Perceptual & Motor Skills: Perception
2013, 117, 1, 1-12. © Perceptual & Motor Skills 2013

MOTOR CONTROL AS THE CONTROL OF PERCEPTION[1]

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Summary.—This paper describes a test of Perceptual Control Theory (PCT), which views motor control as part of a process of controlling perceptual inputs rather than motor outputs. Sixteen undergraduate students (*M* age = 19.9 yr.) were asked to control one of three different perceptual aspects of an animated display—a shape, a motion or a sequence—using the same motor output, a key press. Animation rate was varied while quality of control was measured in terms of the proportion of time that the perception was maintained in the goal state. The results showed that increased animation rate made it hardest to control the more complex perceptions (motion and sequence) even though the same output was used to control all perceptions. This result is consistent with PCT, which predicts that the temporal constraints on control are ultimately a function of the type of perception controlled rather than the type of output used to control it.

One large class of theories of motor control explains behavior in terms of central programs that calculate the outputs that produce behavioral results (Lashley, 1951; Arbib, 1972; Greeno & Simon, 1974; Rosenbaum, Hindorff, & Munro, 1987; Keele, Cohen, & Ivry, 1990). These can be called "controlled output" theories because they assume that behavior results from a process of controlling motor *outputs.* In contrast, a smaller class of theories explains behavior in terms of processes organized around the *results* of motor outputs (Bernstein, 1967; Saltzman, 1979; Mechsner, Kerzel, Knoblich, & Prinz, 2001; Warren, 2006; Schack & Ritter, 2009). These can be called "controlled result" theories of motor control because they assume that behavior is a process of controlling the *results* of motor outputs rather than the motor outputs themselves.

One paradigmatic example of a controlled result theory of motor control is Perceptual Control Theory (PCT) (Powers, Clark, & McFarland, 1960; Powers, 1973). PCT views behavior as a process of controlling the *perceived results* of motor outputs. The motor outputs themselves are seen as part of a negative feedback loop that keeps these results in reference states specified by the behaving system itself.

Both controlled output and controlled result theories of motor control have utilized a hierarchical organization to model complex behaviors. In controlled output theories, higher levels in a hierarchy specify the

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DOI 10.2466/24.23.PMS.117x15z2 ISSN 0031-5125

increasingly complex motor outputs that produce increasingly complex behavioral results (Lashley, 1951; Keele, *et al.*, 1990; Grafton & Hamilton, 2007). In PCT, higher levels specify increasingly complex perceptions of the behavioral results being produced by the motor outputs (Powers, *et al.*, 1960; Powers, 1998).

All hierarchical theories of motor control predict that behaviors originating at higher levels will be produced more slowly than those originating at lower levels of the hierarchy. This prediction is consistent with the fact that less complex (lower level) behaviors, such as an alternating pattern of finger taps, can be produced more quickly than complex (higher level) ones, such as a structurally more intricate pattern of taps (Povel & Collard, 1982; Marken, 2002). Controlled output theories assume that this occurs because of the increased time required to send more complex commands for motor outputs from higher to lower levels. PCT assumes that this occurs because of the increased time required to derive a perception of a complex behavioral result from lower level perceptions in the hierarchy. Thus, hierarchical controlled output theories assume that the time delay in the process of motor control occurs where a higher level motor signal diverges to drive lower level muscular actions. In contrast, PCT proposes that this time delay occurs where lower level sensory signals converge to create the higher level perceptions that are compared with the intended values for these perceptions.

A New Kind of Tracking Task

The present research compares controlled output theories to PCT in terms of their predictions about the source of the time delay in the processes that produce behavior. The comparison is done using a version of a tracking task that is frequently used in the study of motor control (Powers, 1978; Jagacinski & Flach, 2002). In the typical tracking task the participant is to control some aspect of a display, such as the distance between a cursor and target, keeping it in a goal state (i.e., keeping the distance close to zero). In this case, the aspect of the display to be controlled consists of an animated set of objects (see Fig. 1). The objects are circles (as shown) or squares of different sizes, changing screen location (apparent motion) in either a clockwise (shown) or counter-clockwise direction, in a sequence that goes from small to medium to large (shown) or from small to large to medium. Thus, there are three aspects of the display that can be controlled in this tracking task: the shape, direction of motion and sequence of sizes of the objects displayed.

On each trial participants are asked to control one aspect of the displayed objects, keeping it in a goal or target state. For example, a participant might be asked to control the sequence of sizes of the objects, keeping them in the state "small, medium, large." The participant does

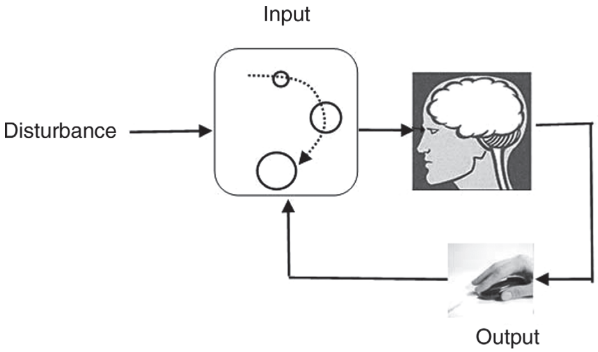

FIG. 1. Tracking task where participant can control any one of three different aspects of a computer display by pressing a button.

this by pressing the mouse button as quickly as possible after a disturbance (Fig. 1d) that changes the state of the display—for example, changing the sequence from “small, medium, large” to “small, large, medium.” The button press restores the display to the goal state.

The participants in this control task are producing different types of behavioral results using a single type of motor output: a button press. The different behavioral results are the different aspects of the display that are being kept under control. So it is possible to produce a simple behavior result—a constant shape (“circle”) or a fairly complex one such as a constant clockwise motion or a repeating sequence (“small, medium, large”)—using the same, simple motor output.

The different perceptual aspects of the display that can be controlled in this task represent different levels of the hierarchy of perceptual control defined by Powers (1973). The levels represent different perceptual aspects of the environment that organisms can control, with higher level perceptions representing more complex aspects of the environment than lower level ones. According to Powers' hierarchical model, the lowest level perceptual aspect of the display that can be controlled in this experiment is shape, which corresponds to Powers' “configuration” level of perception; the next higher level is motion, which corresponds to Powers' “transition” level of perception; the highest level aspect of the display that can be controlled is sequence, which corresponds to Powers' “sequence” level of perception.

Predictions of Controlled Output Theories and PCT

Hierarchical controlled output theories and PCT make very different predictions about the behavior that should be seen in this tracking task. In particular, these theories make different predictions about participants' ability to control the different perceptual aspects of the display when the displayed objects are presented at different rates. How well an aspect of the display can be controlled depends on how quickly the participant can correct for a disturbance by pressing the mouse button. The faster the corrective response the higher the rate at which an aspect of the display can be kept under control (in the goal state). That is, the faster the response the higher the rate at which the behavioral result—a constant shape, motion or sequence—can be produced.

Since the same response, the mouse press, is used to control all aspects of the display the output time delay assumed by controlled output theories is eliminated. Thus, controlled output theories predict that the latency of a response to a disturbance will be the same regardless of which hierarchically related aspect of the display is being controlled. These theories predict that all aspects of the display can be controlled at the same rate, the highest rate at which control is possible being constrained only by how quickly the participant can press the mouse button after a disturbance.

PCT, on the other hand, predicts that the time it takes to respond to a disturbance will differ depending on the hierarchical level of the perceptual aspect of the display that is being controlled. This is because even with the output time delay removed by using the same response to control all aspects of the display there remains an input time delay that increases the time it takes to respond to disturbances to higher level perceptions. This is illustrated in Fig. 2, which shows a PCT model of three hierarchical levels of control loops that control three different perceptual aspects of the same physical display, q_i, using a single output, o (a button press in this case).

The three perceptions in Fig. 2 (p_1, p_2, and p_3) are neural signals that correspond to the three controllable aspects of the display: shape, motion and sequence, respectively. The boxes labeled $i_n()$ are perceptual functions, which consist of neural networks at each of the n levels of the control hierarchy that represent different aspects of the physical display, q_i, as perceptual neural signals. Higher level perceptions (p_3) are presumed to depend on more levels of perceptual functions than lower level ones (p_2, p_3). When a perception is controlled, it is compared (via a comparator function, C) to a reference signal (r_n) and any discrepancy between perception and reference is an error signal that drives the output, o, via the output function m().

The model in Fig. 2 shows that higher level perceptions (like p_3, sequence) depend on more levels of perceptual computation than lower level perceptions (like p_1, shape). Since more perceptual processing is required to perceive higher than lower level perceptions, it should take more time to perceive a sequence than a shape. This implies that it should be possible to perceive a higher level aspect of a display only when it is

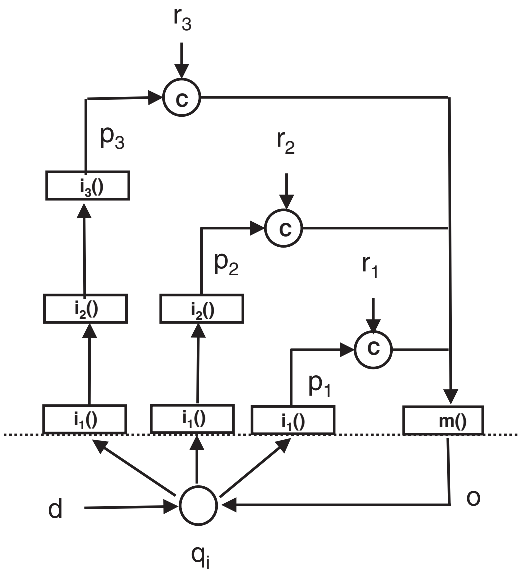

FIG. 2. PCT model of a hierarchy of control systems. The figure shows three control systems at three different levels of a hierarchy. The input functions, i_n(), compute different perceptual aspects of the environmental variable, q_i, which is also influenced by an environmental disturbance, d. Each control system controls a perception, p_n, relative to a reference specification (goal), r_n, using the same output function, m(). When control is successful, each system maintains its perception of q_i at its reference, protected from the effects of the disturbance.

presented at a much lower rate than a lower level one. And there is both empirical and subjective evidence (from watching computer displays) that a higher level aspect of a display, such as a sequence, can only be perceived when it is presented at a much slower rate than a lower level one, such as a shape (Warren, Obusek, Farmer, & Warren, 1969; Marken, 2002). Since it is only possible to control an aspect of the display that can be perceived, PCT predicts that lower level perceptual aspects of the display, such as shape, can be controlled when they are presented at a much faster rate than higher level aspects, such as sequence, even though the same response is used to control all aspects of the display.

The different predictions of the controlled output and PCT theories of motor control were tested by asking participants to control each of the three different aspects of the display in the tracking task described in Fig. 1 when the display is presented at different animation rates. Animation rate should have no effect on the ability to control the different aspects of the display if, as per controlled output theories, the only constraint on the ability to produce these different results is the time required to produce the same button press output. On the other hand, animation rate should have a strong effect on the ability to control the different aspects of the display if, as per PCT, the ability to perceive different aspects of the display depends on the rate at which these aspects of the display are presented. Control of the lower level shape perception should be good at even the fastest animation rates since shape can be perceived when the displayed objects are presented rapidly; control of the higher level motion and sequence perceptions should be poor at the faster animation rates but much better at slower animation rates since these aspects of the display can be perceived only when the displayed objects are presented at a relatively slow rate.

METHOD

Participants

Sixteen volunteer psychology undergraduate students from the University of Manchester participated in this experiment. The mean age of the participants was 19.9 yr. (*SD* = 1.6). All were women. Fourteen were right-handed and two were left-handed. Participants were awarded with course credits and explained that the purpose of the experiment was to assess why some tasks can be performed more quickly than others. Students with corrected vision or sufferers of epilepsy were requested not to volunteer.

Apparatus

A Java program was designed to present an animated series of objects on a computer screen, changing in shape (circle or square), direction of (apparent) motion (clockwise and counterclockwise), and size sequence ("small, medium, large" or "small, large, medium"). At random times during a test trial, a disturbance would change each aspect of the display from its current state to its opposite: the disturbance to shape would change the circle to a square or vice versa; the disturbance to direction of motion would change clockwise motion to counterclockwise or vice versa; and the disturbance to sequence would change the sequence from "small, medium, large" to "small, large, medium," or vice versa.

A schematic representation of the display along with the effect of disturbances on the display is shown in Fig. 3. The figure shows four possible frames of the display animation. The displayed objects were presented in sequence in four different positions in a circular pattern. The first frame (at t_0) shows a circle shape moving from the 12 o'clock position (where it was on the previous frame) to the 3 o'clock position and increasing in size. The next frame (at $t_{0+\tau}$) shows the circle shape moving from 3 o'clock to 6 o'clock, increasing in size and changing to a square shape. The change to a square is the result of the disturbance to the shape aspect of the display.

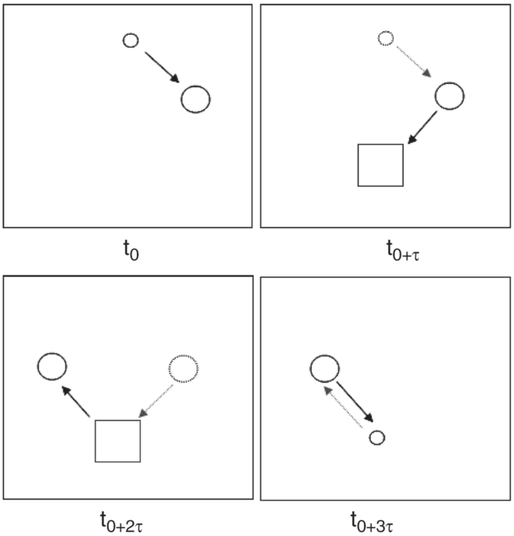

FIG. 3. Four sequential frames of the animated display showing the objects moving clockwise and increasing in size (t_0), changing shape ($t_{0+\tau}$), changing sequence ($t_{0+2\tau}$), and changing direction ($t_{0+3\tau}$).

The next frame (at $t_{0+2\tau}$) shows the large square shape moving from 6 o'clock to 9 o'clock, decreasing in size and changing back to a circle. This change is a disturbance to the sequence aspect of the display: the sequence of sizes was going from medium to large as part of the "small, medium, large" sequence, and it is now going from large to medium which is part of the "small, large, medium" sequence. The last frame (at $t_{0+3\tau}$) shows the medium-size circle moving from 9 o'clock back to 6 o'clock and increasing in size. This is a result of a disturbance to the direction of motion aspect of the display changing the direction from clockwise to counterclockwise.[2]

The participants were able to counter the effect of a disturbance to any aspect of the display by pressing the mouse button. As soon as the mouse button was pressed, the next frame of the display was returned to its pre-disturbance state. Thus, the participant could control any aspect of the display, keeping it in the desired state, by pressing the mouse button. The sooner the mouse button was pressed after a disturbance, the sooner the controlled aspect of the display returned to the goal state. Disturbances to each aspect of the display occurred several times during each test trial. The sooner the mouse button was pressed after each disturbance during

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[2] An example of the type of display used in this experiment can be seen on the World Wide Web at http://www.mindreadings.com/ControlDemo/HP.html.

a trial, the longer the controlled aspect of the display remained in the goal state during a trial. The percentage of time during a trial that the controlled aspect of the display was kept in the goal state—a measure called "% on Target"—was used as a measure of how well that aspect of the display was controlled.

Design

The experiment was a 3 × 4 within-subjects factorial design. One independent variable was the aspect of the display that the participant was asked to control. There were three levels of this variable: shape, motion, and sequence. The second independent variable was the speed of animation of the display. Animation rate was varied by varying the duration of each display frame. There were four levels of this variable: 50 msec./frame, 100 msec./frame, 200 msec./frame, and 450 msec./frame. Each participant was tested in all 12 experimental conditions, each condition representing a different combination of an aspect of the display to be controlled and its animation rate. Each participant was tested in a different random order of conditions. The dependent variable was percentage of a trial with the display in the goal state ("% on Target").

Procedure

On different trials, each participant was instructed to keep either the shape, direction of motion, or sequence of size of the displayed objects in a goal state. The goal state for shape was "circle"; the goal state for direction of motion was "clockwise"; and the goal state for size sequence was "small, medium, large." Participants were instructed to press the mouse button in order to keep the controlled aspect of the display in the goal state.

The experimenter indicated at the start of each trial which aspect of the display the participant was to control. Before starting the test trials participants were given practice controlling all three aspects of the display at the slowest animation rate: 450 msec./frame. This allowed the participants to familiarize themselves with the stimuli to be shown to them, and also practice how to respond when they noticed deviations from the target states.

Analysis

The data from two participants were eliminated prior to conducting the statistical analysis, as their percent on target scores on several trials were below the chance rate of 50%, indicating that they were unable to control the display adequately. A two-way 4 (animation rate) x 3 (controlled aspect of the display) analysis of variance (ANOVA) was conducted on data of the remaining fourteen participants to test for main effects and interaction. This was followed by *post hoc* paired *t* tests to assess simple effects.

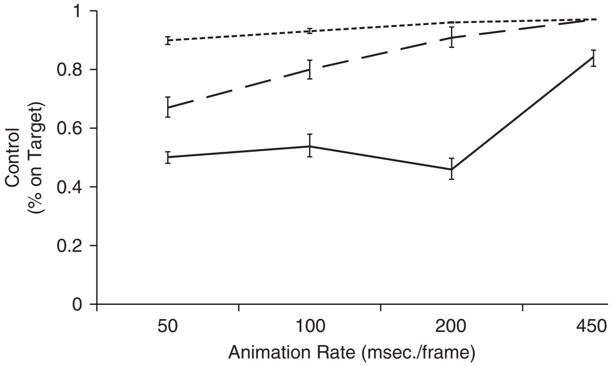

FIG. 4. Mean controllability 'on target' as a function of animation rate for shape (dotted line), motion (dashed line), and sequence (solid line).

RESULTS

The results of this research are shown graphically in Figure 4. These results are consistent with the main hypothesis, which predicted that animation rate would have a different effect on measures of control (% on Target) depending on the aspect of the display being controlled (shape, motion or sequence). Specifically, we predicted that (1) control of shape (the lowest level perception) would be better than control of motion and sequence at all animation rates (2) that control of motion (a middle level perception) would be better than control of sequence up to the slowest animation rate and (3) that control of sequence (the highest level perception) will be poorer than control of shape and motion at all animation rates except for the slowest. The results in Figure 4 are consistent with all three predictions.

A 4 × 3 repeated-measures ANOVA performed on the data presented in Fig. 4 showed that there was a main effect of the aspect of the display controlled ($F_{2,26}=184.59$, $p < .001$, $\eta^2=0.93$) and animation rate ($F_{3,39}=49.93$, $p < .001$, $\eta^2=0.79$). The predicted interaction was also significant ($F_{6,78}=13.371$, $p < .001$, $\eta^2=0.51$). The nature of the interaction was as predicted, as can be seen in Fig. 4. The effect of animation rate on ability to control was different depending on the type of perception—shape, motion or sequence—that was being controlled.

A more detailed analysis of the interaction was done using paired samples t tests. First, data were examined for a difference in ability to control each aspect of the display at the 50 msec./frame animation rate. As predicted, the ability to control shape at this rate was significantly better than the ability to control motion ($t_{13}=6.15$, $p < .001$, $d=1.64$) and the ability to control motion was significantly better than the ability to control sequence ($t_{13}=3.34$, $p=.001$, $d=1.17$).

Next, a difference in ability to control motion and sequence was assessed for animation rate as it slowed from 50 to 100 msec./frame. As expected, the ability to control motion improved significantly ($t_{13}=3.87$, $p=.005$, $d=1.18$) while the ability to control sequence did not ($t_{13}=0.85$, $p=.41$, $d=0.24$). The control of motion continued to improve significantly when animation rate slowed from 100 to 200 msec./frame ($t_{13}=2.15$, $p=.05$, $d=0.58$) but control of sequence still did not improve ($t_{13}=1.63$, $p=.13$, $d=0.47$). There was no significant improvement of controlling motion when animation rate was slowed from 200 to 450 msec./frame ($t_{13}=1.66$, $p=.12$, $d=0.44$), but this was the only rate change where control of sequence improved significantly ($t_{13}=7.72$, $p < .001$, $d=0.45$).

DISCUSSION

The results of this research suggest that the process of motor control—the process that generates the outputs that are seen as motor behavior—is organized around the control of the perceptual results of motor outputs. The participants in this research were able to control a behavioral result as simple as a constant shape or as complex as a repeating sequence by simply pressing a button. But the rate at which the result could be controlled depended on its perceptual complexity rather than on the type of output used to control it; a lower-level perceptual result (a shape) could be controlled at a much faster rate than a higher-level one (a sequence).

It should be noted that the differences in the ability to control associated with the different types of perception cannot be attributed to the increased number of animation frames required to perceive the higher level aspects of the display. It is true that shape could be perceived in a single frame while motion and sequence could be perceived only after at least two frames. However, the change in each of these perceptions could be detected after a single frame change: the change in shape can be seen as soon as the circle in the t_0 frame becomes a square in the $t_{0+\tau}$ frame; the change in direction of motion is evident as soon as, say, the object that had moved clockwise in the t_0 frame moves counterclockwise in the $t_{0+\tau}$ frame; and the change in sequence is evident as soon as the large object that had followed the medium object in the t_0 frame (as part of the "small, medium, large" sequence) is followed by the medium object in the $t_{0+\tau}$ frame (changing the sequence to "large, medium, small").

The results of this research are consistent with previous findings which show that the time required to identify perceptually complex stimuli, such as letter sequences, is longer than that required to identify simple ones, such as shapes (Brebner & Welford, 1980; Luce, 1986). The innovation was to show, using PCT, that this effect of perceptual complexity can be seen as a constraint on the time it takes to produce behavioral results of varying complexity. PCT posits that behavioral results *are* perceptions: behavior such as producing a particular shape, motion or sequence is the control of perception (Powers, 1973).

The results of this research should not be taken to imply that perceptual complexity is always the limiting factor in the rate with which a behavioral result can be produced. In many situations, the rate at which a behavioral result can be produced is limited by the physical properties of the means used to produce it. For example, the rate at which it is possible to produce a sequence of finger taps is limited not only by the perceptual complexity of the sequence but also by the physical properties of the bones and muscles that make up the mechanism that produces the finger taps. The result of the present experiment show that the ability to produce different behavioral results will be limited by the time constraints placed on the ability to *perceive* these results when the same mechanical means (a single button press) can be used to produce them.

An advantage of the PCT approach to explaining the production of behavioral results is that it is less computationally intensive than controlled output models, which explain the production of such results in terms of computation of the necessary output using complex computations of inverse kinematics and model-based prediction. Powers (2008, Pp. 184–187) shows how a PCT model simplifies the generation of the outputs that produce the result of balancing an inverted pendulum. Apparently, the nervous system uses the same solution to the problem of how to compute the outputs that produce behavioral results: control of perception.

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Accepted July 29, 2013.