EMPIRICAL EVIDENCE FOR PERCEPTUAL CONTROL THEORY

This document summarises the published empirical evidence for Perceptual Control Theory (PCT; Powers, Clark & McFarland, 1960a; 1960b; Powers, 1973; 1998; 2005; 2008). It does not include unpublished manuscripts, expansions of the theory or applications that do not test a core principle of the theory. These are included within the links of www.pctweb.org.

The document is divided first by the principle of PCT tested and then subdivided by the hypotheses that follow from this principle. Many of the studies are followed by a brief synopsis and/or abstract. The document is being updated regularly. If you wish to write a summary of a paper or you know of further empirical studies not listed here, please email warren.mansell@manchester.ac.uk.

1. Evidence for the Closed Loop Model of Control

PCT proposes that 'behaviour is the control of perception'. This is exemplified by the negative feedback loop described in the theory. Note that this structure is specified exactly (see Powers, 2008, for a clear recent diagram, also located at http://www.pctweb.org/whatis/whatispct_02alt.html).

Hypotheses 1 (A-E). The relationship between variables in a real system conform to a closed loop model rather than an open loop model. Specifically, an open loop model predicts a high correlation between the environmental variable (EV) and the 'stimulus' or input (I) to the organism, and in turn, a high correlation between I and the behavioural output (O). In contrast, a closed loop model predicts no correlations between these variables, and a high, negative correlation between O and E as the behaviour acts against the environmental disturbance to control I. The closed loop model also predicts that a high correlation between I and the reference value (R), but R is internal to the organism and not measurable directly.

The table below summarises the hypotheses:

Hypothesis	Relationship between Variables	Open Loop	Closed Loop (PCT)
A	E & I	High, positive	Low to zero
B	I & O	High, positive	Low to zero
C	O & E	High, positive	High, negative
D	I & R	N/A	High, positive
E	Behaviour predicted by a mathematical model of…	An open loop system	A closed loop system

The studies testing Hypotheses 1 (A-E) involve the following paradigms: (i) observations of natural behaviour; (ii) manipulations of the environment in experimental tasks; (iii) computer models of closed loop systems; (iv) comparative models of closed and open loop systems

Studies Testing Hypotheses 1 (A-E)

(i) Observations of Natural Behaviour

Pellis, S., & Bell, H. (in press). Closing the circle between perceptions and behavior: A cybernetic view of behavior and its consequences for studying motivation and development. *Developmental Cognitive Neuroscience.*

The dynamic aspect of behavior is exaggerated during social interactions such as sex, combat and rough-and-tumble play where the movements of the two animals involved continually influence one another. The behavioral 'markers' abstracted from this stream can greatly influence the conclusions drawn about the effects of experimental procedures and how changes during development are interpreted. By using methods of analysis that treat behaving systems as being dynamic and governed by negative feedback processes, the behavioral markers that are abstracted can more accurately reflect the underlying mechanisms. Using examples from rats engaged in play fighting, serious fighting and food defense, it is shown that motivational from non-motivational contributions to behavioral output and changes in that output with age can be discerned. For example, while sex differences in the frequency of initiating play by juvenile rats are shown to reflect differences in the motivation to engage in this behavior, sex differences in preferred motor patterns used during play do not. Rather, they reflect differences in perceptual and motor systems. Although an issue that is often neglected, we show that behavioral description, and the theoretical underpinnings of that description, is critical for the study of the mechanisms that produce and regulate behavior. [Abstract]

http://www.sciencedirect.com/science/article/pii/S1878929311000752

(ii) Experimental tasks

Powers, W. T. (1978). Quantitative analysis of purposive systems: Some spadework at the foundations of scientific psychology. *Psychological Review, 85,* 417-435.

A series of six experiments of a computerised tracking task together illustrate the process of control of perception by a human participant. Each task involves a cursor or set of cursors that are moved by a combination of a random disturbance from the computer and the participants own actions – moving a lever. This is analogous to a wealth of real world situations such as walking with a cross wind, steering a vessel in a storm and talking clearly above the noise of crowds. The tasks included the maintenance of a cursor at target, at a fixed distance from the target, and in a smooth pattern. The fifth and sixth experiments demonstrate that a closed loop model can be used to *identify* the perceptual variable being controlled by the participant (the perception they *intend* to experience) from a choice of several options – it is the variable for which environmental disturbances (random disturbance applied to the cursor) correlate strongly and negatively with the output (lever movement). This is the test for the controlled variable. In each task, the environmental variable correlates at around $r = -0.99$ with the output variable even though the 'intervening variable' (movement of the cursor) correlates at $r < 0.1$ with the output variable. As such, in contrast to the closed loop model, a linear environment-stimulus-output model cannot predict this behaviour. [WM]

Marken, R. S. (1980) The cause of control movements in a tracking task. *Perceptual and Motor Skills, 51,* 755-758.

The classical cause–effect or input–output model of behavior breaks down when there is feedback from response to stimulus. Using a compensatory tracking task, it was shown that the response variations of 3 males (2 undergraduates and 1 faculty member) on different occasions were nearly identical, while stimulus variations on these occasions were completely unrelated. This result seemed to rule out stimulus variations as the cause of responses that controlled (stabilize) the stimulus. When feedback exists, the cause of control must be viewed as an internal reference rather than an external stimulus.

Marken, R. S. (1982). Intentional and accidental behavior: a control theory analysis. *Psychological Reports, 50,* 647-650.

Marken, R. S. (1983) "Mind Reading": A Look at Changing Intentions. *Psychological Reports, 53,* 287-270.

Discusses the use of control theory as a method for understanding the purpose of behavior and to discriminate intended from unintended consequences of an organism's actions. By continuously monitoring the stability factor it is possible to observe changes in intention which are not visible in overt behavior. Intentions are viewed as internal models of the desired or reference states of perceptual inputs. The purpose of action is to keep perceptions matching reference states, a process called control. Organisms that control perceptions are control systems. The stability factor is the ratio of expected to observed variance of a suspected controlled variable. [Abstract]

Marken, R. S. (1985). Selection of consequences: adaptive behavior from random reinforcement. *Psychological Reports, 56,* 379-383.

Hershberger, W. A. (1986). An approach through the looking glass. *Learning and Behavior, 14,* 443-451.

This study illustrates that intrinsic negative feedback control is used to realize an animal's intentions. The chicks in the study were placed in an apparatus in which they need to move in the opposite direction in order approach their food. They entered a positive feedback state, running away from their food, unable to learn the behaviour required. [WM]

http://www.springerlink.com/content/8g8ur4221688613m

Jordan, J. S., & Hershberger, W. A. (1989). The behavioral illusion: Misperception of volitional action. In W. A. Hershberger (Ed.), *Volitional action: Conation and Control* (pp. 371-386). Amsterdam: North-Holland.

Pavloski, R. P. (1989). The physiological stress of thwarted intentions. In W. A. Hershberger (Ed.), Volitional action: Conation and control (pp. 215-234). Amsterdam: North-Holland.

This paper reports several studies in which participants carried out tasks (rotating visual images; tracking) in which the level of environmental disturbance was varied. Change in heart rate was considered the result of an output signal that PCT would predict to be closely correlated with the degree of error within the task. These hypotheses were confirmed.

Robertson, R. J., Goldstein, D. M., Mermel, M., & Musgrave, M. (1999). Testing the self as a control system: Theoretical and methodoliogical issues. *International Journal of Human-Computer Studies, 50,* 571-580.

This report describes an evolution of research methodology for adducing evidence regarding whether the self functions as a control system. While there has been a great number of studies in the literature on personality and social psychology aimed at demonstrating that behavior of many kinds can be affected by focusing attention upon the subject's self-concept, or by challenging or threatening it, little attention has been given to the question of why this would be so. A proposed explanation would be that the self functions as a control system. Testing this hypothesis has entailed development of a methodological approach in which control action occurs predictably rather than having a statistical probability. This has required defining a model and testing it by predictions rather than attempting to isolate underlying variables with multivariate techniques. [Abstract] http://www.sciencedirect.com/science/article/pii/S1071581998902567

Vancouver, J. B., Thompson, C. M., & Williams, A. A. (2001). The changing signs in the relationships between self-efficacy, personal goals and performance. *Journal of Applied Psychology*, *86*, 605-620.

The common interpretation of the positive correlation between self-efficacy, personal goals, and performance is questioned. Via self-efficacy theory (Bandura, 1977) it was predicted that cross-sectional correlational results are likely a function of past performance, and via control theory (Powers, 1973) it was predicted that self-efficacy could negatively influence subsequent performance. These predictions were supported with 56 undergraduate participants using a within-person procedure. Personal goals were also positively influenced by self-efficacy and performance, but negatively related to subsequent performance. A second study involving 187 undergraduates found that manipulated goal level positively predicted performance and self-efficacy positively predicted performance in the difficult goal condition. The discussion focuses on conditions likely to affect the sign of the relationship between self-efficacy, goals, and performance. [Abstract]

Vancouver, J. B., Thompson, C. M. Tischner, E. C., & Putka, D. J. (2002). Two studies examining the negative effect of self-efficacy on performance. *Journal of Applied Psychology*, *87*, 506-516.

Although hundreds of studies have found a positive relationship between self-efficacy and performance, several studies have found a negative relationship when the analysis is done across time (repeated measures) rather than across individuals. Powers (1991) predicted this negative relationship based on perceptual control theory. Here, two studies are presented to a) confirm the causal role of self-efficacy and b) substantiate the explanation. In Study 1, self-efficacy was manipulated for 43 of 87 undergraduates on an analytic game. The manipulation was negatively related to performance on the next trial. In Study 2, 104 undergraduates played the analytic game and reported self-efficacy between each game and confidence in the degree to which they had assessed previous feedback. As expected, self-efficacy led to overconfidence and hence increased the likelihood of committing logic errors during the game. [Abstract]

Vancouver, J. B. & Kendall, L. N. (2006). When self-efficacy negatively relates to motivation and performance in a learning context. *Journal of Applied Psychology*, *91*, 1146-1153.

Recent reviews of the training literature have advocated directly manipulating self-efficacy in an attempt to improve the motivation of trainees. However, self-regulation theories conceive of motivation as a function of various goal processes, and assert that the effect of self-efficacy should depend on the process involved. Training contexts may evoke planning processes, where self-efficacy might negatively relate to motivation. Yet the typical between-person studies in the current literature may obscure this effect. To examine this issue, 63 undergraduate students completed a series of questionnaires measuring self-efficacy and motivation before five class exams. Self-efficacy was negatively related to motivation and exam performance at the within-person level of analysis, despite a significant positive relationship with performance at the between-person level. [Abstract]

Pellis, S., Gray, D., & Cade, W. H. (2009). The judder of the cricket: the variance underlying invariance in behaviour. *International Journal of Comparative Psychology, 22,* 188-205.

While the behavior of many animals can be identified as involving discrete and stereotyped actions, there is a persistent tension between emphasizing the fixedness of the actions ("Fixed Action Patterns") and emphasizing the variation in the components comprising those actions ("Modal Action Patterns"). One such action, the back and forward judder of crickets often exhibited in agonistic interactions, was analyzed. Judders occurring on a horizontal surface by *Gryllus bimaculatus* were compared to those occurring on an inclined platform. Although the body movements involved were variable, that variability occurred in the context of maintaining some features of judder invariant. For example, the crickets maintained their bodies so that they were horizontal relative to the substrate, not to gravity, and most features of the back and forward movement (e.g., distance moved, velocity) were maintained as fixed despite differences in posture and movement. At a theoretical level, what these findings suggest is that behavior patterns involve a combination of fixedness and variation in the service of that fixedness. It becomes an empirical issue to discern these complementary components. [Abstract]

http://www.comparativepsychology.org/ijcp-vol22-4-2009/Pellis_etal_final.pdf

Bell, H. & Pellis, S. (in press). A cybernetic perspective on food protection in rats: simple rules can generate complex and adaptable behaviour. *Animal Behaviour.*

Many types of animal behaviour, especially seemingly complex social interactions, have been attributed to the existence of complex cognitive mechanisms. Indeed, as specific behaviours are analysed in greater and greater detail, the increasing number of minor variations observed seem to necessitate the operation of increasingly powerful computational devices. An alternate view, inspired by cybernetic theory, is that what is important is not the specific behaviours used by animals, but the goal of the organism in a particular context. When approached in this way, it is possible to deduce simple rules being used by organisms to attain goal states that account for behavioural variation, and importantly, that do not require impossible levels of cognitive power. In this paper, we apply a cybernetic approach to analysing food protective behaviour in rats. We demonstrate that a simple cybernetic rule, rather than complex computation, produces efficient and effective food protective behaviour in rats. [Abstract]

The discussion of this paper also provide evidence for Hypothesis 1.1, evidence that the observable behaviour of a range of different animals can be understood as the control of perception. [WM]

http://www.sciencedirect.com/science/article/pii/S0003347211002582

Powers, W. T. (2008). Living Control Systems III: The Fact of Control. Benchmark Publications. Chapter Two.

Powers (2008) replicates the test of the controlled variable in a computerised task within which the shape, orientation and location of an object can be controlled by the user. [WM]

http://www.livingcontrolsystems.com/lcs3/content_lcs3.html

(iii) Computer models of a closed loop system

Vancouver, J. B. & Putka, D. J. (2000). Analyzing Goal-Striving Behavior and a Test of the Generalizability of Perceptual Control Theory. *Organizational Behavior and Human Decision Processes*, *82*, 334-362.

Theories that articulate dynamic processes are relatively rare, but methods for testing the theories are even rarer. This study illustrates two methods for examining goal-striving processes and a tool for collecting dynamic data. The first method tests a hypothesis regarding what variable the participants are attempting to maintain. The second method involves creating multi-level models used to describe the dynamic data generated by study participants, which can be used to test between and within-subject manipulations or differences. The tool is a research simulation of a manager's role in scheduling subordinates in a hospital wing. Together these methods and tool are used to test the generalizability of perceptual control theory in explaining striving for cognitive goals. The results confirm the viability of a control theory accounting of goal striving, and highlight the potential of the methods and research tool in future research. [Abstract]

Powers, W. T. (2008). *Living Control Systems III: The Fact of Control*. Benchmark Publications. Chapter Three.

A full working closed loop is modelled which is used to illustrate that changes to the environment are counteracted such that perception is controlled via behaviour that controls the environment. The functional relationship between each of the components of the model can be modified and explored. [WM]

McPhail, C., Powers, W., & Tucker, C. (1992). Simulating individual and collective action in temporary gatherings. *Social Science Computer Review*, *10*, 1-28.

Perception control systems and hierarchies of such systems are described. Perception control system theory asserts that human beings adjust their actions to control their perceptions. Purposive individuals adjust their actions to counter variable circumstances that prevent their perceptions from matching their objectives. Collective action can occur when two or more purposive individuals generate similar objectives independently, or when they do so interdependently, or when they adopt them from a third party. This explanation addresses the most characteristic feature of human behavior in temporary gatherings (crowds): alternating and vaned sequences of individual and collective action. A simulation program is described that varies up to three separate sets of control systems (seeking a destination, avoiding collisions, and seeking the path of other individuals) for each of 1 to 255 individuals constituting a gathering. The program features are illustrated with successive panels of screen prints of the development of nine different sequences of individual and collective action observed repeatedly in field research on temporary gathenngs. Theoretical, research, and practical implications are noted. An appendix descnbes program parameters. [Abstract]

Schweingruber, D. (1995). A computer simulation of a sociological experiment. *Social Science Computer Review, 13,* 351-359.

Abstract: Reports results of the use of the Gathering program, a computer simulation based on the principle of perception control theory, on C. McPhail and R. Wolstein's collective locomotion experiment. The program was used to explain purposive individual and collective locomotion behavior found in the experiment. Ss in five 12-person treatment groups were given a set of instructions, similar to those used by demonstration organizers, involving movement from one point to another. Results show that coordination increased as specificity of instructions rose. The simulation's ability to produce this relationship supports the hypothesis that collective behavior is the result of Ss with similar or related reference signals. However, the current version of the Gathering program is not sophisticated enough to simulate all details of McPhail and Wolstein's study. Suggestions are provided for improving the program.

Moore, R. (2007) PRESENCE: A Human-Inspired Architecture for Speech-Based Human Machine Interaction. *IEEE Transactions on Computers, 56,* 1176-1187.

Abstract. Recent years have seen steady improvements in the quality and performance of speech-based human-machine interaction driven by a significant convergence in the methods and techniques employed. However, the quantity of training data required to improve state-of-the-art systems seems to be growing exponentially, and performance appears to be asymptoting to a level that may be inadequate for many real-world applications. This suggests that there may be a fundamental flaw in the underlying architecture of contemporary systems, as well as a failure to capitalize on the combinatorial properties of human spoken language. This paper addresses these issues and presents a novel architecture for speech-based human-machine interaction inspired by recent findings in the neurobiology of living systems. Called PRESENCE 'PREdictive SENsorimotor Control and Emulation' - this new architecture blurs the distinction between the core components of a traditional spoken language dialogue system and, instead, focuses on a recursive hierarchical feedback control structure. Cooperative and communicative behavior emerges as a by-product of an architecture that is founded on a model of interaction in which the system has in mind the needs and intentions of a user, and a user has in mind the needs and intentions of the system.

In addition to describing an architecture utilising PCT, this paper reports a robotic device built from a closed loop system that self-generates its own rhythm of movements to match the rhythm of sounds it perceives. This resembles very simply mimicry in living organisms. [WM]

Bourbon, W. T. (1989). A control-theory analysis of interference during social tracking. In W. A. Hershberger (Ed.), *Volitional action: Conation and control* (pp. 235-251). Amsterdam: North-Holland.

Powers, W. T. (1989). Quantitative measurement of volition: A pilot study. In W. A. Hershberger (Ed.), Volitional action: Conation and control (pp. 315-334). Amsterdam: North-Holland.

Correlation between model and real behaviour = 0.99841

Bourbon, W. T. (1990). Invitation to the dance: Explaining the variance when control systems interact. *American Behavioral Scientist, 34,* 95-105.

Bourbon, W. T., Copeland, K. E., Dyer, V. R., Harman, W. K., & Mosley, B. L. (1990). On the accuracy and reliability of predictions by control-system theory. *Perceptual Motor Skills, 71,* 1331-1338.

In three experiments we used control-system theory (CST) to predict the results of tracking tasks on which people held a handle to keep a cursor even with a target on a computer screen. 10 people completed a total of 104 replications of the task. In each experiment, there were two conditions: in one, only the handle affected the position of the cursor; in the other, a random disturbance also affected the cursor. From a person's performance during Condition 1, we derived constants used in the CST model to predict the results of Condition 2. In two experiments, predictions occurred a few minutes before Condition 2; in one experiment, the delay was 1 yr. During a 1-min. experimental run, the positions of handle and cursor, produced by the person, were each sampled 1800 times, once every 1/30 sec. During a modeling run, the model predicted the positions of the handle and target for each of the 1800 intervals sampled in the experimental run. In 104 replications, the mean correlation between predicted and actual positions of the handle was .996; SD = .002. [Abstract]

Powers, W. T. (1990). Control theory and statistical generalisations. *American Behavioral Scientist, 34,* 24-31.

In this brief paper, Powers (1990) builds a computer model of a population of 4,000 control systems, and shows how the correlation between their behavioural effort and reward is significant and positive, while at the same time there is a very high negative correlation between effort and reward for individuals who share the same reference value for their desired reward. This represents the negative feedback of each control system – they increase effort when reward is reduced. Thus, a correlation that appears to show evidence of reward causing effort at a population level can be created by individuals who operate according to control theory. [WM]

Marken, R. S. (1989). Behavior in the first degree. In W. A. Hershberger (Ed.), *Volitional action: Conation and control* (pp. 299-314). Amsterdam: North-Holland.

Marken, R. S. (1991). Degrees of freedom in behavior. *Psychological Science, 2,* 92-100.

Coordinated behavior is typically explained in terms of motor programs or coordinative structures. The experiments described in this report suggest that a better explanation may be provided by control theory. In all experiments, subjects controlled the two-dimensional position of a cursor. By varying the disturbances to the two degrees of freedom of cursor movement, it was possible to elicit task-specific, unidimensional movement patterns resembling coordinative structures. Perturbation of one dimension of the movement pattern failed to produce a concomitant response in the other dimension unless there was a link between the degrees of freedom of action and perception. The subjects' behavior was accurately simulated by the behavior of independent feedback control systems. The results show that the problem of coordinating many degrees of freedom of action can be solved by viewing behavior as control of the perceptual consequences of these actions. [Abstract]

http://pss.sagepub.com/content/2/2/92.short

Bourbon, W. T. (1996). On the accuracy and reliability of predictions by perceptual control theory: Five years later. *The Psychological Record, 46,* 39-47.

Demonstrates an idiographic procedure that makes very accurate quantitative predictions of one person's specific actions during a task. The author served as the S. In June, 1988, Condition 1 for each of 8 different runs of a 2-condition pursuit tracking task was completed. Using data from Condition 1, when only the control handle affected the position of the cursor, the constants in the model of behavior from perceptual control theory were estimated, and the model was used to predict the results for Condition 2, when a random disturbance would also affect the cursor. Two of the 8 predicted runs will be done every 5 yrs; 2 were done in July, 1993. Correlations between 1,800 pairs of predicted and actual handle positions were .998 for the 1st run, and .997 for the 2nd. Data from the model and the S were nearly indistinguishable. [Abstract]

Marken, R. S. (2003). Error in skilled performance: a control model of prescribing. *Ergonomics, 46,* 1200-1214.

A control model of skilled performance is proposed as a framework for understanding why prescribing errors occur at a particular rate. Model error rate depends on skill level, system design characteristics, the range of different types of prescriptions that are produced and the time available to complete each prescription. The parameters of the model can be adjusted so it produces error rates that are quantitatively equal to those found in studies of the incidence of different types of prescribing error. The model will also produce error rates that are qualitatively consistent with the results of studies that show increases in prescribing error rates as a result of increases in distractions and workload. The model is used to determine the likely effectiveness of different prescribing error prevention interventions. [Abstract]

http://www.tandfonline.com/doi/abs/10.1080/00140139031000l593568

Vancouver, J. B., Putka, D. J., & Scherbaum, C. A. (2005). Testing a Computational Model of the Goal-Level Effect: An Example of a Neglected Methodology. *Organizational Research Methods, 8,* 100-127.

To encourage the use of computational modeling in organizational behavior research, an example computational model is developed and rigorous tests of it presented. Specifically, a computational model based on control theory was created to test the theory's explanation of the goal-level effect (e.g., higher goals lead to higher performance). Data from simulations of the model were compared with the behavior of 32 undergraduate students performing a scheduling task under various within-subject manipulations and across time. Correlational analyses indicated that the model accounted for most of the participants' data, with coefficients between the model and each participant's behavior mostly in the high nineties. [Abstract]

(A working version of the model can be downloaded (four agents.mdl) and the software used to create and run the model (the learning edition of Vensim©) can be downloaded for free at http://www.vensim.com/. The alternative model described in the paper is downloadable as well (alternative.mdl).

Marken, R. S., & Horth, B. (2011). When causality does not imply correlation: More spadework at the foundations of scientific psychology. *Psychological Reports, 108,* 943-954.

This latest research study demonstrates that input is not correlated with output within a tracking task, as would be expected from an open loop model of stimulus-response, or input-compute-output. This is lack of relationship is maintained at three levels of difficulty. On the other hand, a closed loop model provides a close match to the data obtained from the task. This is because in a closed loop model, output causes input as much as input causes output in a process of dynamic adjustment against disturbances, thereby disrupting any simple correlation between the two.[WM]

Experimental research in psychology is typically based on an open-loop causal model which assumes that sensory input causes behavioral output. This model was tested in a tracking experiment where participants were asked to control a cursor, keeping it aligned with a target by moving a mouse to compensate for disturbances of differing difficulty. Since cursor movements (inputs) are the only observable cause of mouse movements (outputs), the open-loop model predicts that there will be a correlation between input and output that increases as tracking performance improves. In fact, the correlation between sensory input and motor output is very low regardless of the quality of tracking performance; causality, in terms of the effect of input on output, does not seem to imply correlation in this situation. This surprising result can be explained by a closed-loop model which assumes that input is causing output while output is causing input. [Abstract]

http://www.amsciepub.com/doi/abs/10.2466/03.PR0.108.3.943-954?journalCode=pr0

(iv) Comparative Models

Marken, R. S., & Powers, W. T. (1989) Levels of Intention in Behavior. In W. A. Hershberger (Ed.), Volitional action: Conation and control (pp. 409-430). Amsterdam: North-Holland.

Bourbon, W. T., & Powers, W. T. (1999). Models and their worlds. *International Journal of Human-Computer Studies, 50,* 445-461.

Conventional behavioral models can be broadly classed as stimulus-driven (bottom-up, S–R) and brain-driven (top-down, cognitive). Perceptual control theory (PCT) uses a model that has features of both classes, and so can be difficult to distinguish from either one. The difference in PCT is not just in the model of the organism, but in the assumed properties of the world in which the organism behaves. We discuss and experimentally demonstrate the basic models, and the worlds in which they can operate properly. The results show, we believe, that PCT employs the only kind of model that can work in a realistic model of the world. [Abstract]

Marken, R. S. (2001). Controlled variables: Psychology as the center fielder views it. *The American Journal of Psychology, 114,* 259-281.

Perceptual control theory (PCT) views behavior as the control of perception. The central explanatory concept in PCT is the controlled variable, which is a perceived aspect of the environment that is brought to and maintained in states specified by the organism. According to PCT, understanding behavior is a matter of discovering the variables that organisms control. But the possible existence of controlled variables has been largely ignored in the behavioral sciences. One notable exception occurs in the study of how baseball outfielders catch fly balls. In these studies it is taken for granted that the fielder gets to the ball by controlling some visual aspect of the ball's movement. This article describes the concept of a controlled variable in the context of research on fly ball catching behavior and shows how this concept can contribute to our understanding of behavior in general. [Abstract]

Marken, R. S. (2005) Optical trajectories and the informational basis of fly ball catching, *Journal of Experimental Psychology: Human Perception & Performance, 31,* 630 – 634.

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) replotted 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. [Abstract]

http://mindreadings.com/OpticalTrajRM.pdf

Vancouver, J. B. & Scherbaum, C. A. (2008). Do We Self-Regulate Actions or Perceptions? A Test of Two Computational Models. *Computational and Mathematical Organizational Theory, 14,* 1-22.

Self-regulation theories in applied psychology disagree about whether action or perceptions are the focus of regulation. Computational models based on the two conceptualizations were constructed and simulated. In one scenario, they performed identically and in conjunction with participants in a study of the goal-level effect (Vancouver et al., Organ Res Methods 8:100–127, 2005). In another scenario they created differentiating predictions and only the computational model based on the self-regulation of perceptions matched the data of participants. Implications for research and practice are discussed. [Abstract]

Takagi, F., Sakahara, H., Tabata, T., Yamagishi, H., Suzuki, T., & Miyazaki, F. (2009). Navigation control for tracking and catching a moving target. *Intelligent Robotics and Systems, Oct 2009,* 866-871.

This paper presents feedback control laws for pursuing and catching a fly ball by taking Chapman's hypothesis into the closed-loop system connecting perceptions and actions. Through the analysis of the closed-loop system, we make it clear that the hypothetical trajectory Chapman showed is a special dynamic solution of the closed-loop system. Moreover, using a motion-analyzing technique over a finite time, it is shown that the proposed feedback control laws make it possible to generate a pursuing trajectory automatically that a fly ball can be caught in the right place and at the right time. It is also shown that the pursuing trajectory gets closer to the one Chapman showed as a feedback gain increases. In addition, we compare the proposed feedback control laws with Proportional Navigation (PN) which is the most common navigation technique for tracking a moving target, and demonstrate that the proposed control laws perform better than PN. (Abstract]

Rabinovich, Z., & Jennings, N. R. (2010). A hybrid controller based on the egocentric perceptual principle. *Robotics and Autonomous Systems, 58,* 1039-1048.

In this paper we extend the control methodology based on Extended Markov Tracking (EMT) by providing the control algorithm with capabilities to calibrate and even partially reconstruct the environment's model. This enables us to resolve the problem of performance deterioration due to model incoherence, a problem faced in all model-based control methods. The new algorithm, *Ensemble Actions EMT (EA-EMT)*, utilises the initial environment model as a library of state transition functions and applies a variation of prediction with experts to assemble and calibrate a revised model. By so doing, this is the first hybrid control algorithm that enables on-line adaptation within the egocentric control framework which dictates the control of an agent's perceptions, rather than an agent's environment state. In our experiments, we performed a range of tests with increasing model incoherence induced by three types of exogenous environment perturbations: *catastrophic*—the environment becomes completely inconsistent with the model, *deviating*—some aspect of the environment behaviour diverges compared to that specified in the model, and *periodic*—the environment alternates between several possible divergences. The results show that EA-EMT resolved model incoherence and significantly outperformed its EMT predecessor by up to 95%.

2. Evidence for Conflict between Closed Loops

PCT proposes that when two closed loops attempt to control the same variable, *conflict* occurs, whereby error is maintained in both systems. This is an unstable state that requires *reorganisation* to resolve (see later).

Studies of conflict involve the following paradigms: (i) observations of natural behaviour; (ii) computer models of closed loop systems

van de Rijt-Plooij, H. H. C., & Plooij, F. X. (1987). Growing independence, conflict and learning in mother-infant relations in free-ranging chimpanzees. *Behaviour, 101,* 1-86.

van de Rijt-Plooij, H., & Plooij, F. (1988). Mother-infant relations, conflict, stress and illness among free-ranging chimpanzees. *Developmental Medicine and Child Neurology, 30*, 306-315.

van de Rijt-Plooij, H., & Plooij, F. (1993). Distinct periods of mother-infant confl ict in normal development: Sources of progress and germs of pathology. *Journal of Child Psychology and Psychiatry, 34*, 229-245.

Powers, W. T. (1999). A model of kinesthetically and visually controlled arm movement. *International Journal of Human-Computer Studies, 50*, 463-479.

This paper describes a preliminary simulation of kinesthetic control systems that operate a humanoid arm having three degrees of freedom. The design is in part a literal interpretation of the stretch and tendon reflexes considered as control systems. A second level of control converts independent control of three joint angles into a trio of systems controlling the tip of the arm in pitch, yaw and distance coordinates centered on the shoulder. The basic properties of muscles are included, and the arm movements are calculated using equations describing the physical dynamics of the arm. A "visual servo" level of control is included in preliminary form. The model exhibits realistic behavior, producing stable and fast control without computing either inverse kinematics or inverse dynamics. [Abstract]

http://www.ingentaconnect.com/content/ap/hc/1999/00000050/00000006/art00261

Powers, W. T. (2008). Living Control Systems III: The Fact of Control. Benchmark Publications. Chapter Six.

http://www.livingcontrolsystems.com/lcs3/content_lcs3.html

Carey, T. A. (2008). Conflict, as the Achilles heel of perceptual control, offers a unifying approach to the formulation of psychological problems. *Counselling Psychology Review*, 23, 5-16.

PCT suggests that the way in which mental health disorders are currently understood in terms of categorizing groups of symptoms could be improved by focusing, instead on the goals associated with any particular disorder. From a PCT perspective, psychological distress can be understood as the consequence or by-product of conflicted goals. When one control system attempts to create a perception that is incompatible with the perception being created by another control system a situation of instability is reached where neither control system is able to control its perceptual signal. To investigate the parameters of conflict I used the Crowd simulation program developed by Powers (2005). The programs provides parameters that can be adjusted for each agent. Using the program two agents were produced. Agent A had a 'goal' of seeking a particular destination and also a 'goal' for maintaining a particular distance from Agent B. Agent B had a 'goal' of maintaining a particular proximity to Agent A. To begin with parameters were established such that Agent A and Agent B could both successfully control. Then I investigated the minimum number of parameters that needed to be manipulated to produce conflict. Changing the loop gain of Agent B by a multiplicative factor of four made Agent B approach Agent A more rapidly and created conflict Agent A. In this situation Agent A produced a trace on the screen of oscillations and immobility indicative of the instability that is a feature of internal perceptual conflict. From this initial conflict situation it was discovered that by manipulating the loop gain of A produced different patterns of oscillation and immobility. The results are discussed in terms of their clinical implications. To complement this modelling clinical descriptions of actual clients are provided in which the presenting symptoms are described as well as the underlying conflicts associated with the symptoms. The formulation of psychological distress as conflict between control systems provides new avenues for both clinical practice and research programs to enhance our understanding and treatment of mental health disorders. [TC]

3. Evidence for Hierarchical Models of Closed Loops

PCT proposes that closed loops are organised within hierarchies in order to achieve more complex skills and goals. Specifically, each level in the system controls a different perceptual variable, and the outputs of higher level systems set the reference values for lower level systems.

Studies of hierarchical control involve the following paradigms: (i) observations of natural behaviour; (ii) manipulations of the environment in experimental tasks; (iii) computer models of closed loop systems.

(i) Observations of natural behaviour

Powers, W. T., Clark, R. K., & McFarland, R. L. (1960b). A general feedback theory of human behaviour: Part II. Perceptual and Motor Skills, 11, 309-323.

In addition to explaining the hierarchy of closed loops, this paper describes the procedures and results of a number of qualitative demonstrations of levels of control using arm movements that are easily replicated by the reader.

Plooij, F. X. (1984). The behavioural development of free-living chimpanzee babies and infants. (Monographs on Infancy No. 3). Norwood, NJ: Ablex.

This monograph reports the detailed observations of baby chimps and explains how each stage of development can be understood as a new level of control, that starts as invariant and then becomes flexibly varied at the next stage of development. For example, newborn chimps locate the mother's nipple by ascending a gradient of sensations of perceived warmth – known as 'comfort-contact search' , which presumes they have a fixed target that is not varied. However, after two months, they can tolerate breaks in physical contact with the mother, suggesting that there is now variability in the process of 'comfort contact search'. This monograph is also explained in Plooij & van de Rijt-Plooij (1990). [WM]

Plooij, F. X., & van de Rijt-Plooij, H. H. C. (1990). Developmental transitions as successive reorganizations of a control hierarchy. American Behavioral Scientist, 34, 67-80.

(ii) Computer models

Marken, R. S. (1990). Spreadsheet analysis of a hierarchical control system model of behavior. Behavior Research Methods, Instruments and Computers, 22, 349-359.

The behavior of a hierarchy of control systems can be simulated with an electronic-spreadsheet. Each control system is a column of three cells representing the reference signal, perceptual signal, and output variable of the system. All of the control systems are closed-loop, the input to each system being a function of its output. The circular references in the spreadsheet are resolved through iterative recalculation. When the parameters of each control system (amplification and slowing factors) are set to appropriate values, all control systems in the hierarchy continue to match perceptual signals with reference signals. A three-level hierarchy with four systems at each level is simulated in the spreadsheet. The spreadsheet model makes it possible to observe the dynamic behavior of the control systems as they correct for the effects of environmental disturbance and changes in higher order reference signals. It is possible to "reorganize" the system by changing the perceptions controlled by systems at different levels of the hierarchy. The user can also test to determine the variables being controlled by the system. [Abstract]

http://www.springerlink.com/content/2t70533x942m1264/

Kennaway, R. (1999). Control of a multi-legged robot based on hierarchical PCT. Journal of Perceptual Control, 1, 1-7.

We describe an experiment in robot control, using a simulated six-legged robot. The robot, herein called Archy, is capable of standing, resisting disturbing forces, and walking over uneven terrain and up and down a staircase. It can continue to stand up and control its body position and orientation even when some legs are removed. The control systems are all simple PID controllers, with a couple of fuzzy controllers for navigating when walking. [Abstract]
http://www2.cmp.uea.ac.uk/~jrk/PCT/jp9913p.pdf

Powers, W. T. (2008). Living Control Systems III: The Fact of Control. Benchmark Publications. Chapter Eight.

http://www.livingcontrolsystems.com/lcs3/content_lcs3.html

Marken, R. S. (1986). Perceptual organisation of behavior: A hierarchical control model of coordinated action. Journal of Experimental Psychology: Human Perception and Performance, 12, 267-276.

Compared the behavior of 4 college students and 2 faculty members (including the present author) with a hierarchical control system model of behavioral organization. Ss varied the position of 2 control handles simultaneously to keep the distance constant between 2 pairs of lines. Three variations on this basic experiment that illustrate some fundamental properties of coordinated action showed (1) how independent actions, compensating for unpredictable and undetectable disturbances, can produce a single behavioral result; (2) how the ability to produce a particular result is maintained when the connection between action and result is changed; and (3) how 2 independent outputs can appear to be related as coordinative structures when one output disturbs a result being controlled by the other. The correlation between the behavior of Ss and the model in all experiments was typically on the order of .99. A detailed examination of the operation of the model demonstrated that actions are structured by perception, not by central commands or equations of constraint. [Abstract]

http://www.sciencedirect.com/science/article/pii/S0096152307608220

4. Evidence for Reorganisation

PCT proposes that a process known as *reorganisation* is required for learning within a control system, resulting in reduced *intrinsic error* within the control systems necessary for survival. Reorganisation is driven by intrinsic error and involves random changes to the speed and direction of change of the properties of control systems which persist until intrinsic error begins to reduce. Reorganisation may be global (across all systems in the hierarchy) or localised to specific units.

Studies of hierarchical control involve the following paradigms: (i) observations of natural behaviour; (ii) computer models of closed loop systems.

van de Rijt-Plooij, H. H. C., & Plooij, F. X. (1987). Growing independence, conflict and learning in mother-infant relations in free-ranging chimpanzees. *Behaviour, 101,* 1-86.

Pavloski, R. P., Barron, G. T., & Hogue, M. A. (1990). Reorganization: Learning and attention in a hierarchy of control systems. American Behavioral Scientist, 34, 32-54.

This study models individual performance on dual task paradigm and plots how the control of two different variables (cursor position and numeric value of a digit) are managed in real time. The plots for a novice participant who had learned the tasks separately, revealed a switch between the two tasks – at any one time only one variable is controlled. In contrast, the plots of an experienced participant who had practised the dual task revealed that both tasks were managed simultaneously. The authors concluded from these results that the experience participant had developed an input function for the task that represented a novel conjunction between the two variables. Within PCT, a logical conjunction of this kind would be represented at the program level of perception, and would be formed through reorganisation to reduce error during practice. [WM]

Carey, T. A., Carey, M., Stalker, K., Mullan, R. J., Murray, L., & Spratt, M. (2007). Psychological change from the inside looking out: A qualitative investigation. *Counselling and Psychotherapy Research, 7,* 178-85.

This study addresses the questions 'What is psychological change?' and 'How does it occur?' from patients' viewpoints. Answers to these questions were sought using qualitative methodology. At the end of treatment, 27 people were interviewed about their experience of change. Interviews were taped and transcripts analysed using the Framework approach. Change occurred across three domains – feelings, thoughts, and actions. Participants described change as both a gradual process and an identifiable moment. In relation to how change occurred, six themes emerged – motivation and readiness, perceived aspects of self, tools and strategies, learning, interaction with the therapist, and the relief of talking. Change was experienced in similar ways irrespective of type of treatment. Current stage models of change might not be suited to the explanations of change provided by the participants of this study. The process of insight through reorganization might be a more accurate explanation. Understanding change as a process involving sudden and gradual elements rather than a process occurring through sequential stages could inform the development of more efficacious psychological treatments. [Abstract]

Higginson S, Mansell W. (2008). What is the mechanism of psychological change? A qualitative analysis of six individuals who experienced personal change and recovery. *Psychology and Psychotherapy: Theory, Research and Practice*, *81,* 309-28.

Objective. The mechanism of psychological change, whether this occurs as a result of psychotherapeutic intervention or during natural recovery, remains unknown. The aim of this study was to explore and understand how and why psychological change occurs. **Design.** This study presents the accounts of six individuals who experienced psychological change and recovery following a significant problem in their lives using the qualitative method of interpretative phenomenological analysis (IPA). **Method.** A semi-structured interview covered several aspects of their experience which included details of the problem they faced, how the problem affected their lives, how they were able to overcome the problem, and how they felt about their problem looking back. **Results.** Four superordinate themes emerged from the analysis: hopelessness and issues of control; the change process; new self versus old self; and putting the problem into perspective. **Conclusions.** Findings are discussed in relation to existing literature on hopelessness and locus of control, experiential avoidance, acceptance and mindfulness, insight, and adversarial growth. The findings are also discussed in relation to a theory of self-regulation known as perceptual control theory (PCT). It is proposed that this theory may provide a valid account of the mechanism of psychological change.

Gianakis, M., & Carey, T. A. (in press). An interview study investigating experiences of psychological change without psychotherapy. *Psychology and Psychotherapy: Theory, Research & Practice.*

Objectives. Given that most people who experience psychological distress resolve this distress without the assistance of psychotherapy, the study sought to increase our understanding of naturally occurring change including the facilitators of this change.
Design. The study sought to replicate and extend earlier work in this area. The design involved recruiting participants who had experienced some form of psychological distress and had resolved this distress without accessing psychotherapy services.
Methods. Qualitative methods were used for this study because the lived experience of the participants was of interest. Semi-structured interviews were used following a proforma developed in earlier work. Interpretive Phenomenological Analysis was the analytical method adopted for this study to identify themes and patterns in the transcripts of the interviews of the participants.
Results. Data analysis identified the themes of identity, connection, threshold, desire to change, change as a sudden and gradual process, and thinking process. An unexpected finding was the subjectivity associated with deciding whether or not a problem had actually resolved.
Conclusions. The results are discussed in terms of their implications for clinical practice including the apparent importance of people reaching an emotional threshold prior to change. A sense of identity also appears to be important in change experiences.

(ii) Computer models

Marken, R. S., & Powers, W. T. (1989). Random-walk chemotaxis: trial-and-error as a control process. Behavioural Neuroscience, 103, 1348-1355.

The biased random-walk chemotaxis of the bacterium Escherichia coli is a remarkably effective method of navigation based on random trial-and-error responding rather than steering. Humans restricted to the same mode of responding are able to navigate to target locations, just like the bacterium. This mode of navigation can be modeled as an input control process that selectively retains favorable and rejects unfavorable consequences of the random responses. The selection process is determined by the internal organization of the system rather than the external influence of the environment (as in natural selection or reinforcement). [Abstract]

http://www.sciencedirect.com/science/article/pii/S0735704402013940

Powers, W. T. (2008). Living Control Systems III: The Fact of Control. Benchmark Publications. Chapter Seven.

http://www.livingcontrolsystems.com/lcs3/content_lcs3.html

Powers, W. T. (2008). Living Control Systems III: The Fact of Control. Benchmark Publications. Chapter Eight.

http://www.livingcontrolsystems.com/lcs3/content_lcs3.html

5. Further Components of PCT

Powers (1973) described several other components of the theory, including the function of memory within a closed loop, and the notion of modes that represent specific functional dissociations of the hierarchy: controlled, automatic, passive observation and imagination. Powers (1973) also makes proposals around the neurophysiology of perceptual control and the conceptualisation of emotion within PCT. To date, none of these components have been tested in published empirical papers.

In addition there are a range of empirical studies with evidence pertaining to the hypotheses derived from PCT that psychological distress represents loss of control; that this is caused by chronic conflict between closed loop systems (assessed as 'goals' within self-report studies); and that change is mediated through changes to systems that are superordinate to the location of the conflict. Reviews of this research are described elsewhere (e.g. Carey, 2008; Higginson, Mansell & Wood, 2011; Kelly, Mansell & Wood, submitted; Watkins, 2011).

Finally, there are adaptations made to PCT by authors other than Powers, which have themselves been tested empirically. For the sake of simplicity, this document does not include these studies.