The Hierarchical Behavior of Perception

A slightly expanded version of this paper was published in *Closed Loop, Journal of Living Control Systems*, Vol 3 No 4, Fall 1993. For back issues of this journal, see INTROCSG.NET. For Closed Loop restored complete, see www.pctresources.com

For more experiments and Fig 2.,
see *Levels of Intention in Behavior*
in *Mind Readings: Experimental Studies of Purpose.*
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THE HIERARCHICAL BEHAVIOR OF PERCEPTION

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Abstract

This paper argues that the coincidental development of hierarchical models of perception and behavior is no coincidence. Perception and behavior are two sides of the same phenomenon -- control. A hierarchical control system model shows that evidence of hierarchical organization in behavior is also evidence of hierarchical organization in perception. A number of studies of the temporal structure of behavior are shown to be consistent with studies of the temporal structure of perception. A surprising implication of the control model is that temporal limitations of behavior are based on temporal limitations of perception. Action systems cannot produce controlled behavioral results faster than the rate at which these results can be perceived. Behavioral skill turns on the ability to control a hierarchy of perceptions, not actions.

Introduction

Psychologists have developed hierarchical models of both perception (eg. Bryan and Harter, 1899; Palmer, 1977; Simon, 1972; Povel, 1981) and behavior (eg. Albus, 1981; Arbib, 1972; Greeno and Simon, 1974; Lashley, 1951; Martin, 1972; Keele, Cohen and Ivry, 1990; Rosenbaum, 1987). This could be a coincidence, a case of similar models being applied to two very different phenomena. On the other hand, it could reflect the existence of a common basis for both perception and behavior. This paper argues for the latter possibility, suggesting that perception and behavior are two sides of the same phenomenon -- control (Marken, 1988). Control is the means by which organisms keep perceived aspects of their external environment in desired states (Powers, 1973). The existence of hierarchical models of both perception and behavior is a result of looking at control from two different perspectives; that of the person doing the controlling (the actor) and that of the person watching control (the observer). Depending on the perspective, control can be seen as a perceptual or a behavioral phenomenon.

From the actor's perspective, control is a perceptual phenomenon. The actor is controlling his or her own perceptual experience, making it behave as desired. However, from the observer's perspective, control is a behavioral phenomenon. The actor appears to be controlling variable aspects of his or her behavior in relation to the environment. For example, from the perspective of a typist (the actor), typing involves the control of a dynamically changing set of kinesthetic, auditory and, perhaps, visual perceptions. If there were no perceptions there would be no typing. However, from the perspective of someone watching the typist (the observer), perception is irrelevant; the typist appears to be controlling the movements of his or her fingers in relation to the keys on a keyboard.

These two views of control have one thing in common; in both cases, control is seen in the behavior of perception. For the actor, control is seen in the behavior of his or her own perceptions. For the observer, control is seen in the behavior of his or her own perceptions of the actor's actions. (The observer can see the means of control but can only infer their perceptual consequences as experienced by the actor). If control is hierarchical then it can be described as the behavior of a hierarchy of perceptions. Hierarchical models of perception and behavior can then be seen as attempts to describe control from two different perspectives, those of the actor and observer, respectively. This paper presents evidence that hierarchical models of perception and behavior reflect the hierarchical structure of control.

A Perceptual Control Hierarchy

The concept of control as the behavior of perception can be understood in the context of a hierarchical control system model of behavioral organization (Powers, 1973; 1989). The model is shown in Figure 1. It consists of several levels of control systems which control perceptions of different aspects of the external environment. All systems control perceptions in the same way; by producing actions that reduce the discrepancy between actual and intended perceptions. Intended perceptions are specified by the reference inputs to the control systems. The actions of the control systems coax perceptual inputs into a match with reference inputs via direct or indirect effects on the external environment. The actions of the lowest level control systems affect perceptions directly through the environment. The actions of higher level control systems affect perceptions indirectly by adjusting the reference inputs to lower level systems.

Insert Figure 1 Here

See Living Control Systems I, page 278

The hierarchy of control systems is a working model of purposeful behavior (Marken, 1986; 1990). The behavior of the hierarchy is purposeful inasmuch as each control system in the hierarchy works against any opposing forces in order to produce intended results. Opposing forces come from disturbances created by the environment as well as interfering effects caused by the actions of other control systems. The existence of disturbances means that a control system cannot reliably produce an intended result by selecting a particular action. Actions must vary to compensate for varying disturbances. Control systems solve this problem by specifying what results are to be perceived, not how these results are to be achieved. Control systems control perceptions, not actions. When set up correctly the control systems in the hierarchy vary their actions as necessary, compensating for unpredictable (and, often, undetectable) disturbances, in order to produce intended perceptions. Indeed, the term "control" refers to this process of producing intended perceptions in a disturbance prone environment.

Levels of Perception.

Powers (1990) has proposed that each level of the hierarchy of control systems controls a different class of perception. These classes represent progressively more abstract aspects of the external environment. The lowest level systems control perceptions that represent the intensity of environmental input. The next level controls sensations (such as a colors), which are functions of several different intensities. Going up from sensations there is control of configurations (combinations of sensations), transitions (temporal changes in configurations), events (sequences of changing configurations), relationships (logical, statistical, or causal co-variation between independent events), categories (class membership), sequences (unique orderings of lower order perceptions), programs (if-then contingencies between lower level perceptions), principles (a general rule that exists in the behavior of lower level perceptions) and system concepts (a particular set of principles exemplified by the states of many lower level perceptions; see Powers, 1989, pp. 190-208). These eleven classes of perception correspond to eleven levels of control systems in the hierarchical control model. All control systems at a particular level of the hierarchy control the same class of perception, though each system controls a slightly different exemplar of the class. Thus, all systems at a particular level may control configuration perceptions but each system controls a different configuration.

The rationale for hierarchical classes of perceptual control is based on the observation that certain types of perception depend on the existence of others. Higher level perceptions depend on (and, thus, are a function of) lower level perceptions. For example, the perception of a configuration, such as a face, depends on the existence of sensation (color) or intensity (black/white) perceptions. The face is a function of these sensations and intensities. The lower level perceptions are the independent variables in the function that computes the higher level perception. Their status as independent variables is confirmed by the fact that lower level perceptions can exist in the absence of the higher level perceptions, but not vice versa. Color and intensity perceptions can exist without the perception of a face (or any other configuration, for that matter) but there is no face without perceptions of intensity and/or color.

The Behavior of Perceptions.

From the point of view of the hierarchical control model, "behaving" is a process of controlling perceptual experience. Any reasonably complex behavior involves the control of several levels of perception simultaneously. For example, when typing the word "hello", one controlled perception is the sequence of letters "h", "e", "l" ,"l" and "o". The perception of this sequence is controlled by producing a sequence of keypress event perceptions. Each keypress event is controlled by producing a particular set of transitions between finger configuration perceptions. Each finger configuration is controlled by a different set of force sensations which are themselves controlled by producing different combinations of intensities of tensions in a set of muscles.

The perceptions involved in typing "hello" are all being controlled simultaneously. Transitions between finger configurations are being controlled while the force sensations that produce the configuration perceptions are being controlled. The typist is not necessarily aware of the behavior of all these levels of perception. When people type they are probably only aware of the highest level perceptions that they intend to produce, such as the word they intend to type. Nevertheless, people can direct their attention to the different levels of perception involved in behavior. For example, it is possible to attend to perceptions of muscle tension, finger movement and finger tip pressure that are produced while typing.

People do not ordinarily attend to the behavior of their perceptions because doing so leads to a deterioration of performance. Paying attention to one's own behavior in this way is the opposite of "zen" behavior, where you just attend to the particular (perceptual) results that you intend to produce, letting the lower level perceptions required to produce these results occur automatically (Herrigal, 1971). While it violates the principles of zen, attention to the perceptions involved in the production of behavioral results can provide interesting hints about the nature of the perceptual control hierarchy.

The Perception of Behavior.

The behavior of an actor who is organized like the hierarchical control model consists of changes in the values of variables in the actor's environment. An observer cannot see what is going on inside the actor; he or she can only see the actor's actions and the effect of these actions on the external environment. The effect of these actions is to cause purposeful behavior of certain variables in the environment; the variables that correspond to perceptions that the actor is actually controlling. The purposefulness of the behavior of these variables is evidenced by the fact that consistent behaviors are produced in the context of randomly changing environmental disturbances. Thus, a typist can consistently type the word "hello" despite changes in the position of the fingers relative to the keyboard, variations in the push-back force of the keys or even a shift from one keyboard arrangement to another (from QWERTY to Dvorak, for example).

Since the actor controls his or her own perceptions, the observer cannot actually see what the actor is "doing"; the actor's "doings" consist of changing the intended states of his or her own perceptions. All the observer sees is variable results of the actor's actions; results that may or may not be under control. For example, the observer, might notice that a click occurs each time the typist presses a key. The click is a result produced by the typist and the observer is likely to conclude that the typist is controlling the occurrence of the click. In fact, the click may be nothing more than a side effect of the typist's efforts to make the key feel like it has hit bottom. There are methods that make it possible for the observer to tell whether or not his or her perceptions of the actor's behavior correspond to the perceptions that are being controlled by the actor (Marken, 1989). These methods make it possible for the observer to determine what the actor is actually doing (i.e. controlling).

Hierarchical Control

The hierarchical nature of the processes that generate behavior would not be obvious to the observer of a hierarchical control system. The observer could tell that the system is controlling many variables simultaneously but he or she would find it difficult to demonstrate that some of these variables are being controlled in order to control others. For example, the observer could tell that a typist is controlling letter sequences, keypress events, finger movements and finger configurations. But the observer would have a hard time showing that these variables are hierarchically related. The observer could make up a plausible hierarchical description of these behaviors; for example, finger positions seem to be used to produce finger movements which are used to produce keypresses which are used to produce letter sequences. But finding a hierarchical description of behavior does not prove that the behavior is actually produced by a hierarchical process (Davis, 1976; Kline, 1983).

Hierarchical Invariance

Hierarchical production of behavior implies that the commands required to produce a lower level behavior are nested within the commands required to produce a higher level behavior. For example, the commands that produce a particular finger configuration would be nested within the commands that produce a movement from one configuration to another. Sternberg, Knoll and Turlock (1990) refer to this nesting as an invariance property of hierarchical control. Lower level commands are like a subprogram that is invoked by a program of higher level commands. The invariance of hierarchical control refers to the assumption that the course of such a subprogram does not depend on how it was invoked from the program (low level invariance); similarly, the course of the program does not depend on the nature of the commands carried out by the subprograms (high level invariance).

Convergent and Divergent Control.

The hierarchical control model satisfies both the low and high level invariance properties of hierarchical control. The commands issued by higher level systems have no effect on the commands issued by lower level systems and vice versa. It is important to remember, however, that the commands in the control hierarchy are requests for input, not output. Higher level systems tell lower level systems what to perceive, not what to do. This aspect of control system operation solves a problem that is either ignored or glossed over in most hierarchical models of behavior: How does a high level command get turned into the lower level commands that produce results that satisfy the high level command? If commands specify outputs then the result of the same command is always different due to varying environmental disturbances. The high level command to press a key, for example, cannot know which lower level outputs will produce this result on different occasions. This problem is solved by the hierarchical control model because intended results are represented as a convergent function rather than a divergent network.

Most hierarchical models of behavior require that a high level command be decomposed into the many lower level commands that produce the intended result. In the hierarchical control model, both the high level command and the intended result of the command are represented by a single, unidimensional signal. The signal that represents the intended result is a function of results produced by many lower level commands. But the high level command does not need to be decomposed into all the appropriate lower level commands (Powers, 1979). The difference between the high level command and the perceptual result of that command is sufficient to produce the lower level commands that keep the perceptual result at the commanded value (Marken, 1990).

Levels of Behavior

The hierarchical invariance properties of the control hierarchy provide a basis for determining whether its behavior is actually generated by hierarchical processes. Hierarchical control can be seen in the relative timing of control actions. In a control hierarchy, lower level systems must operate faster than higher level systems. Higher level systems cannot produce a complex perceptual result before the lower level systems have produced the component perceptions on which it depends. This nesting of control actions can be seen in the differential speed of operation of control systems at different levels of the control hierarchy. Lower level systems not only correct for disturbances faster than higher level ones; they carry out this correction process during the higher level correction process. The lower level control process is temporally nested within the higher level control process.

Arm Movement.

Powers, Clark and McFarland (1960) describe a simple demonstration of nested control based on relative timing of control system operation. A subject holds one hand extended straight ahead while the experimenter maintains a light downward pressure on it. The subject is to move his or her arm downward as quickly as possible when the experimenter signals with a brief, downward push on the subject's extended hand. The result of this simple experiment is always the same: the subject responds to the downward signal push with a brief upward push followed by downward movement of the arm. An electromyograph shows that the initial upward push is an active response and not the result of muscle elasticity.

The arm movement demonstration reveals one level of control nested within another. The subject's initial upward push (which cannot be suppressed) is the fast response of a lower level control system that is maintaining the perception of arm position in a particular reference state (extended forward). The behavior of this system is nested within the response time of a higher level system that moves the arm downward. The higher level system operates by changing the reference for the arm position control system. The downward signal push causes the brief upward reaction because the signal is treated as a disturbance to arm position. This is particularly interesting because the signal is pushing the arm in the direction it should move; the lower level reaction is "counter productive" with respect to the goal of the higher level system (which wants to perceive the arm down at the side). The reaction occurs because the lower level system starts pushing against the disturbance to arm position before the higher level system can start changing the reference for this position.

Polarity Reversal.

A more precise test of nested control were performed in a series of experiments conducted by Marken and Powers (1989). In one of these experiments, subjects performed a standard pursuit tracking task, using a mouse controller to keep a cursor aligned with a moving target. At intervals during the experiment the polarity of the connection between mouse and cursor movement was reversed in a way that did not disturb the cursor position. Mouse movements that had moved the cursor to the right now moved it to the left; mouse movements that had moved the cursor to the left now moved it to the right.

A sample of the behavior that occurs in the vicinity of a polarity reversal is shown in Figure 2. The upper traces show the behavior of a control system model and the lower traces show the behavior of a human subject. When the reversal occurs, both the model and the subject respond to error (the deviation of the cursor from the target) in the wrong direction, making it larger instead of smaller (any deviation of the error trace from the zero line represents an increase in error). The larger error leads to faster mouse movement which causes the error to increase still more rapidly. A runaway condition ensues with error increasing exponentially.

Figure 2 Here.
See *Levels of Intention in Behavior*, Figure 2 on page 116
in *Mind Readings: Experimental Studies of Purpose.*

About 1/2 second after the polarity reversal the subject's behavior departs abruptly from that of the model. The subject adjusts to the polarity reversal and the error returns to a small value. The model cannot alter its characteristics and the error trace quickly goes off the graph. These results provide evidence of two nested levels of control operating at different speeds. The faster, lower level system control the distance between cursor and target. This system continues to operate as usual even when, due to the polarity reversal, this causes an increase in perceptual error. Normal operation is restored only after a slower, higher level system has time to control the relationship between mouse and cursor movement.

Levels of Perception

The arm movement and polarity shift experiments reveal the hierarchical organization of control from the point of view of the observer. The hierarchical control model suggests that it should also be possible to view hierarchical organization from the point of view of the actor. From the actor's point of view, hierarchical control would be seen as a hierarchy of changing perceptions. One way to get a look at this hierarchy is again in terms of relative timing; in this case, however, in terms of the relative timing of the perceptual results of control actions rather of the actions themselves.

Computation Time Window.

The hierarchical control model represents the results of control actions as unidimensional perceptual signals. A configuration, such as the letter "h", is a possible result of control actions, as is a sequence of letters, such as the word "hello". The model represents these results as perceptual input signals, the intensity of a signal being proportional to the degree to which a particular result is produced. This concept is consistent with the physiological work of Hubel and Wiesel (1979) who found that the firing rate of an afferent neuron is proportional to the degree to which particular environmental event occurs in the "receptive field" of the neuron.

Many of the higher level classes of perception in the control hierarchy depend on environmental events that vary over time. Examples are transitions, events, and sequences. The neural signals that represent these variables must integrate several lower level perceptual signals that occur at different times. Hubel and Weisel found evidence of a computation time window for integrating perceptual signals. Certain cells respond maximally to configurations (such as "lines") that move across a particular area of the retina at a particular rate. These are "motion detector" neurons. The neuron responds maximally to movement of a configuration that occurs within a particular time window. Movement that occurs outside of this time window is not included in the computation of the perceptual signal that represents motion.

Levels by Time

The hierarchical control model implies that the duration of the computation time window increases as you go up the hierarchy. The computation time window for the perception of configurations should be shorter than the computation time window for the perception of transitions which should be shorter than the computation time window for the perception of sequences. I have developed a version of the psychophysical method of adjustment which makes it possible to see at least four distinct levels of perception by varying the rate at which items occur on a computer display. A computer program presents a sequence of numbers at two different positions on the display. The presentation positions are vertically adjacent and horizontally separated by 2 cm. The numbers are presented alternately to the two positions. The subject can adjust the rate at which the numbers occur in each position by varying the position of a mouse controller.

At the fastest rate of number presentation subjects report that the numbers appear to occur in two simultaneous streams. The fact that the numbers are presented to the two positions alternately is completely undetectable. However, even at the fastest rate of number presentation subjects can make out the individual numbers in each stream. At the fastest rate, there are approximately 20 numbers per second in each stream. This means that there is a 50 msec period available for detecting each number. This duration is apparently sufficient for number recognition suggesting that the computation time window for perception of configuration is less than 50 msec. Studies of the "span of apprehension" for sets of letters suggest that the duration of the computation time window for perception of visual configuration may be even less than 50 msec, possibly as short as 15 msec (Sperling, 1960).

As the rate of number presentation slows the alternation between numbers in the two positions becomes apparent. Subjects report perception of alternation or movement between numbers in the two positions when the numbers in each stream are presented at the rate of about 7 per second. At this rate, an alternation from a number in one stream to a number in another occurs in 160 msec. This duration is sufficient for perception of the alternation as a transition or movement from one position to the other suggesting that the computation time window for transition perception is on the order of 200 msec. This duration is compatible with estimates of the time to experience optimal apparent motion when configurations are alternately presented in two different positions (Kolers, 1972).

The numbers presented in each stream are always changing. However, subjects find it impossible to perceive the order of the numbers as they alternate from one position to another even though it is possible to clearly perceive the individual numbers and the fact that they are alternating and changing across positions. The rate of number presentation must be slowed considerably, so that each stream of numbers is presented at the rate of about two per second, before it is possible to perceive the order in which the numbers occur. At this rate numbers in the sequence occur at the rate of four per second. These results suggest that the duration of computation time window for the perception of sequence is about 0.5 seconds. This is the time it takes for two elements of the sequence to occur, the minimum number that can constitute a sequence.

The numbers in the rate adjustment study did not occur in a fixed, repeating sequence. Rather, they were generated by a set of rules, a program. The sequence of numbers was unpredictable unless the subject could perceive the rule underlying the sequence. One rule was: if the number on the right is even then the number on the left will be odd. The other rule was: if the number on the left is greater than 5 then the one on the right will be less than 5. (Numbers in the sequence were also constrained to be between 0 and 9). Subjects could not perceive the program underlying the sequence of numbers until the speed of the two streams of numbers was about .5 numbers per second so that the numbers in the program occurred once per second. The perception of a program in a sequence of numbers requires considerably more time then it takes to perceive the order of numbers in the same sequence.

The perception of a sequence or a program seems to involve more mental effort than the perception of a configuration or a transition. Higher level perceptions, like programs, seem to represent subjective rather than objective aspects of external reality; they seem more like interpretations than representations. These higher level perceptions are typically called "cognitions". Of course, all perceptions represent subjective aspects of whatever is "out there"; from the point of view of the hierarchical control model, the location of the line separating perceptual from cognitive representations of reality is rather arbitrary. Behavior is the control of perceptions which range from the simple (intensities) to the complex (programs).

General Sequence Perception Limits.

The hierarchical control model says that all perceptions of a particular type are controlled by systems at the same level in the hierarchy. This implies that the speed limit for a particular type of perception should be about the same for all perceptions of that type. The 150 msec computation time window for perception of transition, for example, should apply to both visual and auditory transition. There is evidence that supports this proposition. Miller & Heise (1950) studied the ability to perceive an auditory transition called a "trill". A trill is the perception of a temporal alternation from one sound sensation or configuration to another. The speed limit for trill perception is nearly the same as the speed limit for visual transition perception found in the number rate adjustment study -- about 15 per second. As in the visual case, when the rate of alternation of the elements of the auditory trill exceeds the computation time window the elements "break" into two simultaneous streams of sound; the perception of transition (trill) disappears even though the sounds continue to alternate.

There is also evidence that the four per second speed limit for sequence perception found in the number rate adjustment study applies across sensory modalities. Warren, Obusek, Farmer, & Warren (1969) studied subjects' ability to determine the order of the components sounds in a sound sequence. They found that subjects could not perceive the order of the components until the rate of presentation of the sequence was less than or equal to four per second. This was a surprising result because it is well known that people can discriminate sequences of sounds that occur at rates much faster than four per second. In words, for example, the duration of the typical phoneme is 80 msec so people can discriminate sequences of phoneme sounds that occur at the rate of about 10 phonemes per second. But there is reason to believe that the phonemes in a word are not heard as a sequence; that is, the order of the phonemes cannot be perceived. Warren (1974) showed that subjects can learn to tell the difference between sequences of unrelated sounds that occur at rates of 10 per second. However, the subjects could not report the order of the sounds in each sequence; only that one sound event differed from another. A word seems to be a lower order perception -- an event perception -- which is recognized on the basis of its overall sound pattern. There is no need to perceive the order of the phonemes occur; just that the temporal pattern of phonemes (sound configurations) for one word differs from that for other words.

The Relationship Between Behavior and Perception

Configurations, transitions, events, sequences and programs are potentially controllable perceptions. An actor can produce a desired sequence of sounds, for example, by speaking sound events (phonemes) in some order. An observer will see the production of this sequence as a behavior of the actor. The hierarchical control model suggests that the actor's ability to produce this behavior turns on his or her ability to perceive the intended result. Since perception depends on speed, it should be impossible for the actor to produce an indented result faster than the result can be perceived. The observer will see this speed limit as a behavioral limit. An example of this can be seen in the arm movement experiment described above. In that experiment it appears that the time to respond to the signal push is a result of a behavioral speed limit; the inability to generate an output faster than a certain rate. But a closer look indicates that the neuromuscular "output" system is perfectly capable of responding to a signal push almost immediately, as evidenced by the immediate upward response to the downward signal push. The same muscles that produce this immediate reaction must wait to produce the perception of the arm moving downward. The speed limit is not in the muscles. It is in the results that the muscles are asked to produce; a static position of the arm (a configuration perception) and a movement of the arm in response to the signal push (a relationship perception).

Sequence Production and Perception. Some of the most interesting things people do involve the production of a sequence of behaviors. Some recent studies of temporal aspects of sequence production are directly relevant to the hierarchical control model. In one study, Rosenbaum (1989) asked subjects to speak the first letters of the alphabet as quickly as possible. When speed of letter production exceeded four per second the number of errors (producing letters out of sequence) increased dramatically, indicating a loss of control of the sequence. The speed limit for sequence production corresponds to the speed limit for sequence perception -- four per second.

The letter sequence study does not prove that the speed limit for letter sequence production is caused by the speed limit for letter sequence perception. It may be that the speed limit is imposed by characteristics of the vocal apparatus. However, in another study Rosenbaum (1987) found the same four per second speed limit for production of errorless finger tap sequences. The speed limit for finger tap sequence production is likely to be a perceptual rather than a motor limit because we know that people can produce finger taps at rates much higher than four per second. Pianists, for example, can do trills (alternating finger taps) at rates which are far faster than four per second. Further evidence of the perceptual basis of the finger tap sequence speed limit would be provided by studies of finger tap sequence perception. When a subject produces a sequence of finger taps he or she is producing a sequence of perceptions of pressure at the finger tips. A perceptual experiment where a pressure is applied to the tip of different fingers in sequence should show the four per second speed limit. Subjects should have difficulty identifying the order of finger tip pressures when the sequence occurs at a rate faster than four per second.

Confounding Levels.

It is not always easy to find clear-cut cases of behavioral speed limits that correspond to equivalent perceptual speed limits. Most behavior involves the control of many levels of perception simultaneously. People control higher level perceptions (like sequences) while they are controlling lower level perceptions (like transitions). This can lead to problems when interpreting behavioral speed limits. For example, Rosenbaum (1983) presents some finger tapping results that seem to violate the four per second speed limit for sequence perception. When subjects tap with two hands they can produce a sequence of at least 8 finger taps per second. But each tap is not necessarily a separate event in a sequence. Some pairs of taps seem to occur at the rate at which sequences are experienced as events. A sequence of finger taps is an event in the same sense that the sequence of muscle tensions that produce a finger tap is an event; the order of the components of the sequence cannot be perceived. These finger tap events are then unitary components of the sequence of finger tap perceptions. The fact that certain pairs of finger taps are produced as events rather than ordered sequences is indicated by the order errors made at each point in the finger tap sequence. Order errors are greater for the fast pairs than for the slower pairs suggesting that the order of the fast pairs is not under control.

Changing Perception Can Change Behavior.

The relationship between perception and behavior can be seen when a person learns to perform a task by controlling a new perceptual variable. An example of this can be seen in simple pursuit tracking tasks. In the typical tracking task the target moves randomly. When, however, a segment of target movement is repeated regularly the subject's tracking performance improves markedly (Pew, 1966). According to the hierarchical control model, control is improved because the repeated segment of target movement can be perceived as a predictable event. With the random target the subject must wait to determine target position at each instant in order to keep the cursor on target. With the repeated target, the subject controls at a higher level. keeping a cursor movement event matching a target movement event. The fact that the subject is now controlling a higher level perception (an event rather than a configuration) is evidence by the longer reaction time when responding to a change in target movement. When controlling the target-cursor configuration the subject responds almost immediately to changes in target position. When controlling target-cursor movement events it takes nearly 1/2 second to respond to a change to an unexpected target movement pattern.

An experiment by Robertson and Glines (1985) also shows improved performance resulting from changed perception. Subjects in the Robertson and Glines study performed a learning task where the solution to a computerized game could be perceived at several different levels. Subjects who were able to solve the game showed three distinct plateaus in their performance. The level of performance, as indicated by reaction time measurements, improved at each succeeding plateau. Because the same outputs (keypresses) were produced at each level of performance, each performance plateau were taken as evidence of that the subject was controlling a different perceptual variable.

Behavior/Perception Correlations.

Few psychologists would be surprised by the main contention of this paper: that there is an intimate relationship between perception and behavior. However, most models of behavior assume that the nature of this relationship is causal: behavior is guided by perception. This causal model provides no reason to expect a relationship between the structure of perception and behavior: no more than there is to expect a relationship between the structure of computer input and output. This does not mean that there might not be such a relationship; it is just not demanded by the causal model.

The control model integrates perception and behavior with a vengeance. Behavior is no longer an output but, rather, a perceptual input created by the combined effects of the actor and the environment. Behavior is perception in action. From this point of view, behavioral skills are perceptual skills. Thus, it is not surprising to find some indication of a correlation between behavioral and perceptual ability (Keele, Pokorny, Corcos and Ovry, 1985). Keele and his colleagues have found that the ability to produce regular time intervals between actions is correlated with ability to perceive these intervals. These correlations are fairly low by control theory standards but they are expected if the production of regular time intervals involves control of the perception of these intervals.

Conclusion

This report has presented evidence that human behavior involves control of a hierarchy of perceptual variables. The behavior of other organisms is likely to involve control of a similar hierarchy of perceptions (Plooij and van de Rift-Plooij, 1990). A model of hierarchical control shows how studies of perception and behavior provide evidence about the nature of control from two different perspectives. Perceptual studies provide information about the ability to perceive potentially controllable consequences of actions. Behavioral studies provide information about the ability to produce desired consequences. The factors that influence the ability to perceive the consequences of action should also influence the ability to produce them. In both cases we learn something about how organisms control their own perceptions.

The hierarchical control model shows that limitations on the ability to produce behavior may reflect limitations on the ability to perceive intended results. The speed at which a person can produce an errorless sequence of events, for example, is limited by the speed at which the order of these events can be perceived. But not all skill limitations are perceptual limitations. Controlled (perceived) results are produced, in part, by the outputs of the behaving organism. The ability to produce certain outputs can limit the ability to control certain perceptions. For example, it is impossible to perceive oneself lifting a 300 pound barbell until the muscles have been developed to the point that they are able to generate the output forces necessary to control this perception.

Perception and behavior are typically treated as two completely separate phenomena. Perception is input: behavior is output. But the concept of control as the behavior of perception suggests that this separation is artificial. Perception and behavior are just two sides of the process of control. In order to understand how this process works it will be necessary to understand how organisms perceive (perception) and how they act to affect their perceptions (behavior). Studies of perception and behavior should become an integral part of the study of a single phenomenon, control.

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Figure 1. Perceptual Control Hierarchy (after Powers, 1989, p 278)

Figure 2. Lower level runaway response to mouse-cursor polarity reversal.