement is sensed by the participant, and causes the hand to move 2 degrees.

Now let us say that behind the scenes, the effect of the lever on the pointer is doubled, by moving the pivot point closer to the place where the lever is grasped. If the participant continues to succeed in bringing the pointer to the target position each time the target moves, we will now see that a 10-cm movement of the target produces a hand movement of only 10 degrees. It now seems that the sensitivity of the participant to target movements has changed: a stimulus of 10 cm of target movement causes only half as much response as before. It seems as if the participant has become less responsive to changes in the stimulus.

In fact, the responsiveness of the participant has not changed at all. The task is to put the pointer next to the target, and this is accomplished whether doing it requires a large or a small movement of the lever. The ratio of hand movement to target movement is determined, in that case, entirely by the placement of the fulcrum, which changes the "feedback function" that connects the participant's action (lever movement) to the position of the pointer. The feedback function is a simple constant of proportionality in this thought experiment, but the same principle will obviously hold for any form of the feedback function, given that the participant continues to keep the pointer on the target. The lever angle, and hence the hand position, is just the inverse feedback function of the target position – a property of the physical environment, not of the participant.

The Behavioral Illusion and Scientific Psychology

Powers (1973a) has pointed out that the possible existence of this behavioral illusion has important implications for scientific psychology. Most experimental research in psychology involves manipulation of an environmental stimulus variable, e, as an independent variable and measurement of concomitant variation in a behavioral response variable, o, as a dependent variable (Marken, 1997). Any observed functional relationship between e and o is assumed to reflect characteristics of the organism under study. If o is found to be a function of e, such that o = f(e), the function, f, is assumed to reflect characteristics of the organism.

If, however, the organism under study is a closed-loop control system then e is likely to be a disturbance to a perceptual variable, p, that the organism is controlling and o is likely to be the means the organism uses to counter the effects of e and keep p under control. That is, the independent variable in an experiment is likely to be equivalent to the moving target in the tracking example described above. The dependent variable is likely to be equivalent to the movement of the hand on the lever. And the controlled variable, p, would be equivalent to the distance between pointer and target. The controlled variable, if it exists in an experiment, will be difficult to notice because it is a perception controlled by the organism itself, not by the experimenter.

An observed functional relationship between independent and dependent variable in a psychology experiment is assumed to reflect characteristics of the organism under study. Thus, if o is found to be a function of e, such that o = f(e), the function, f, is assumed to reflect characteristics of the organism. If, however, the organism is a closed-loop control system, then f is actually the inverse of the feedback function, g, which relates o to the controlled variable, p. That is, if p = g(o) then f = g^{-1}.

So the functional relationship between independent and dependent variable found in an experiment on a closed-loop system will appear to reflect properties of the organism when, in fact, it may actually reflect properties of the environmental feedback connection between an the organism's output and a perceptual variable it is trying to keep under control. Thus, the observed functional relationship between e and o that seems to characterize the organism under study may be a behavioral illusion if the organism is actually a closed-loop control system.

Stevens' Power Law

It is somewhat difficult to find possible examples of the behavioral illusion in the psychological research literature because the environmental variables manipulated in psychological experiments are typically qualitative. Therefore, the results of such experiments are rarely expressed in the form of an equation showing the quantitative relationship between the independent (e) and dependent (o) variable. One example of research where the relationship between e and o is expressed in the form of an equation is in studies of the relationship between stimulus and psychological magnitude. These are the magnitude estimation experiments developed by S. S. Stevens (1957).

In magnitude estimation experiments a "standard" stimulus is presented and the participant is told a value to assign to it: a "modulus". Then the same stimulus with a different magnitude is presented and the participant is told to express its perceived magnitude as a second number. The ratio of the second number to the modulus is taken to be the ratio of perceived magnitudes of the stimuli. The obtained data led to the Power Law, where the exponent and the constant of proportionality were determined by curve-fitting:

$$(1) \quad o_n = k e_s^{\,a}$$

where e_s is the environmental stimulus variable and o_n is the participant's numerical response, which is taken to be proportional to the perceptual magnitude of e_s, $\psi(e_s)$. Assuming as Stevens did that $\psi(e_s) = o_{n,}$ we can write

$$(2) \quad \psi(e_s) = k_S \, e_s^a$$

The Power Law caused quite a sensation because it seemed to contradict Fechner's law, which held that the relationship between stimulus and perceptual magnitude is logarithmic (Boring, 1950). Fechner's law is given by the following equation:

$$(3) \quad \psi(e_s) = k_F \log(e_s)$$

Fechner's law was based on Ernst Weber's finding that the size of a Just Noticeable Difference or JND between two magnitudes of the same stimulus, e_{s1} and e_{s2}, was proportional to stimulus magnitude. This translates into equation 1, assuming that the subjective size of the JND, in terms of the perceptual magnitudes of e_s, $\psi(e_{s1})$ and $\psi(e_{s2})$, is constant over all magnitudes of e_s.

Control of Magnitude Estimates

The two laws can be reconciled by recognizing that the Power Law may be an example of a behavioral illusion. The exponential relationship between e and o that is observed in magnitude estimation experiments seems to characterize the nature of the participant's response to different stimulus magnitudes but it may actually characterize the nature of the feedback function in a control loop. This possibility can be seen by recognizing that the participant in a magnitude estimation task is *controlling* a relationship between the perception of stimulus magnitude and a perception of the number given as an estimate of that magnitude.

The situation is shown in Figure 1. The independent variable in the experiment is the magnitude of the stimulus presented on each trial, e_s, and the dependent variable is the number assigned to that stimulus, o_n. The participant is to produce a value of o_n that somehow matches the magnitude of e_s. Interpreted as a control process, this means that the participant must keep the perception of o_n, $\psi(o_n)$, equal to the perception of e_s, $\psi(e_s)$, on each trial. So the controlled perception in the experiment is $\psi(e_s)$ - $\psi(o_n)$ and the participant is to keep this difference equal to zero (as indicated by the 0 next to the reference in Figure 1), which will happen when $\psi(e_s) = \psi(o_n)$.

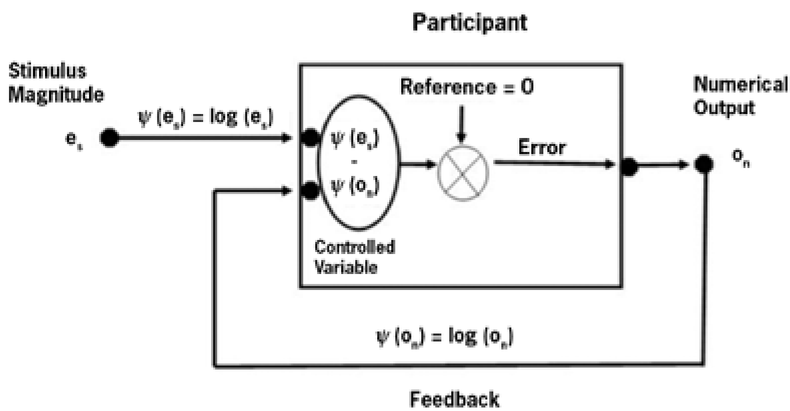

Figure 1. Closed-loop analysis of magnitude

In order to keep $\psi(e_s)$ - $\psi(o_n) = 0$ on each trial the participant must produce numerical estimates, o_n, that are perceived to be equal to the perceived stimulus magnitudes, $\psi(e_s)$. The relationship between numerical estimates, o_n, and how they are perceived, $\psi(o_n)$, is described by the function connecting o_n to $\psi(o_n)$ in Figure 1. This is a feedback function but in this case the function is a characteristic of the perceptual rather than the environmental connection between output and input. This is the function that relates the perception , $\psi(o_n)$, of the magnitude of numbers to the number stimuli themselves, o_n. Assuming that Fechner's law applies to the perception of the magnitude of numbers as well as to the magnitude of any other stimulus, we have:

(4) $\psi(o_n) = k_1 \log (o_n)$

for the perception of number magnitude and

(5) $\psi(e_s) = k_2 \log (e_s)$

for the perception of stimulus magnitude.

When the participant in a magnitude estimation experiment selects a number, o_n, such that $\psi(o_n) = \psi(e_s)$ (keeping the controlled perception $\psi(o_n) - \psi(e_s) = 0$) it follows that:

(6) $k_1 \log(o_n) = k_2 \log(e_s)$, or after simplification,

(7) $o_n = e_s^{(k2/k1)}$

Thus, assuming that participants are controlling a relationship between perceptions of stimulus and numerical magnitude in a magnitude estimation task and that Fechner's law applies to perception of the sizes of numbers as well as other stimuli, it is predicted that in the magnitude estimation experiment the participant will pick a number proportional to a power of the stimulus.

Equation (7) is an example of the behavioral illusion to the extent that it is seen as a reflection of the nature of the human response to varying stimulus magnitudes. Control theory shows that the Power Law relationship described by equation (7) is not a characteristic of the organism's perceptual system but, rather, is the inverse of the logarithmic feedback relationship that exists between numerical outputs, o_n, and the controlled perception: $\psi(o_n) - \psi(e_s)$.

Discussion

A PCT analysis of the magnitude estimation task (Figure 1) shows that the observed Power Law relationship between the size of stimuli, e_s, and the numbers that are used to describe their size, o_n, could be a behavioral illusion in the sense that it could be the inverse of a logarithmic feedback connection between actions and a controlled perceptual variable. Participants in a magnitude estimation experiment can be seen to be controlling the relationship between the perception of e_s and o_n; this relationship is a controlled perceptual variable. The logarithmic function relating numerical responses to the perception of those responses represents the feedback connection between the participants' outputs and the controlled variable. PCT predicts that the relationship between e_s and o_n will be the inverse of this feedback function, which is the Power Law. When magnitude estimation is seen as the control of the relationship between $\psi(o_n)$ and $\psi(e_s)$, Stevens' Power Law can be seen as a behavioral illusion completely predicted by Fechner's logarithmic law. The Power Law describes not characteristics of the perceptual system of the organism but the inverse of those characteristics.

The inverse relationship between Stevens' Power Law and Fechner's Logarithmic Law has been known for some time (MacKay, 1963). What is original in the present analysis is the use of this relationship to illustrate a "behavioral illusion" that can occur in research aimed at determining the internal organization of what turns out to be a closed-loop control system. In the magnitude estimation experiment, the "illusion" is that the internal organization (perceptual function) that relates stimulus to response magnitude is the observed Power Law when, in fact, it is a logarithmic function. This illusion occurs because magnitude estimation is a closed-loop task that requires control of the perception of a relationship between two stimulus magnitudes.

The possible existence this "behavioral illusion" should serve as a caution to all researchers who study behavior by looking at the relationship between environmental variables and behavioral responses. An "illusory" relationship between these variables will be seen whenever an environmental variable (such as stimulus magnitude, e_s in the magnitude estimation task) acts as a disturbance to a perceptual variable (such as the relationship between stimulus magnitudes) that is being controlled by a closed-loop control system. The control system will act to counter the disturbance with behavior (such as the numerical response, o_n, in the magnitude estimation task) that operates on the controlled variable through an environmental feedback path. This creates the illusion that the observed relationship between environmental and behavioral variables describes a causal path through the organism when, in fact, it describes the inverse of the feedback connection between behavior and controlled variable (Powers, 1973a, 1978).

The way to avoid the behavioral illusion is to make sure that there is no possibility that the system under study is closed-loop with respect to the variables in an experiment. This can be done using the control theory-based Test for the Controlled Variable or TCV (Marken, 1997; 2001; 2005). The TCV makes it possible to determine whether the independent and dependent variables can be treated as the beginning and end on an open-loop causal chain (as is typically assumed) or must be treated as having opposing influences on a perceptual variable controlled as part of a closed-loop.

Acknowledgment

I would like to thank William T. Powers for his helpful suggestions and comments on this paper.

8 · Control Theory for Whom?[19]

Control theory is a set of mathematical equations that describe the mechanisms that make it possible for living and artificial systems to control variables in their environment. Engineers use the theory as a basis for building artificial control systems (such as thermostats) and behavioral scientists use it as a basis for understanding the behavior of living control systems (such as humans). While the control theory used by engineers is mathematically identical to that used by behavioral scientists, the way the theory is used is quite different in the two cases. The difference turns on the fact that engineers know what variables they want their artificial systems to control while behavioral scientists want to find out what variables living systems actually do control. Engineers use the equations of control theory to help them build systems that will effectively control the variables they (the engineers) want controlled. Behavioral scientists use the equations of control theory to help them understand how living systems effectively control the variables that they (the living systems) want controlled.

While there are many texts that describe control theory for the benefit of engineers, there are few that describe it for the benefit of behavioral scientists. *Control theory for humans* represents an attempt to remedy this imbalance by providing a detailed description of control theory for students in the behavioral sciences. The book is successful inasmuch as it provides a very complete and lucid description of the mathematical details of control theory itself. It is less successful, however, in presenting the theory in a way that is useful to the behavioral scientist. This is because the book approaches control theory more from the point of view of the

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19 A review of *Control theory for humans: Quantitative approaches to modeling performance* By R. Jagacinski and J. Flach (NJ: Erlbaum, 2002)

engineer than from that of the behavioral scientist. In particular, the book assumes that the behavioral scientist, like the engineer, knows what variables are being controlled by the system under study. Control theory is then presented as a way of evaluating how well the system (a human, in this case) is controlling these variables rather than as a way of determining what variables the system is actually controlling.

Control theory for humans introduces the tools of control theory in the context of a control task called manual tracking, where a person acts to keep a cursor aligned with a target. Manual tracking is an excellent example of human controlling because all the variables involved in control are clearly identifiable. But it is a poor example of human controlling for the same reason. In manual tracking a person is instructed to control a particular variable, such as the relationship between cursor and target position, and to keep that variable in a particular state, such as "cursor aligned with target". If the person follows instructions (and most do) then we know that the relationship between target and cursor is under control and we can use the tools of control theory (linear systems analysis, Bode plots and so on, which are described so well in *Control theory for humans*) to evaluate how well this control is being carried out. But manual tracking is a poor example of human controlling because it gives the false impression that the variables involved in everyday examples of human control – particularly the variables that people are controlling – can be easily identified. In fact, they cannot. Indeed, the main problem involved in understanding everyday control behaviors (such as walking, talking, and catching fly balls) is identifying the variables people are controlling when they carry out these behaviors.

The variables people control are called *controlled variables*. A controlled variable is a perceived aspect of a person's environment that is kept in a predetermined state and protected from disturbances by the person's actions. The relationship between cursor and target in a tracking task is a controlled variable that is kept in a predetermined state (cursor aligned with the target) and protected from disturbance (such as movements of the target) by the person's actions (such as movements of a "control" stick). Controlled variables can be simple (such as the relationship between cursor and target) or complex (such as the relationship between a husband and wife). They are perceptual variables because they are often complex functions of many physical variables. For example, "sweetness" is a variable that people control yet this variable corresponds to no single physical variable in the environment. Human behavior is organized around the control of such perceptual variables (Powers, 1973) so knowing what perceptual variables people control is essential to the analysis of human behavior from a control theory perspective.

The fact that controlled variables are perceived aspects of a person's environment is one reason why it is difficult to notice these variables when we observe everyday examples of human controlling. It is difficult to notice, for example, what a baseball outfielder is controlling because the controlled variable is a perception in the fielder, not in the person observing the fielder's behavior. Although controlled variables are difficult to identify, they must be identified before the tools of control theory can be used to model and evaluate human controlling. But controlled variables and the methods for detecting them are never mentioned in *Control theory for humans*. This is unfortunate because it limits the application of control theory to situations where the variable being controlled by the system under study is already known with considerable confidence. That is, it limits behavioral science applications to engineering-type applications of control theory.

The application of control theory need not be limited in this way because simple and intuitively satisfying methods exist that can be used to identify the variables a system is controlling. Controlled variables can be identified without telling the system what to control, as in manual tracking tasks. Methods for identifying controlled variables have been referred to collectively as "the test for the controlled variable" or simply the TCV (Marken, 1997). The basic idea behind all methods that make up the TCV is that a controlled variable is a perceived aspect of a person's environment that will be protected from disturbance. The first (and possibly the most difficult) step in finding out what a person is controlling is to identify variables in the environment that the person might be perceiving and controlling. In the case of a person walking down the street, for example, that might be (among other things) the distance between the person and other people. If this variable is, indeed, under control then the person will protect it from disturbances, such as people who get too close, by moving appropriately. Thus, it is possible to determine whether or not a variable is under control by applying disturbances (such as by moving closer or farther from a person) to the suspected controlled variable and looking to see if that variable is protected from these disturbances. If it is, then the variable is likely to be under control. If not, then another hypothesis about the variable under control is tested.

Once we know what variables people control we can understand a lot about why they act as they do. This is because the actions of a control system (such as a person) are aimed at bringing controlled variables to preferred states and maintaining them in those states, protected from disturbance. Changes in preference for or disturbances to the state of a controlled variable result in observable actions that can be predicted based on an understanding of the environmental constraints under which these control actions occur. In order to make such predictions with accuracy it is necessary to be able to build a model of the human controller. *Control theory for humans* does an excellent job of introducing modeling as an approach to understanding the behavior of human controllers. However, the success of such models, in terms of how well the behavior of the model matches that of the human being modeled, depends, in large part, on including a correct representation the controlled variable.

The models discussed in *Control theory for humans* assume that the modeler knows what variable a person is controlling when carrying out a particular behavior, such as driving and shows how the equations of control theory can be used to produce a model that is dynamically stable, like the person being modeled. But the book does not show how one determines what variable the model should control in order to act like the human. This is a serious omission in a book aimed at behavioral scientists since it is often the successful selection of the appropriate controlled variable that makes the difference between models that do and don't fit the observed human behavior (Marken, 2001).

Control theory for humans provides an excellent description of the tools that can be used to model and analyze the behavior of living control systems once the variables controlled by these systems have been identified. In this sense, it can be considered the second half of a textbook on control theory for the behavioral sciences, the first half of which has yet to be written. The first half of that textbook will explain how "control theory for humans" differs from "control theory for thermostats". That is, it will explain how to find out what living control systems are controlling and why we have to know this in order to understand their behavior. Until that first half is written, however, some existing books may fill the void. In particular I am thinking of *Behavior: The control of perception* (Powers, 1973) and *Mind readings: Experimental studies of purpose*

(Marken, 1991*)*. Although these books are not written intentionally as introductory texts, they do cover the introductory topics that are missing from *Control theory for humans.* These books explain what control is, what it looks like when seen in living systems and how to identify the variables living systems are controlling when they are engaged in everyday behaviors. By reading these books first as a preamble to *Control theory for humans*, the student of behavioral science will see why it's true that control theory is for humans, not just for thermostats.

A Methodological Revolution

9 • You Say You Had A Revolution: Methodological Foundations of Closed-Loop Psychology[20]

Abstract – To the extent that a scientific revolution represents a fundamental change in a discipline, the cognitive revolution in psychology was not particularly revolutionary. What changed least in this revolution was methodology. The experimental methods used in cognitive psychology are the same as those used in the behaviorism it overthrew. This methodological continuity results from the fact that both behaviorism and cognitive psychology are based on the same paradigm, which is also the basis of experimental psychology: the open-loop causal model of behavioral organization. A truly revolutionary approach to understanding the mind has been largely ignored because it is built on a paradigm that is inconsistent with conventional research methods. This new approach to psychology, called Perceptual Control Theory (PCT), is based on a closed-loop control model of behavioral organization that is tested using control engineering methods that are unfamiliar to most psychologists. This paper introduces the methodological foundations of closed-loop psychology, explains why the closed-loop revolution has not happened yet and suggests what psychology might look like after the revolution has occurred.

Thomas Kuhn (1962) published his influential treatise on scientific revolutions at about the same time that scientific psychology started going through a revolution of its own. It was a time when

20 Reprinted from Marken, R. S. (2009) You Say You Had a Revolution: Methodological Foundations of Closed-Loop Psychology, *Review of General Psychology*, 13, 137-145 with permission of the American Psychological Association.

revolution, scientific and otherwise, was in the air. Kuhn described a scientific revolution as a significant shift in the fundamental theoretical framework or "paradigm" of a discipline. The revolution in psychology involved a shift from the behaviorist paradigm, which views psychology as the study of observable behavior, to the cognitive paradigm, which views psychology as the study of mental processes. There is now some consensus that this shift was, indeed, revolutionary and it has been dubbed the "cognitive revolution" (Dember, 1974; Gardner, 1987; Mandler, 2002; Miller, 2003).

While there was much about the cognitive revolution that was revolutionary, there was also much that was not. What was revolutionary was the development of theories of mind, especially coming at a time when the behaviorist paradigm viewed such theories as non-scientific. What was not revolutionary was the way cognitive research was done. The methods used by cognitive psychologists to study the mind are the same as those used by behaviorists to study behavior while ignoring (or denying) the mind.

Experimental Psychology

There are many different ways to do research in psychology, including surveys, correlational studies, and quasi-experiments. But the gold standard for research in psychology is the experiment. The typical psychology experiment involves manipulation of a variable in an organism's environment as the independent variable (IV) while measuring some aspect of the organism's behavior as the dependent variable (DV). When an experiment is done properly, so that all possible confounding variables are held constant, an observed relationship between the IV and DV is taken as evidence that the environmental variable is a cause of variations in the behavioral variable. This approach to experimental research in psychology can be called *causal methodology* because the goal is to determine the causes of behavior (Levitin, 2002).

The results of an experiment using causal methodology can be represented in a graph like that in Figure 1, which shows the average value of the DV at each of the different levels of the IV. These results could have come from an experiment performed by a behaviorist prior to the cognitive revolution or by a cognitive psychologist after it. For example, the IV could be the size of the reinforcement that follows a bar press and the DV could be running rate in an operant conditioning experiment, as in a classic experiment of behaviorism (Teitelbaum, 1957). Or the IV could be the angular difference between pairs of perspective drawings of objects and the DV could be the time to say "same", as in a classic experiment of cognitive psychology (Shepard and Metzler, 1971).

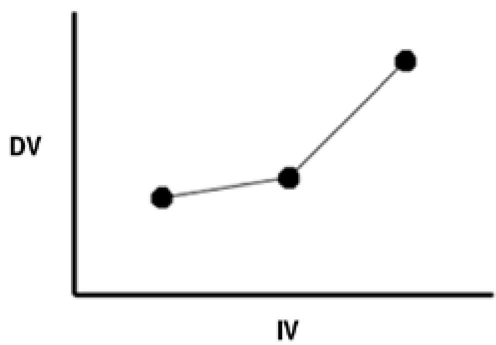

Figure 1. The results of a typical experiment using causal methodology. The IV is an external environmental variable and the DV is a behavioral output variable. Average values of the DV are shown for each level of the IV.

Both the behaviorist and the cognitive psychologist would quite reasonably see experimental results like those in Figure 1 as evidence of a causal relationship between the IV and DV. The behaviorist sees these results as evidence that the size of reinforcement (IV) causes variations in the rate of running (DV) and the cognitive psychologist sees them as evidence that the angular difference between the perspective drawings of objects causes the variations in the time it takes to say "same". Clearly, the experimental methodology and the conclusions drawn from it are the same for both the behaviorist and cognitive psychologist, and for good reason: both behaviorism and cognitive psychology are based on the same open-loop causal model of behavioral organization that is also the basis of experimental research in psychology.

Open-Loop Causality

The open-loop causal model is shown in Figure 2. It is also known as the General Linear Model, which is the basis of the statistical analysis of experiments in psychology (Cohen & Cohen, 1983). The model assumes that behavior is the last step in a causal chain that begins with variations in an environmental variable in the world outside of the behaving system and ends with variations in behavior. The environmental variable causes variations in the sensory input, I, to the system, ultimately causing variations in the behavioral output, O, from the system. The behaving system itself is viewed as a "transfer function" that converts sensory input into behavioral output. The graph inside the box labeled "system" represents this function. The model is "open-loop" because it assumes that causation runs in a one-way path from environmental input to behavioral output; the system's output does not "loop back" and affect its input.

Causal methodology is based on the assumption that organisms are organized according to the open-loop causal model. In an experiment using causal methodology, the IV is typically an environmental variable and the DV corresponds to a behavioral variable. The goal of experiments based on this model is to determine the causes of behavior, which means determining the nature of the organism transfer function. Essential to the validity of this approach is that the causal path from IV to DV be one-way or open loop. Only if this is the case can any observed relationship between the

IV and DV be considered a reflection of the nature of the organism transfer function in Figure 2. Researchers of all theoretical persuasions who use causal methodology must assume, therefore, that organisms are organized as open-loop causal systems. Since both behaviorists and cognitive psychologists use causal methodology, the open-loop causal model should be apparent in the theoretical narratives of both behaviorism and cognitive psychology, and, indeed, it is.

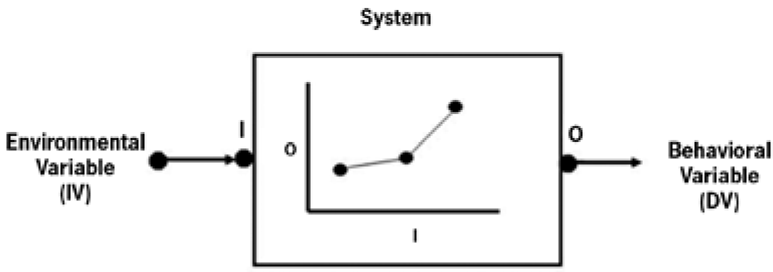

Figure 2. The open-loop causal model of behavioral organization. External environmental variables cause sensory inputs, I, that cause behavioral outputs, O. The system is a transfer function that converts the sensory inputs, I, into behavioral outputs, O. An example transfer function is shown inside the system

Open-loop Behaviorism and Cognitive Psychology

The open-loop causal model is explicit in the stimulus-response or S-R approach of behaviorism. According to S- R theory environmental stimuli (S) cause behavioral responses (R) via the organism. The organism itself is treated as a "black box" where what goes on inside the box is of less concern than observable relationships between stimulus inputs into the box and response outputs from it. The goal of research in behaviorism is to discover these S-R relationships, which are the "laws of behavior".

In cognitive psychology, the open-loop causal model of behavior shows up as the computational theory of mind, which is nicely described by Pinker (1997):

> "…beliefs and desires are information, incarnated as configurations of symbols. The symbols …symbolize things in the world because they are triggered by those things via our sense organs…If the bits of matter that constitute a symbol are arranged to bump into the bits of matter that constitute another symbol in just the right way, the symbols corresponding to one belief can give rise to symbols corresponding to another belief logically related to it, which can give rise to symbols corresponding to other beliefs, and so on. Eventually the bits of matter constituting a symbol bump into bits of matter connected to the muscles, and behavior happens." (Pinker, 1997, p. 25).

This description suggests that the processing that goes on between input and output can be quite complex, with many loops and branches. But this processing ultimately goes in one direction, starting with information about external environmental variables ("things in the world") and ending with behavioral output that "happens" at the end of this open-loop causal chain.

Normal Science and Paradigm Shifts

The open-loop causal model is a scientific paradigm in the sense that it is a theoretical framework for understanding the basic subject matter of psychology. It is also a paradigm in the sense that it defines what constitutes the practice of "normal science" in psychology (Hoynongen-Huene, 1993; Kuhn, 1970). Because both behaviorism and cognitive psychology are based on this paradigm, the cognitive revolution required no change in the conduct of normal science. It was possible to change from behaviorist to cognitive psychologist without having to change anything about how one went about the business of doing psychological science.

The cognitive revolution would have been a much harder sell if it had required that psychologists change the way they do normal science. We can see this by looking at the reception accorded a theory of behavioral organization that did require such a change. The theory, which is now called Perceptual Control Theory (PCT), was developed by William T. Powers and his colleagues (Powers, et al., 1957) and later described in detail by Powers in his book *Behavior: The Control of Perception* (Powers, 1973c). PCT came along at the height of the cognitive revolution. But it has been largely ignored, possibly because it requires a completely new approach to the practice of psychological science[21]. PCT is based on a new theoretical paradigm that cannot be tested using causal methodology. The new paradigm is a closed-loop control model of behavioral organization.

Closed-loop Control

The closed-loop control model is shown in Figure 3. The model is very similar to the open-loop causal model except that it explicitly shows the behavioral output of the system, O, looping back to affect the sensory input, I. The effect of output on input is called *feedback*. Although reading the diagram from left to right makes it seem like the feedback effect of output on input occurs *after* the "feed-forward" effect of input on output, feedback and

21 Kuhn himself did not ignore Powers' work. Asked to review the manuscript for the 1973 book, he provided this comment for the book jacket: "Powers' manuscript, *Behavior: the control of perception*, is the most exciting I have read in some time. The problems are of vast importance, and not only to psychologists… I shall be watching with interest what happens to research in the directions to which Powers points." He did not see the research in his lifetime.

feed-forward are actually occurring at the same time. Variations in input are causing variations in output *while* variations in output are causing variations in input. This corresponds to real life situations, such as driving a car, where one's view of the location of the car relative to the road (sensory input) is causing steering wheel movements (behavioral outputs) that are simultaneously influencing the view that is causing those movements.

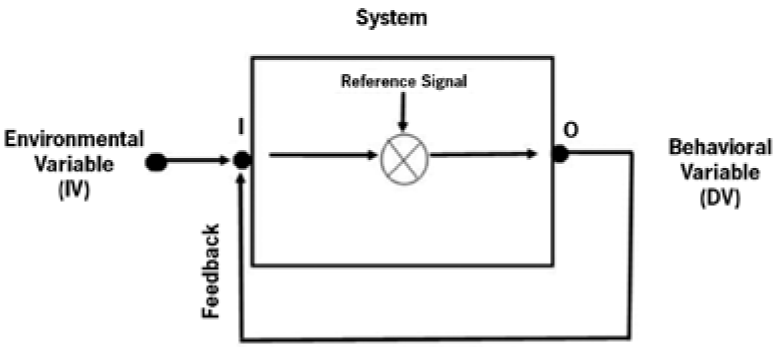

Figure 3. The closed-loop control model of behavioral organization. Sensory inputs, I, cause behavioral outputs, O. At the same time behavioral outputs have a feedback effect on the sensory inputs that are causing those same outputs. There is a circle of cause and effect that runs from I to O via the organism (the feed-forward path) and from O to I via the environment (the feedback path). The result is that the system acts to keep I matching an internal reference specification, protected from the disturbance caused by the environmental variable (IV). This process is called control.

Because feedback and feed-forward occur simultaneously in a closed-loop system, the behavior of the system must be defined by two simultaneous equations rather than by a single equation as in the open-loop causal model. One equation describes the feed-forward path from input to output, which is the same as the organism transfer function for an open-loop system. The other describes the feedback path that goes through the environment from output to input.

When the feedback in a closed-loop system is negative, such that the effect of output on input is to reduce the effect of input on output, the solution of the simultaneous equations that define the system's behavior shows that the system acts to *control* its input (Powers, 1978). Control involves varying system output in order to maintain an input variable at a pre-specified goal or reference value, protected from *disturbances*. Disturbances are external environmental variables that cause variations in sensory input that tend to "push" that input away from the reference value. The outputs of a closed-loop negative feedback system "push back" against these disturbances in order to keep the sensory input at the reference value. Because the function of a closed negative feedback system is to control its input, the closed-loop model of behavioral organization is called a *control* model.

The desired or reference value of the input controlled by a closed-loop control system is specified inside the system itself by a *reference signal* like the one shown in Figure 3. Reference signals represent the cognitive component of the closed-loop control model. These signals function as intentions in the sense that they specify desired or goal results of the system's actions.

The variables controlled by closed-loop control systems are actually perceived aspects of the sensory input to those systems. For example, one of the many aspects of sensory input that is controlled when one drives a car is the perceived distance between the front of the car and the middle line in the road; another is the perceived speed of the movement of the car relative to other cars. The aspect of the sensory input that is controlled by a closed-loop control system is, therefore, a perceptual representation of that input. Thus, the behavior of a closed-loop negative feedback control system can be described as "the control of perception", as in the title of Powers' landmark text.

Causal Methodology and Closed-loop Systems

IV as Disturbance. When experiments based on causal methodology are used to study a system that happens to be closed-loop, then the IV is actually a disturbance to the input controlled by the system, as shown in Figure 3. If the DV is the output that protects the input from these disturbances then the result of an experiment on a closed-loop system using causal methodology will be a clear relationship between the IV and the DV, such as that in Figure 1. This relationship reflects the disturbance resistance that is characteristic of the behavior of a closed-loop control system. When a disturbance pushes a controlled input variable in one direction the output of the system pushes back in the opposite direction. So a strong negative relationship between IV and DV will typically be observed when causal methodology is used to study a closed-loop control system (Powers, 1978).

Powers (1973b) showed that the nature of the relationship between disturbance (IV) and output (DV) variations that is observed in experiments on closed-loop systems depends on characteristics of the environmental feedback function that connects system output (DV) to controlled input (I) and not on characteristics of the behaving system itself. This is because the feedback function determines how much output the system must produce in order to counter the effects of any disturbance (IV) to the controlled input. For example, the amount of force (output) that a bicyclist must produce to stop a bike using handlebar brakes will differ depending on the wetness of the road. A change in wetness changes the feedback connection between brake squeeze force (output) and the perception of stopping (input), resulting in a change in the relationship between disturbance (such as a pedestrian moving into the bike's path) and output (the squeeze force exerted by the bicyclist on the brake). The bicyclist will appear to have become more responsive as the wetness of the road increases. But the change is in the environment (wetness of the road), not the bicyclist.

So, when causal methodology is used to study closed-loop systems, an observed relationship between the IV and DV may actually reflect characteristics of the environmental feedback connection between a system's output and input rather than internal properties of the system itself. This surprising and counter-intuitive fact about the results of experiments on closed-loop systems gives rise to what has been called the "behavioral illusion" (Cziko, 2000). Powers first described the behavioral illusion and its implications in a paper that appeared in *Science* in 1973 (Powers, 1973b). In a response to comments on that paper Powers said the following: "If control system theory does indeed correctly describe the relationship between organisms and their environments, behaviorism has been in the grip of a powerful illusion since its conceptual bases were laid" (Powers, 1973c). Unfortunately, the same can now be said of cognitive psychology as well.

Closed-loop Methodology

It is impossible to tell whether organisms are open or closed-loop systems by simply looking at the IV-DV relationships obtained using causal methodology. Such relationships will be observed whether the system is open or closed-loop. A new approach to doing psychological research is needed only if organisms are in fact closed-loop systems. So the first step in the closed-loop revolution in psychology must be to determine whether organisms are organized as open or closed-loop systems. It is possible to do this by performing the appropriate tests, which apply methods adapted from control engineering. The most important of these methods is called the test for controlled variables or TCV (Marken, 1997).

The TCV is the basic methodology for studying living control systems. It is based on control engineering techniques designed to measure the quality of control in man-made closed-loop control systems, such as the thermostat. Man-made control systems are designed to keep certain variables at pre-selected values, protected from disturbances. The thermostat, for example, is designed to keep the temperature of the air in a room at a pre-selected value, such as 70° Fahrenheit, protected from disturbances, such as variations in outside air temperature. The input variable controlled by the control system is called a *controlled variable* (CV). Room temperature is the CV of a thermostat. A control system controls well to the extent that it keeps the CV close to the pre-selected or *reference* value of that variable over time despite disturbances.

What psychologists want to know about control systems is somewhat different than what control engineers want to know. While control engineers want to know how well a system controls a known CV, psychologists want to know whether the system under study is, in fact, a closed-loop control system and, if it is, what variables it is controlling. The TCV can be used to answer both of these questions.

The TCV, as adapted for use in psychology, starts with a hypothesis about a CV. For example, consider a beaver building a dam. One hypothesis might be that a variable controlled by the beaver is the loudness of the noise of flowing water; the beaver might want to keep the noise level at zero dB. Water noise is, thus, a hypothesized CV. The next step in the TCV is to see if the system acts to protect the hypothesized CV from disturbances. If water noise is a CV then disturbances will have little or no effect on the perceived noise level. If, on the other hand, disturbances do have an effect then water noise is not under control.

Amplifying the sound of water near the beaver is one way to produce a disturbance to perceived water noise level. If this disturbance increases perceived water noise level then water noise is not under control. If, however, this disturbance has very little effect on perceived water noise level – because, for example, the beaver is piling material around the loudspeaker, keeping the noise level at zero dB – then the hypothesized CV may be under control. The TCV continues until the experimenter is convinced that all disturbances that should affect the hypothesized CV have little or no effect on it, at which point the experimenter can tentatively conclude that the variable is, indeed, under control[22]. Although the TCV has never been systematically done on dam building behavior, observations suggest that beavers might, indeed, control water noise level, along with other variables, by building dams (Richard, 1983).

In the process of determining whether a particular variable is controlled, the experimenter is also implicitly determining whether or not the system under study is a closed-loop control system, at least with respect to the variable that is hypothesized to be the CV. If the TCV rules out a hypothesized CV as being under control then the system is not organized as a closed-loop control system, at least with respect to that variable (Marken, 1997).

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22 Some critics have suggested that the TCV reveals no more than what could be revealed about a closed-loop system using causal methodology. It has been claimed, for example, that one can tell that a thermostat is controlling room temperature by observing the relationship between an IV, such as changes in the heat produced by a heater near the thermostat's sensor, and a DV, such as changes in the heat output produced by the thermostat's furnace. While it is true that such a relationship will be observed for a thermostat that is controlling room temperature, it will also be observed for a system that is controlling some other variable, such as humidity. The only way to tell what variable a system is actually controlling is to use the TCV.

Closed-loop versus Causal Methodology

The TCV differs from causal methodology mainly in its aims. The aim of causal methodology is to find the environmental variables that cause system behavior; the aim of the TCV is to find the sensory inputs that are controlled by the behaving system. But besides the difference in aims there are also some important differences in procedure. One difference is that the TCV is used to test one individual at a time rather than groups of individuals (Runkel, 1998). The TCV is not a statistical approach to understanding mental processing based on measuring the average performance of groups of individuals. Also, whereas causal methodology looks for an effect of external environmental variables on behavioral variables, the TCV is aimed at finding a *lack of effect* of these variables on a hypothetical controlled variable. The TCV recognizes that, if the system under study is closed-loop, then external environmental variables are likely to be disturbances to input variables that are being controlled by the system.

The focus of the TCV is always on the discovery of controlled variables rather than on the discovery of relationships between environmental and behavioral variables. If the system under study is closed-loop then all possible relationships between environmental and behavioral variables can be deduced once the researcher knows the variables the system is controlling and how environmental and behavioral variable affect the state of these variables.

Finally, because the TCV is used to study closed-loop control systems, the proper use of this methodology requires a good "feel" for how control systems work. This "feel" comes from a clear understanding of the nature of control and, in particular, the nature of a CV (Marken, 2001).

We All Want to Change the World

If control theory is right and organisms are, indeed, closed-loop systems then why has the closed-loop revolution not happened yet? One reason may be that the results of experiments using causal methodology are exactly what would be expected if organisms are open-loop causal systems; variations in an IV seem to cause concomitant variations in a DV. Since there is nothing surprising about the results of conventional psychology experiments psychologists have seen no reason to suspect that these results might be misleading (as per the "behavioral illusion" described above). Control theory, itself, suggests why this would be the case: even if organisms are closed-loop control systems, psychological experiments using causal methodology will produce results, like those in Figure 1, that are completely consistent with what is expected based on the open-loop causal model.

Another reason why there has been no revolution may be because there has been no *experimentum crucis* in psychology, comparable to the Michelson and Morley (1887) experiment in physics, that demands reconsideration of the foundations of the discipline. There has been no closed-loop revolution because there seems to be no reason to revolt. Nevertheless, there are several observations that, taken together, suggest that there might be reason for a cautious reappraisal of, if not open rebellion against, the current approach to doing research in psychology.

Cause of Behavior. The closest thing psychology has to a Michelson-Morley experiment may be Powers' (1979b) demonstration that causality does not work as expected in a closed-loop control task. The demonstration involves a simple compensatory tracking task where the participant is asked to keep a cursor aligned with a fixed target by moving a handle in order to compensate for an invisible disturbance to the cursor's position. Powers showed that the correlation between cursor variations and handle movements in this task is close to zero while that between invisible disturbance variations and handle movements is on the order of -.99. This result is surprising from the point of view of the open-loop causal model because cursor variations are the only possible cause of the handle movements; cursor variations are the only variable that can tell the participant how to move the handle in order to keep the cursor on target. While correlation does not imply causality, lack of correlation does imply lack of causality. So absence of a correlation between cursor variations and handle movements in this simple tracking experiment leads to the paradoxical conclusion that the only possible cause of the behavior (handle movements) in this task is not the cause of that behavior.

In an attempt to resolve this paradox, I repeated the compensatory tracking experiment using a procedure that would make it possible to determine whether there was *anything* about cursor variations that could be considered the cause of handle movements (Marken, 1980). The procedure was based on the fact that the handle movements in these tracking tasks are almost perfectly negatively correlated with disturbance variations. By repeating the same disturbance variations on two different trials the participant produced nearly identical handle movements on those trials. If something about the cursor variations is the cause of handle movements, then cursor variations on those trials should also have been highly correlated, but they were not.

The behavior in a compensatory tracking task occurs in a closed-loop: cursor variations affect handle movements while handle movements affect cursor variations. The studies by Powers (1979b) and Marken (1980) show that the open-loop causal model of behavior cannot explain closed-loop behavior. Nevertheless, these studies have had little impact, perhaps because the results are not obviously relevant to anything other than perceptual-motor control tasks. But there is reason to believe that these results have more general implications because much of what we see as "behavior" seems to be closed-loop inasmuch as it involves control, which is a closed-loop process (Marken, 1988). For example, a complex behavior like "playing chess" involves making moves in order to "control the center". But even if all behavior is not closed-loop the possibility that some might be should encourage researchers to at least test this, using the TCV, before going on to study the behavior using causal methodology.

Statistical results. One of the most obvious signs that there might be something wrong with the open-loop causal model is the fact that the results of research using causal methodology are extremely noisy, so much so that statistical analysis is a standard component of the analysis of the results of any psychological experiment. The random component of the variation in the DV observed in the typical psychology experiment is so large that statistical tests must be used to decide whether any apparent effect of the IV was real or due to chance. When it can be concluded that an IV does have an effect, it rarely accounts for more than 30% of the variance in the DV. This kind of result suggests that behavior is highly variable with a large random component. However, Runkel (2003) points out that this level of random variability is not at all evident in everyday behaviors such as walking and driving a car. For example, people rarely take a step and fall. But this kind of success requires enormous behavioral consistency. Even if the probability of a successful step were as high as .999 a person walking at 100 steps per minute would fall once every ten minutes (Runkel, 2003, pp. 167). If behavior were anywhere near as variable as it appears to be in conventional psychological experiments we would see people falling all the time; in fact, we don't.

Control theory suggests that the apparent random variability seen in experiments using causal methodology could come from looking at behavior the wrong way, as open rather then closed-loop. If behavior is, indeed, a closed-loop process than much of the apparent random variability in behavior could be due to systematic differences between organisms in terms of variables that are ignored by causal methodology, specifically, controlled variables and the varying reference specifications for these variables. Some evidence that these factors may be contributing to the apparent random variability of behavior comes from the fact that research using closed-loop methodology, which does take controlled variables and varying reference specifications into account, typically accounts for over 96% of the variance in observed behavior (e.g., Marken, 1986). This level of predictability could become commonplace when closed-loop methodology becomes standard procedure in scientific psychology.

Establishing operations. One way to characterize the difference between open and closed-loop systems is that the former have no purpose while the latter do. The purpose of a closed-loop system is to keep perceptual variables in reference states. Therefore, purpose determines how and, indeed, whether a closed-loop system will react to disturbances, which are the IVs in experiments using causal methodology. Purpose shows up as the "establishing operations" given to participants in such experiments. Establishing operations, such as the verbal instructions given to humans or the deprivation regimens given to animals, give participants a purpose inasmuch as they encourage the participant to control a particular perception. For example, the participants in the mental rotation study were instructed to have the purpose of saying, as quickly as possible, whether two perspective drawings were of the same object or not. The participant is being asked to control for a relationship between what they say ("same" or "different") and what they see and to do this as quickly as possible. Unless the participant adopts this purpose, the IV (angular difference between objects) will have no apparent effect at all on the DV; pairs of perspective drawings do not ordinarily lead people to say "same" or "different" as quickly as possible.

Purpose in the form of establishing operations is an essential part of every psychology experiment. If it were not, psychologists would not be able to find any relationship between an IV and a DV using causal methodology. Carrying out a purpose is equivalent to controlling a perceptual variable: bringing it to a specified reference state while protecting it from disturbances (Powers, 1978). The fact that the participants in all psychological experiments must be instructed to carry out a purpose if the experiment is to work at all suggests that these participants are closed-loop control systems. What is usually not clear is exactly what purpose the participants are carrying out. In control theory terms, what we don't know is exactly what perceptual variables the participants are trying to control. As noted above, much of the apparently random variability in conventional psychological experiments may result from the fact that each participant in a conventional psychology experiment may be controlling a somewhat different perception, even though each was given exactly the same instructions.

While the correlations observed in tracking tasks, the noisy relationships between IV and DV and the need for establishing operations are not proof that organisms are closed-loop systems, they are strong evidence of that possibility. These characteristics of contemporary scientific psychology have not been enough to set off a revolution but they should at least be enough to encourage a careful re-evaluation of the validity of the open-loop causal basis of experimental research in psychology.

Co-Opting the Revolution

It is hard enough to have a scientific revolution when all that is involved is a change in theory, but it's nearly impossible to have one when it also requires a fundamental change in the way one goes about the business of doing research. To most scientific psychologists causal methodology *is* the scientific method. Therefore, many psychologists who have become interested in the closed-loop approach to psychology have assumed that the proper way to test the theory is with causal methodology. Carver and Scheier (1981, 1998) provide a case in point. These researchers developed a model of "self-regulation" that is explicitly based on Powers' control theory model of mind. They clearly and correctly described the closed-loop organization of their self-regulation model but they have tested it using causal methodology, looking for causal relationships between external environmental variables and behavioral output variables. So their research methods are based on the assumption that the organisms under study are organized as open-loop causal systems, contrary to the predictions of their own theory. If, indeed, organisms are closed-loop control systems, then the use of causal methodology is revealing more about the environments in which people "self-regulate" than about the mental process that are involved in self-regulation.

The psychologists who have co-opted the closed-loop revolution have done so by embracing the idea that organisms are closed-loop systems while acting as though such systems can be studied using causal methodology. This co-opting is surely unintentional, resulting from the fact that all psychologists are trained to look at behavior through "open-loop glasses", which make it appear as though causal methodology is the only conceivable way to do science (Marken, 2002a). Through open-loop glasses the closed-loop control model appears to be completely consistent with the prevailing open-loop paradigm. The result is that the closed-loop revolution has not happened and causal methodology is still the main approach to doing psychological research, even when psychologists are testing closed-loop models of behavior (e.g., Smith et al., 2001; Jagacinski & Flach, 2002).

The closed-loop revolution in psychology cannot begin until psychologists start using a methodology like the TCV, which recognizes the possibility that organisms are closed-loop control systems. Before this revolution occurs it might be useful to imagine what scientific psychology will look like when it is based on a closed-loop control model of behavioral organization.

Closed-Loop Psychology

The main goal of a closed-loop approach to psychology would be to determine the kinds of perceptual inputs organisms control. PCT assumes that organisms control a hierarchy of different types of perceptual variables (Powers, 1973c). The lowest level perceptions in the hierarchy are what psychologists have called sensations. These are perceptions such as the loudness and pitch of sound or the brightness and hue of light. Higher-level perceptions are often called cognitions. These are perceptions of variables such as the level of honesty of a sales pitch or the degree to which one has control of the center in a chess game.

Research in closed-loop psychology would be aimed at discovering what perceptual inputs organisms control when they are carrying out certain activities. One example of such research is the study of how people catch fly balls (Dienes & McLoed, 1993; Babler & Dannemiller, 1993; McBeath, et al., 1995; Tresilian, 1995). The goal of this research is to determine the visual variables that are controlled (the CVs) when a person moves to catch a ball. Several hypotheses have been proposed regarding the variables controlled when catching balls, including the optical trajectory, acceleration and velocity of the ball (Marken, 2001). So far the appropriate tests to determine which of these variables is actually controlled have not been performed (Marken, 2005). Nevertheless, research in this area gives a very clear picture of what a closed-loop psychology would look like. Researchers understand that catching a ball is a closed-loop process that is organized around the control of perceptual input variables (CVs). And in at least one case, something very much like the TCV has been done using the variable path of a Frisbee as a disturbance to a hypothetical CV (Shaffer et al., 2004).

Another example of research aimed at discovering the perceptual inputs organisms control is found in the study of two-handed coordination (Mechsner et al., 2001). In a series of ingenious experiments, Mechsner and his colleagues have shown that coordinated movement is organized around the control of the perceptual consequences of hand movements. While more research is needed to determine the CVs involved in two-handed coordination tasks, Mechsner and his colleagues have shown that two-handed coordination – which appears to involve the open-loop generation of hand movements – is a closed-loop control process. The perceptual variables controlled in this loop are visual and proprioceptive consequences of hand movements. Closed-loop research on two-handed coordination should be aimed at determining what these variables are.

The perceptual variables controlled when catching a ball or making coordinated movements will probably be found to be at a relatively low level in the perceptual control hierarchy. Robertson et al. (1999) have shown how the TCV can be used to determine whether people control higher-level perceptions such as "self image". These researchers applied disturbances, in the form of words that were thought to be either consistent or inconsistent with the self-image a person was trying to control. The researchers were able to predict with great accuracy the words that would be rejected as inconsistent with and those that would be accepted as consistent with the hypothesized self-image, showing that individuals do control a variable that represents a higher-level perception of themselves.

Powers (1992) has also shown how the TCV can be used to test for control of a cognitive variable. The research was done as a simple tracking task where the goal was to keep the name of a U.S. president – the target name – displayed on the screen while disturbances act to change the displayed name to that of a previous or subsequent president. In order to compensate for this disturbance it was necessary to move a handle in the correct direction to restore the target name to the display. In order to maintain control the subject had to remember the order of the presidents that preceded and followed the target. Subjects were able to do this, demonstrating their ability to control a high level concept through the use of information stored in memory.

I have done research aimed at determining the hierarchical relationships between lower-level sensation-type perceptions and higher-level cognitive-type perceptions that are proposed in Powers' PCT model of mind (Marken, 2002b, p. 85-112). This research is based on the assumption that the control loops involved in controlling lower level perceptions are faster than those controlling higher-level perceptions. This difference in speed is a basic stability requirement for a hierarchical organization of control systems, as demonstrated in models of hierarchical control (Powers, 1979a). Using the exact same "stimulus" variables presented at different speeds I have found evidence for a hierarchy of controlled perceptions ranging from very fast control of configuration (shape) perceptions (controlling for a square rather than some other shape) to the much slower control of sequence perceptions (controlling for shapes appearing in a particular sequential ordering of size, for example).

Besides testing for controlled perceptual variables, the study of closed-loop cognition would also have to tackle traditional topics like remembering, thinking, and imagining. Closed-loop studies of these topics would focus on the purposes involved in carrying out these activities. Control is an inherently purposeful activity (Marken, 1990) because it involves acting to achieve a pre-specified goal result or purpose. Studies of remembering, for example, might be aimed at determining a person's purpose when trying to memorize a set of items, as in a simple free recall task. Questions addressed by this research might be: Is the person doing the recall task trying to remember every item, just the most recently presented items or items from the beginning of the list? Hypotheses about the purposes involved in cognitive tasks are hypotheses about CVs that exist only in the mind. Testing to determine whether these mental CVs are actually under control will require the development of innovative new ways of doing the TCV.

How to Have a Revolution

The closed-loop revolution in psychology will be truly revolutionary, which means that it will require a radical change in how scientific psychology is practiced and taught. One might hope that it would be possible to make an evolutionary rather than a revolutionary transition from an open to a closed-loop psychology, thus minimizing the discomfort that would result from such a revolution. But it is impossible to gradually change from one paradigm to another. There is no compromise possible between an open and closed-loop view of organisms, just as none is possible between round-earthers and flat-earthers. One either uses causal methodology, assuming an open-loop system, or the TCV, assuming a closed-loop system. There are no conceptual or methodological steps in between.

The move to closed-loop psychology, when it happens, will be like starting psychology all over again, based on a new foundation: the closed-loop control model of behavioral organization. If, while pursuing the new psychology, we find useful or suggestive results obtained from the old one, so much the better. But the focus must be on doing a new kind of research that is appropriate for the study of closed-loop control systems. This research would be aimed at mapping out the perceptual variables that individual organisms control.

10 · Methods, Models and Revolutions[23]

Rodgers (2010) describes a quiet revolution that has occurred over the last decade as scientific psychologists have moved from null hypothesis statistical testing (NHST) to model testing as a way to evaluate the results of behavioral research. This revolution represents an important scientific advance for psychology and Rodgers does the field a great service by pointing it out and describing it so well. I would argue, however, that what Rodgers describes as a methodological revolution has actually been an analytical revolution in psychology.

The move from NHST to model testing represents a change in the way behavioral data is analyzed, not in the methods used to collect it. Indeed, there has been no methodological revolution in psychology, though I have argued that such a revolution may be needed (Marken, 2009). The argument for a methodological revolution is based on a modeling approach to understanding behavioral data (Runkel, 1990). So, while the move from NHST to model testing may not represent a revolution in methodology, it can pave the way for one.

The relevance of modeling to methodology shows up most clearly in the design of psychology experiments. Experimental design is currently based on an input-output model which views sensory input, i, as the ultimate cause of behavioral output, o. In mathematical form the model says that o = f(i), where f() characterizes the causal processes that link input to output.

23 This is a comment on "The Epistemology of Mathematical and Statistical Modeling: A Quiet Methodological Revolution," by J.L. Rodgers (*American Psychologist*, v. 65, January, 2010, pp. 1-12).

According to the input-output model, the way to learn about the causes of behavior is to vary sensory input, i, under controlled conditions to determine its effect on behavioral output, o. Sensory input is typically varied indirectly by manipulating an environmental variable – the independent variable, IV, in an experiment – while behavioral output is measured as the dependent variable, DV (Levitan, 2002).

If the input-output model of behavioral organization is correct then an observed relationship between IV and DV provides a picture of f(), the causal path from input to output. If this model is not correct, however, then the observed relationship between IV and DV gives a very misleading picture of the causal structure of behavior (Powers, 1978). Therefore, the validity of current experimental methodology depends on the correctness of the input-output model itself. One piece of evidence regarding the correctness of this model is available thanks to the analytical revolution described by Rodgers (2010). Researchers now report their results not only in terms of the usual measures of statistical significance but also in terms of measures of the goodness of fit to the input-output model. Goodness of fit is measured as the proportion of variance in the DV that is accounted for by the IV using a form of the input-output model called the general linear model (Cohen & Cohen, 1983). A perfect fit occurs if 100% of the variance in the DV is accounted for by the IV. I have done a survey of the results of several recent experimental studies and found that, on average, the IV accounts for little more than 34% of the variance in the DV in these studies.

Another piece of evidence regarding the correctness of the input-output model comes from the observation that many behaviors, such as catching a fly ball, are clearly closed-loop; inputs (such as the sight of the ball) cause outputs (running) that have an immediate feedback effect on the inputs that cause those outputs (Marken, 1997). The input-output model is open-loop inasmuch as it assumes that output has no effect on input. So the input-output model doesn't seem to apply to closed-loop behaviors. This has not been considered a problem for research based on the input-output model because behavior in the typical psychology experiment appears to be open loop; outputs (DV) have no obvious effect on inputs (sensory effects of the IV).

Whether or not the behavior in psychology experiments appears to be open-loop depends to a large extent on what is identified as the input in these experiments. An open-loop model views input as the sensory consequence of variations in the IV. A closed-loop model views input as a controlled consequence of simultaneous variations in the IV and DV – input being controlled in the sense that it is maintained in a goal state by the actions of the organism (Marken, 2005). The difference between these two views can be illustrated by a simple reaction time experiment where participants are asked to press a key when a tone comes on but not otherwise. An open-loop model would see the input in this experiment as the sensory consequence of the tone (IV). A closed-loop model would see the relationship between tone and key press as the variable the participant is trying to control.

The superiority of the closed- over the open-loop interpretation of the experiment can be seen in the fact that tones do not ordinarily cause key presses. Participants press the key when the tone comes on only if they have adopted doing this as a goal. The controlled input in this case is a logical variable, "true" when the key is pressed after the tone and "false" when the key is pressed after no tone. The participant controls for keeping this input in the state "true". When participants do this they will appear to be reacting to the sensory consequence of the tone but, in fact, they are controlling a logical variable. Their behavior will appear to be open-loop when it is actually closed-loop.

The modeling approach to data analysis suggests that closed-loop models may be more appropriate than open-loop models of organisms. This has revolutionary implications for methodology because the methods used to study closed-loop systems are quite different from those used to study open-loop systems (Marken, 2009). The methods used to study open-loop systems are the familiar methods of experimental psychology, which aim to determine the variables (inputs) that are the cause of outputs. The methods used to study closed-loop systems are based on those used in control engineering, which aim to determine the variables the system is controlling and how it controls them.

The Future of Experimental Psychology

11 · Looking Back Over the Next Fifty Years of PCT[24]

The year 2003 is the 30th anniversary of the publication of William T. Powers' *Behavior: The control of perception* (*B: CP*), the first book to describe the theory of behavior that has come to be known as Perceptual Control Theory or PCT. It is also, as stated in the request for contributions to this volume, the 50th anniversary of Powers' "initial steps in the research that has led to PCT". I might add that it is also the 25th anniversary of my own involvement with PCT, which began in earnest in 1978. So now seems like a nice time to take stock of the state of PCT. And we are doing this with this well-deserved Festschrift in honor of William T. Powers. I would like to contribute to this Festschrift by looking forward rather than backward. I have done my share of reminiscing about the past history of PCT, so far as I am familiar with it. I have lamented, in private and in print, the failure of PCT to attract the interest of behavioral scientists over the last 30 years, since the publication of *B: CP* made the PCT perspective readily accessible to the behavioral science community. What I would rather do now is look back on the future of PCT by taking an imaginary look at what I think the next 50 years of PCT will have been like.

Looking back over the next fifty years I see that PCT has become the dominant perspective in the behavioral sciences, having replaced behaviorism, cognitive science and evolutionism. I see this because to see anything else would be foolish. If PCT has not become dominant then this essay, and the Festschrift for which it was composed, will have been completely forgotten. So what do

24 Paper presented as a contribution to the Festschrift for William T. Powers at the 2003 meeting of the Control Systems Group, Loyola Marymount University, Los Angeles, CA.

the behavioral sciences look like now that they are based on PCT? Perhaps what is most obvious to this visitor from 50 years in the past is the almost complete absence of statistical analysis in behavioral research. Research aimed at testing theories of individual behavior is now based on control models of individuals rather than statistical models of aggregates. Researchers no longer report statistical significance but real significance, in terms of how well the behavior of the model matches the behavior they have observed.

Modeling is now the basis of behavioral science research. Modeling tools are available which make it easy for the researcher to quickly build a model of the behaving system that includes an accurate model of the physical environment in which the system's behavior is produced. These modeling tools take advantage of the ever-increasing power of digital technology to produce real-time digital simulations of dynamic interactions between system and environment. Behavioral research, like physics and chemistry, is now a science based on modeling rather than a guessing game based on statistical significance testing.

Behavioral science is based on modeling because behavioral research methods are now based on testing for controlled variables (Marken, 1997). Behavioral scientists now understand that the apparent randomness of behavior was an illusion created by ignoring the variables that organisms control. What behavioral scientists had called "responses" are now understood to be actions that protect controlled variables from disturbances. Disturbances correspond to what behavioral scientists had called "stimuli". When many disturbances affect the state of a controlled variable, actions will appear to be randomly related to any one of those disturbances (stimuli). PCT has moved the focus of behavioral science from the randomly-noticed stimulus-response relationships that were the subject of statistical studies of behavior to the consistently controlled perceptions that are now the centerpiece of models of behavior (Marken, 2001).

Research in all areas of behavioral science is now organized around testing for controlled variables. Behavioral scientists no longer ask, "What is the cause of the organism's behavior?" They now ask, "What perceptual variable(s), if controlled by the organism, would lead me to see the organism behaving in this way?" This emphasis on testing for controlled perceptual variables has led to a new style of research in which the subjects of behavior studies are allowed to have better control over variables in their environment. The style of research which was aimed at measuring an organism's "responses" to the presentation of discrete "stimuli" has been replaced by research aimed at measuring an organism's ability to control perceptual variables that are being influenced by smooth variations in environmental variables that are disturbances to these variables.

Ingenious new experimental techniques have been developed that allow researchers to observe the state of hypothetical controlled variables while the variables are being disturbed. These techniques are similar to those developed long ago in the study of the perceptions controlled by baseball outfielders when they catch a fly ball. For example, McBeath, et al. (1995) used a video camera attached to a fielder's shoulder to observe the state of optical variables, such as the optical trajectory and acceleration of the ball, that the fielder might be controlling while catching fly balls. These early efforts were often limited by the failure of the researchers to record disturbances, such as the actual trajectory of the ball, to these hypothetical controlled variables. But these studies were important precursors to current PCT-based research inasmuch as they focused the attention of researchers on the importance of monitoring the state of possible controlled variables.

Research aimed at the identification of the perceptual variables controlled by humans and other organisms has been going on for several decades and the catalog of controlled variables continues to grow. Much of the research effort these days is aimed at classifying controlled variables and studying the relationship between systems controlling different types of perceptual variables. Much of this work supports the basic framework of a hierarchy of perceptual control systems that was originally proposed by Powers (1973, 1998). In particular, the research results are consistent with Powers' brilliant suggestion, based at the time only on subjective experience, that the hierarchy of control is organized around a limited number of different classes of perceptual variables. Although these perceptual classes are not precisely the same as those suggested by Powers it is now clear that there are a limited number of different kinds of perceptual variable. The research is also consistent with Powers' suggestion that lower level classes of perceptual variables are used as the means of controlling higher level classes of perceptual variables. It is a testament to the scientific depth of Powers' work that this hierarchical relationship between perceptual classes was suggested well before there was any significant objective data to support it.

Progress in research and modeling has gone hand in hand ever since scientists started looking at behavior through PCT glasses (Marken, 2002). This is because research and modeling are inextricably interrelated in the PCT approach to behavior. Progress in research depends on the development of models that explain the research results. Similarly, progress in the development of models of behavior depends on research aimed at testing the predictions of these models. This tight interrelationship between research and modeling has resulted in the development of models that produce behavior that is remarkably realistic. Some early models based on PCT (Powers, 1999; Marken 2001) hinted at the kind of realism that could be produced by models based on PCT. Current models benefit from many years of research into the variables that organisms actually control while carrying out various behaviors. They also benefit from the realism that can now be achieved in terms of simulation of the physical environment in which behavior actually occurs.

The science of PCT has not only increased our understanding of behavior, it has also contributed to developments in many areas of practical endeavor. For example, PCT-based models of behavior have paved the way for the development of robots that can perform very complex and dangerous tasks in highly unpredictable, disturbance-prone environments. PCT models of economic behavior have made it possible for policy experts to design economic policies that preserve the best results of capitalism, in terms of the production of wealth, while eliminating its worst wrongs, such as the maintenance of egregious wealth inequality. World population is stabilizing near zero population growth, poverty has now been largely eliminated and sustainable, prosperous no-growth economies are now a feature of nearly all world societies. The new economic model has resulted in the development of economic systems that depend more on reuse of existing resources than depletion of natural resources so that environmental pollution has been reduced to very low levels.

PCT has also become part of the popular understanding of "how people work". This means that people in general now have a better understanding of how to deal with each other on an everyday basis. In particular, people are better able to deal with the inevitable conflicts that arise between themselves and others. People now understand conflicts to be the result of conflicting goals rather than conflicting actions. They also understand that the solution to conflict does not lie in pushing harder against it.

When they find themselves in conflict, people are now more apt to look at themselves and ask, "What do I really want?" rather than look at their adversary and ask, "How can I get them to change?" The prevalence of the PCT view of human nature has not turned the world into utopia but it has reduced the level of violence in the world considerably since violence is now understood to be the cause of rather than the solution to interpersonal (and international) conflict.

Looking back over the next 50 years I see that perhaps the greatest legacy of PCT is a change in the tone of the conversation regarding the nature of human nature. The argument between liberals who believed that all human ills were caused by society and conservatives who believed that all human ills were the result of freely made bad choices has become more nuanced. PCT shows that the difference between liberals and conservatives was simply a difference in the part of the control loop at which one focused their attention. The liberals saw disturbance resistance as evidence of social control of behavior while conservatives saw the existence of a higher level goal as evidence of free choice. The liberal/conservative argument has largely disappeared with the realization that both points of view were correct. We can reduce social ills by reducing social disturbances, such as poverty, so that people can control more effectively. But we can also reduce social ills by freely choosing goals such as moderation and kindness that reduce conflict by reducing the degree to which we, ourselves, are social disturbances to others.

Thirty years before the beginning of these next 50 years, William T. Powers' introduced an exciting and revolutionary new view of behavior to the scientific establishment of the day. The new view was that behavior is the *control of* perception. Powers proposed this view at a time when the prevailing view was that behavior is *controlled by* perception. Thus, when Powers' introduced his new view of behavior it was rarely understood, often ignored and sometimes angrily rejected. Now the idea that behavior is the control of perception is taken for granted. This Festschrift is a long overdue celebration of the work and person of William T. Powers, who first presented the perceptual control view of behavior to a skeptical and often hostile audience.

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