Preface

> Maybe we are reaching the day of the theorist in psychology, much as it exists in other sciences such as physics.
>
> (Newell, 1973, p. 306)

This book develops a theory, and now is an exciting time for developing psychological theories. We are currently witnessing an upsurge of interest in theoretical psychology (D. G. MacKay, in preparation), and many new and interesting theories are being constructed, especially in cognitive psychology (e.g., Holland, Holyoak, Nisbett, & Thagard, 1986; McClelland, Rumelhart, & the Parallel Distributed Processing Research Group [PDP], 1986).

Now is also an exciting time for exploring the relations between perception and action, the main theme of the present book. Perception and action have been central concerns of experimental and theoretical psychology for over a hundred years, and the last two decades have seen a steadily growing interest in the relation between these core topics. By and large, however, perception and action have been treated separately in the past, and very few books have been published on relations between the two. The present book is designed to fill this gap. Its primary goal is to review recent findings relating perception and action and to develop a coherent and relatively simple explanation of these relationships. As such, the book provides both an integrated and in-depth picture of the field and a spur to further research. The book also illustrates a new approach to relationships between perception and action that is emerging in psychology and related disciplines: the small but rapidly growing tradition that treats perception and action as "integrated and equal" rather than "separate and unequal" (Chapter 1; see also D. G. MacKay, Allport, Prinz, & Scheerer, 1987).

Finally, the present book examines skilled behavior, and now is an exciting time for that, too. Many new theories and findings are breathing fresh life into old questions in this area (e.g., Gentner, 1985; Keele, 1987; Levelt, 1984), and the present book summarizes some of these old questions and contributes one new theory, several new findings, and many new questions to the fresh life. In addition, the book takes up some interesting but relatively unexplored issues in

Preface (pp. vii-ix), introduction (xiii-xxii), references (194-200), and epilogue (200-215). In MacKay, D.G. (1987). *The organization of perception and action: A theory for language and other cognitive skills* (1-254). Berlin: Springer-Verlag.

skilled behavior, such as the mechanisms for sequencing, timing, and processing perceptual feedback in language and other cognitive skills.

I address this book to anyone with a serious interest in psychological theories, especially parallel distributed theories of relations between perception and action. However, I make no call in the book for converts to a new theoretical approach. Some readers may think that the field needs a different sort of theory, or that the predictions of my theory are uninteresting or unworthy of test. These readers nevertheless have something to gain from this book. Virtually every chapter begins with a set of requirements for a viable theory—the fundamental facts or constraints that any theory must explain. Although no current theory satisfies all of these constraints without modification, the constraints will remain as a challenge for anyone attempting to develop a more adequate theory in the future.

I have used this book as required reading for graduate and undergraduate seminars and as optional reading for large lecture classes in psycholinguistics, perception, and cognitive psychology. The 10 chapters of the book fit nicely into a 10-week quarter, and I have found that advanced undergraduates can readily comprehend all of the ideas developed here. I also hope that my ideas are comprehensible to anyone with a general interest in psychology, the brain sciences, and cognitive science disciplines such as artificial intelligence, philosophy, anthropology, linguistics, phonetics, and kinesiology. For these readers I have introduced technical language sparingly, I have defined generally accepted psychological terms, and I have described well-known phenomena and experiments in detail. Nonpsychologists can also take comfort in knowing that the bibliography at the end of the book contains references to background material.

I also address this book to colleagues and graduate students who are engaged in the research and simulation required for the development of theory in the cognitive and brain sciences. The book provides a detailed examination of topics long considered fundamental to researchers in psychology and related disciplines. I hope this second set of readers will forgive the descriptions of concepts and phenomena with which they are already familiar. In return they will discover in this book many new ideas for simulation and many new predictions for experimental test. Students of perception will find the discussion of consciousness in Chapter 4 especially provocative, and specialists in artificial intelligence may find Chapters 8 to 10 especially interesting from the standpoint of computer simulation. The relative noninteractiveness (locality or self-containedness) of the theoretical mechanism discussed there (self-inhibition) will tremendously simplify the task of simulating the theory's predictions and checking them against the available data. Specialists in the brain sciences should find Chapter 5 (The Temporal Organization of Perception and Action) especially rewarding; determining *which* brain events represent *which* processes is often quite difficult, but it is relatively easy to determine *when* a brain event occurs, which is the central theme of Chapter 5. Finally, empirically oriented psychologists will discover something of interest at many points in the book; there are new experimental findings, reported here for the first time, but obtained originally without the benefit of explicit theory. Although I say *new*, some of these data are now 20 years old, gathered at a time when my own orientation was primarily empirical. I had long ago filed these data away as either not making sense or not fitting the rapidly changing *Zeitgeist* in the field. What prompted me to dig out these "old" data was a new perspective on the vicissitudes of the *Zeitgeist* (D. G. MacKay, in preparation) and a new theory (developed in the remainder of this book) within which these data finally made sense.

I am pleased to record my indebtedness to the many colleagues and students who have commented on and thereby improved the contents of this book. I am especially grateful to Jay McClelland at Carnegie-Mellon University; Deborah Burke and Leah Light at the Claremont Colleges; Carol Fowler at Dartmouth College; Werner Deutsch, Uli Frauenfelder, Marie-Louise Kean, Pim Levelt, and Chris Sinha at the Max-Planck-Institut für Psycholinguistik, Nijmegen, The Netherlands; Wayne Wickelgren at the University of Oregon; Gary Dell at the University of Rochester; Andrew Comrey and Jerry Kissler at UCLA; and Alan Allport, Bruce Bridgeman, Lex van der Heiden, Herbert Heuer, Steve Keele, Dom Massaro, Doug Mewhort, Odmar Neumann, Wolfgang Prinz, and Eckart Scheerer, all members of the Research Group on Perception and Action at the Center for Interdisciplinary Research (ZiF) at the University of Bielefeld, Federal Republic of Germany. They have prevented many mistakes, and without their help, some of the conceptual butterflies in this book might still be caterpillars, but they are not responsible for any additional mistakes or infelicities that I may have made despite their advice.

I also thank John O'Connor at UCLA for the financial assistance and leave of absence during 1984 –1985 that enabled me to write the book, and I thank Herbert Heuer, Odmar Neumann, Wolfgang Prinz, and Peter Wolff for the invitation to join the Research Group on Perception and Action at the ZiF in Bielefeld, where much of the book was written. I also thank Wolfgang Prinz for the opportunity to help organize a conference entitled "Common Processes in Listening, Speaking, Reading, and Writing," which took place at the ZiF in July 1985. The many provocative ideas that arose from that conference (D. G. MacKay et al., 1987) provided a valuable stimulus for the present book. Finally, I thank the state of Nordrhein-Westphalia for providing the necessary funds and support facilities for carrying out these activities at the ZiF.

For their skillful typing of the first draft of the book, I thank Lorraine Cronshaw, Kathy Hacker, Charlana Watling, and the UCLA Central Word Processing Unit. For their help with word processing and computer programming, I thank Nancy Back and Lynn Thomas. For their help in running subjects and analyzing data, I thank Robert Bowman, Michael Birnbaum, and Brian Burke. For their help in proofreading the final copy and compiling the subject index, I thank Kent Bullard, Rana Matteson, and Julie Platus. Finally, I thank Pim Levelt and William Marslen-Wilson for providing two research fellowships at the Max-Planck-Institut für Psycholinguistik, where the book was completed.

Introduction

> The scientific description of verbal behavior (by linguists, of course, not by psychologists) is far advanced over any other area of behavioral description and so provides a glimpse of what other behavioral theories may look like eventually.
>
> (Miller, Gallanter, & Pribram, 1960, p. 154)

I wrote this book during a very enjoyable year that I spent in West Germany with a group of colleagues from universities around the world. All 20 of us were interested in the relations between perception and action, and together we formed the Research Group on Perception and Action organized by Wolfgang Prinz at the Center for Interdisciplinary Research (ZiF), located in the woods above the University of Bielefeld.

Before coming to Europe, I saw the year as an opportunity to broaden my interests. I already had formulated some ideas on the relation between speech perception and production, and the ZiF provided an interdisciplinary context that enabled me to examine these ideas from different perspectives. At the ZiF I had a chance to interact with colleagues from a variety of backgrounds—not just cognitive psychology, developmental psychology, and psycholinguistics, but neurobiology, neurophysiology, neurology, kinesiology, epistemology, and the philosophy of mind. The influence of these various perspectives can be found throughout the book.

My initial plan for the year was to determine whether my ideas on speech perception–production applied to other types of perception and action and to expand this comparison into a detailed and coherent book on the relations between perception and action. With this plan in mind, I wrote a preliminary paper comparing the organization of speech and visual perception, and I collaborated with John Annett (University of Warwick) on an experimental project exploring relations between speech and everyday actions such as tying one's shoelaces.

However, I soon found that my initial goal was too broad. The topics of perception and action have been of interest for so long and to so many disciplines, and have been approached with so many different methods, theoretical frameworks, and lexicons of description as to make detailed integration difficult. Even within psychology, so many findings are relevant that coherence requires selectivity.

The problem is that a coherent account can expect criticism for seeming to select arbitrarily from among the wide array of available data, and this led me to think about possible principles for data selection. The problem scarcely arises in advanced sciences such as physics and biology. The reason is simple. These fields have developed generally accepted theories that automatically provide the principles for selecting examples. By enabling physicists and biologists to see a wide range of facts as examples of the same underlying principle, theories have also reduced the complexity and conceptual heterogeneity of these fields. However, there exists no generally accepted theory in psychology, certainly not a theory capable of providing principled selection and simplification of available data on relations between perception and action. So, I decided to develop a theory of my own that synthesizes the wide range of perception–action issues that I myself have worked on over the past 25 years: the nature and causes of errors in the perception and production of speech and other cognitive skills, the mirror-image problems of ambiguity in perception and synonymy in production, the role of self-produced feedback in the integration of behavior, relations between timing and sequencing in perception and action, and relations between the cognitive and the physical aspects of action control.

I call my theory the "node structure" theory of perception and action, and I wish to point out some of its limitations at the outset. First, the theory only applies to the organization of *skilled* behavior, and many interesting topics fall outside its scope. For example, the topic of creativity necessarily involves behaviors that are unlearned, unpracticed, and therefore, unskilled. Nevertheless, I covertly took creativity into consideration in constructing the theory. Although a theory cannot attempt to explain everything at once, it must at least be consistent with established phenomena falling outside its limited scope. Awareness, attention, and learning are other important topics that I leave virtually untouched here but intend eventually to include in a more comprehensive theory (D. G. MacKay, 1987).

Another limitation of the theory concerns its emphasis on speech production–perception. Although I discuss other skilled behaviors such as piano playing, typing, and the generation of Morse code, I give the lion's share of attention to speech. Speech is more proficient (D. G. MacKay, 1981) and better described than other cognitive skills (Miller et al., 1960), but I believe that the principles of speech perception–production apply more generally to other perception–production systems, and I support this belief with enough examples throughout the book to justify including *Other Cognitive Skills* in the title. However, the issue of whether speech is unique promises to occupy the field for many decades to come, and I don't pretend that the present book has put it to rest. As Anderson (1980) notes, "The status of language is shaping up to be a major issue for cognitive psychology. The issue [of the uniqueness of language] will be resolved by empirical and theoretical efforts more detailed than those reviewed [here]" (p. 398).

The theory's essentially psychological focus represents another of its limitations. Like my colleagues at the Center for Interdisciplinary Research, I feel that interdisciplinary teamwork will eventually prove essential for establishing a theory of the relation between perception and action; and like McClelland et al. (1986), I feel that my theory can be readily mapped onto neuroanatomical constructs. However, the present book develops very few of these mappings. It touches only lightly on physiological data concerning effects of brain damage on sequencing and timing, perceiving and acting. Linguistic data on the structure of sentences have also fallen outside the scope of the theory. Unlike Chomsky (1957), I am not trying to describe the competence underlying our ability to produce all possible sentences in English or any other language. Nor do I attempt an exhaustive description of how we produce even a single sentence. All sentences are produced with some intonation, for example, but my theory includes no account of intonation. Of course, keeping the goals of physiology and linguistics in the background is not equivalent to disregarding them altogether. Both linguistic and physiological considerations will arise at various points, if only as reminders of phenomena that a more general theory eventually must explain.

Some might consider the relatively unformalized character of the theory a serious limitation. I am not so sure. Most scientific theories—for example, the wave theory of sound and the atomic theory of matter—began with qualitative descriptions before acquiring their more sophisticated mathematical form, and even with quantitative expressions firmly in place, a qualitative formulation invariably remains and provides the basis for using and extending a theory to new domains (Holland et al., 1986; Thagard & Holyoak, 1985). Moreover, as McClelland and Elman (1986, p. 13) point out, premature concern with formal or computational adequacy can obscure attention to fundamental properties of a theory such as its ability to account for available empirical laws.

I therefore view the qualitative state of my theory as a necessary precursor to later stages of development. The theory is in progress, a first step in the right direction. Three potentially parallel processes for developing the theory lie ahead: (1) real-time computer simulations resembling those of McClelland and Elman (1986) in some respects; (2) conceptual extensions (e.g., introduction into the theory of mechanisms for attention, awareness, and learning in response to novel experience; D. G. MacKay, 1987); and (3) experimental tests. When tested, some of the currently formulated predictions of the theory will turn out to be wrong, but the research required to simulate and test these predictions will provide the basis for a more complete and accurate theory in the future. Theories either stimulate advances in our understanding and knowledge or pass from the scene. However, this book will still be of value once the shortcomings of the present theoretical formulation have become apparent. Virtually every chapter spells out a set of fundamental facts or constraints that any viable theory must explain, and these constraints will remain as a challenge for anyone attempting to replace my own theory with a more adequate one in the future.

Comparisons With Other Theories

The node structure theory resembles other current theories in many respects. For example, like McClelland and Elman (1986) and Marslen-Wilson and Tyler (1980), the node structure theory deals with dynamic, on-line, or real-time perceptual processes. However, the node structure theory is much broader in scope than other current theories. It deals not just with perceptual processes but also with action and the relations between perception and action: for example, the units underlying perception and action, how they are activated in sequence, and how they are timed, not just how perception–production systems *construct* time—as happens when one produces a sentence at a voluntarily determined rate—but also how they *alter* time—as happens when one repeats the same sentence at different rates. The theory integrates a wide array of data on sequencing and timing, providing new explanations for phenomena such as constant relative timing, effects of practice on timing and sequencing in behavior, and regularities in the nature of sequential errors (e.g., speed–accuracy trade-off, the sequential class regularity, and the level-within-a-system effect (the fact that the probability of error is greater for lower than higher level units within the same system).

Unlike most other theories, the node structure theory postulates shared rather than completely separate units for perceiving and producing cognitive skills. These shared perception–production units provide new ways of conceptualizing well-known perceptual phenomena such as interactions between the timing of perception and action, perceptual–motor adaptation, categorical perception and its exceptions, contextual effects on phoneme perception, visual dominance and its exceptions, perceptual errors, and the time to comprehend ambiguous sentences. Shared perception–production units also provide the basis for some new hypotheses about the role of internal and external feedback in detecting and correcting errors, about differences in how we perceive self-produced versus other-produced speech, and about the cause of feedback-induced stuttering and its non-pathological analogue, the effects of auditory feedback that is amplified and delayed by about 0.2 s (Fairbanks & Guttman, 1958).

What is novel about the theoretical ideas I have developed is their integrative combination, and Chapter 1 begins by relating my theory to the 2000-year-old tradition of thought and experiments on relations between perception and action. Later chapters compare detailed aspects of the node structure theory with current theories of either perception or action or both. Theories discussed include McClelland and Elman's (1986) TRACE theory of speech perception; McClelland and Kawamoto's (1986) theory of ambiguity and "shades of meaning"; Marslen-Wilson and Tyler's (1980) cohort theory of word recognition; the motor theory of speech perception; Norman and Rumelhart's (1983) theory of sequencing and timing in typing; chain association and scanning theories of sequencing; Klapp, Anderson, and Berrian's (1973) buffer theory of production onset time; stage of processing theories of timing; Shapiro's (1977) programming theory of constant relative timing; efference copy/corollary discharge theories of how action influences perception; editor theories of error detection and correction; and the feedback control theory of Adams (1976) and others. Here I want to map out some more general relations between my theory and two broad classes of theoretical alternatives: production systems and parallel distributed processing (PDP) theories. I will argue that in general PDP models are too parallel and production systems are too serial to handle available data on relations between perception and action. The node structure theory represents an integration of these approaches that attempts to overcome the weaknesses of both.

Comparison With Parallel Distributed Processing Theories

Like the PDP theories of McClelland, Rumelhart, and the PDP Research Group (McClelland et al., 1986; Rumelhart, McClelland, & the PDP Research Group, 1986), the node structure theory represents knowledge in the connections between nodes and describes mental processes in terms of inhibitory and excitatory interactions occurring in parallel between nodes in a highly interconnected network. Another similarity is that nodes in the node structure theory simultaneously integrate many different sources of information so as to capture the multiple simultaneous constraints seen in behaviors such as word recognition, the motor control of typing, and the grasping of objects in everyday environments (Rumelhart, McClelland, & Hinton, 1986).

The theory also exhibits content addressability in its retrieval of information from memory, emergent properties such as constant relative timing and the processing of self-produced feedback, and graceful degradation – at least in the case of nodes representing the form or content of perception and action. Destroying a single content node will have only minor and difficult-to-detect effects on performance of the overall system, and as more and more content nodes are destroyed, performance will deteriorate gradually rather than catastrophically. Unlike serial symbol processing systems, disrupting a single step cannot incapacitate the entire system (Rumelhart, McClelland, & Hinton, 1986).

These similarities aside, my theory differs from PDP theories in several important respects. One is its distinction (discussed in detail in Chapter 3) between activation (a nonautomatic and sequential process that causes connected nodes to become primed and is necessary for conscious awareness and action) and priming (an automatic and parallel process that prepares a connected node for possible activation). Although other theorists have seen the need for such a distinction (e.g., Lashley, 1951; Mandler, 1985; McClelland & Elman, 1986, p. 77), the node structure theory is the only theory making systematic use of the priming–activation distinction.

Another difference is that the node structure theory represents "sequential rules" directly, rather than or in addition to indirectly, as properties arising automatically from the normal functioning of the network. This contrasts with McClelland and Elman (1986) and other PDP theories, where "linguistic rules" *only* receive indirect representation as emergent properties of the network. These sequential rules provide a natural description for sequential behaviors such as the rapidly produced sequences of phonemes in speech production, a problem for purely PDP models such as Boltzmann machines (Hinton & Sejnowski, 1986), which are notoriously bad at representing sequence.

A third and not altogether minor difference is that the node structure theory does not allow mutual inhibition between content nodes. Mutual inhibition between content nodes would make language production impossible in the node structure theory, despite its potential benefits for perception (McClelland & Elman, 1986). The node structure theory obtains these same benefits via inhibitory relations between *sequence* nodes, the control structures that activate content nodes during both perception and production.

A fourth difference concerns the flexibility of conscious versus unconscious processing. PDP theories provide viable accounts of subcognitive or unconscious processes using small (subsymbolic or microstructural) units and may eventually offer a description of cognitive or conscious processes as well (Rumelhart, Smolensky, McClelland, & Hinton, 1986). However, current PDP theories will have difficulty with the fact that normally unconscious processes can become conscious. For example, the microstructural becomes conscious and cognitive when we become aware of making a subphonemic slur during speech production (D. G. MacKay, 1987). Unlike PDP theories, the node structure theory provides mechanisms for representing the flexibility of conscious versus unconscious processing.

Finally, we come to an area where similarities and differences between the node structure theory and PDP theories form a complex mix: the issue of distributed versus central, localized, or local processes and representations. That is, discussions of distributed processing must distinguish between three different senses of the term *distributed.* One sense contrasts distributed with *central* processes, meaning roughly that distributed processes lack a central executive upon which all processing depends (as in production systems). In this sense, the node structure theory is definitely a distributed theory. A second sense concerns the issue of whether a processing characteristic is distributed throughout a system rather than localized at a particular processing stage in a sequence of stages for specifying the output. In this sense, too, timing, sequencing, and the form or content of perception and action depend on distributed processes and mechanisms in the node structure theory.

The third sense of distributed concerns *local* versus *mass action* representations of information for perception and action. Local theories represent a single concept with a single node (although they don't necessarily use a single node for representing only one concept; Chapter 2), whereas mass action theories represent a single concept with many nodes and use each node to represent many concepts. Information is represented not by particular units but by patterns of activity among large numbers of units. Some of the units in the PDP theories of McClelland et al. (1986) are not distributed processors in this sense and neither are the content nodes in the node structure theory. Each content node codes a given piece of information uniquely. Interestingly, however, timing in the node structure theory seems to be distributed in the mass action sense: The same timing node may represent different rates of output by varying its periodicity or rate of spontaneous reactivation, and a set of coupled timing nodes are required to generate any given rate of output.

Comparison With Standard Production Systems

Production systems (e.g., Anderson, 1976) represent knowledge via quasi-linguistic units and represent mental processes via sequential inferences resembling those observed during the conscious introspection of ongoing thought. More specifically, 'conditions' are cyclically matched against 'condition–action rules,' and a production becomes activated when its condition is met. Only one production can be activated at a time, and a central executive oversees the general flow of information and calls up subroutines to carry out a given task. As Hofstadter (1985) points out, the abstract and serial properties of production systems seem well suited for characterizing conscious but not unconscious, subcognitive, or microstructural processes.

Like production systems, the node structure theory represents rules directly, but its sequential rules are not the building blocks or basic units of the theory; they are called up in parallel and are triggered by a competitive activation mechanism rather than by a central algorithm for choosing which rule to trigger. Also unlike production systems, the node structure theory has no centralized processor for directing the flow of information and no condition–action rules for matching against conditions and triggering productions. Also, more than one sequential rule can fire at any given time or cycle, because sequence nodes in different "systems" can be activated simultaneously. Finally, the node structure theory combines parallel and sequential processes in a way that is not seen in production systems. For example, content nodes are activated in sequence but are primed in parallel.

Themes of the Book

Three major themes run throughout the book: representation (which units represent perception and action?), processing (what are the processes underlying perception and action and how do they differ?), and the integration of perception and action, as occurs during the perceptual processing of self-produced feedback. Readers interested in either representation, processing, or the integration of perception and action, but not in all three, are warned that these issues are not completely separable, and that the contents of this book are cumulative. Each chapter builds on information from the previous chapters, and reading the book from start to finish is advisable on the first pass.

Representational Issues

Representational issues in the present book focus on what I call the "middle ground" of cognitive psychology (see also Marr & Poggio, 1977; Rumelhart, McClelland, & Hinton, 1986). My strategy has been to start upstream at the highest level where conceptual waters seem clear and to work my way down as far as the available light permits. In the case of speech, the highest level for me has been the sentence and the lowest level has been the phonological feature. I found very little to say about the complex structures that intervene between sensory receptors (such as the basilar membrane) and the phonological features for speech perception, and I found even less to say about the structures that intervene between phonological features and the muscles for producing speech sounds. I do not claim these lower level perception–production structures are unimportant or that psychology should abandon its attempts to understand them. It is only that for molar units such as the sentence, structures at these levels are extremely complex and variable and in any case are beyond my current capacity to analyze.

The book distinguishes between three types of representational issues, depending on the type of information being represented: content versus sequence versus timing information. The representational issue for content information has been the main focus of other theorists (e.g., Anderson, 1983) and comes up here in Chapter 2: How is the basic form or content of perception and action represented? The representational issue for sequencing comes up in Chapters 3 and 4: How are the sequences of components for habitual actions and percepts represented? The third and most commonly neglected representational issue concerns timing and comes up in Chapter 5: How is rate and timing information represented in habitual actions and perceptual judgments? As we will see, the units representing sequence and timing in the node structure theory constitute control structures that are themselves hierarchically organized and activate the hierarchically organized content nodes that represent the form of perception and action. Representations of the relation between action and self-produced feedback constitute a fourth issue that other theories are forced to address but the node structure theory is not. Under the node structure theory, the other three representations for perception and action suffice to explain the representation of self-produced feedback.

Processing Themes

Four processing themes emerge at various points in the book. The main one is whether a single fundamental process (activation) adequately describes perception and action, as most other theories assume, or whether two fundamental processes (priming and activation) are required, as in the node structure theory. Related to this theme are the nature of sequential errors in speech production (Chapter 3), differences between conscious versus unconscious processes (Chapter 4), and the role of attention in modifying the weighting of different kinds of perceptual evidence (Chapters 4 and 7). As we will see, this processing theme has a direct bearing on representational issues; content nodes in the node structure theory obey a *hierarchic* principle of representation with respect to the process of activation but obey a *heterarchic* principle of representation (Kelso & Tuller, 1981) with respect to the process of priming (Chapters 3 and 4).

The second processing theme concerns the processes that enable nodes to become activated at the proper time and in the proper sequence during perception and action. Chapter 5 deals with the timing processes, and Chapters 3 and 4 with the sequencing processes.

The third processing theme concerns similarities and differences between the processes that give rise to perception versus action. The similarities are discussed in Chapters 2 and 5, which examine a set of parallelisms and interactions between perception and production. The differences are discussed in Chapter 6, which examines a set of phenomena that are fundamentally asymmetrical between perception versus action. Differences discussed in Chapter 9 between perceiving self-produced versus other-produced inputs also contribute to this theme.

The fourth processing theme concerns the frequently overlooked issue of how skill or practice influences the processes of sequencing and timing in perception and action. An example from this theme is the issue of why periodicity and systematic deviations from periodicity develop as a function of skill or practice in behaviors such as typing and handwriting (Chapter 5).

The Integration of Perception and Action

The integration of perception and action is the third major theme of the book, and in Chapter 7 this theme forms part of the larger issue of how any two heterogeneous types of information become integrated in the nervous system. Chapters 8 through 10 examine the core of the integration of perception and action, the perceptual processing of self-produced feedback. Phenomena discussed in Chapter 2 such as "rapid shadowing" and perceptual–motor adaptation also illustrate the integration of perception and action, as does the temporal incompatibility phenomenon discussed in Chapter 5, which is the curious interaction between timing mechanisms for perception and action seen in our inability to simultaneously produce and perceive rhythms with incompatible timing characteristics.

Overview of the Book

Having outlined the main themes and the intellectual context of the book, some signposts are in order regarding its chapters, their main lines of argument, and how they interconnect. In brief overview, the first half of the book develops the basics of the node structure theory, and the second half deals with applications, implications, and extensions of these basics.

Chapter 1 outlines some conceptual antecedents of the theory and defines the basic theoretical constructs that recur throughout the book: content nodes (units representing the basic components of action and perception); sequence nodes (units for determining the sequence in which content nodes become activated); and timing nodes (units for determining when and how rapidly the content nodes become activated); the basic structural properties and organizational characteristics of nodes (e.g., "more-or-less hierarchies" of content nodes within systems); their basic processing characteristics (e.g., priming and activation); and their short- and long-term memory characteristics (e.g., priming and strength of connections).

Chapter 2 focuses on the representation-of-content issue: What units represent the form or content of perception and action and how are perceptual units related to production units? I argue that some content nodes represent neither sensory experience nor patterns of muscle movement but higher level mental components common to both perception and production in speech and other cognitive skills.

The next three chapters deal with sequencing and timing in perception and action. Chapter 3 examines the sequencing of action, the question of how the components of skilled behavior become activated in proper serial order in a parallel connectionist theory, and develops detailed sequencing mechanisms for everyday skills such as producing a sentence, typing a word, or playing a phrase on the piano. Chapter 4 examines perceptual sequencing, the processes whereby perception-production units (mental nodes) perceive and register sequences of input. Chapter 4 also reviews a wide range of supporting data for a general principle of perceptual processing that follows from the node structure theory, the principle of higher level activation. Chapter 5 takes up the frequently neglected issue of timing, beginning with some general constraints on theories of timing for perception and action, and ending with a theory that meets these constraints and makes predictions for future test.

Chapter 6 points out some important asymmetries between processes in the theory that give rise to perception versus action, shows how these asymmetries explain a large number of empirical differences between perception and action, and predict some new differences for future test. Chapter 7 examines the functions of mental nodes and concludes that mental nodes evolved to enable the rapid and economic integration of many other heterogeneous sources of information in addition to perception and action. Chapter 7 also discusses problems with current explanations of visual dominance or "capture" effects and develops a new account of these effects.

The last three chapters of the book explore the processing of self-produced feedback, both in theory and in available empirical data. Chapter 8 examines self-inhibition, an inhibitory process that follows the activation of a node, and shows how self-inhibition plays a role in the processing of self-produced feedback. It also reviews supporting evidence for self-inhibition from a wide range of areas: neurophysiology, electromyography, errors in speech and typing, the misspellings of dysgraphics, the perception and recall of experimentally planted misspellings by normal individuals, and an apparently universal pattern of phoneme repetition in the structure of languages. Chapter 9 examines recent findings on the role of perceptual feedback in detecting and correcting self-produced errors, reviews the shortcomings of current theories for explaining these findings, and shows how errors are detected and corrected in the node structure theory. Chapter 10 examines how feedback in certain forms can disrupt ongoing action and discusses the constraints such disruptions provide for theories of the relationship between perception and action. A prominent example is the disruption of speech production that occurs when normal subjects hear the sound of their own voice amplified and delayed by about 0.2 s.

The Epilogue concludes the book by summarizing its main themes and concepts in a new way, analyzing the main strengths and weaknesses of the node structure theory, and pointing to fruitful directions for future research into relations between perception and action.

Epilogue

> To help with the division of labor in a field of this scope, researchers have adopted what might be called the dichotomization strategy. Commonsense dichotomies having intuitive or practical appeal rather than theoretical significance are used to segregate the field, and create subfields with more manageable research literatures.
>
> (D. G. MacKay, 1982, p. 485)

> During the late 1800s and early 1900s, leading psychologists such as Wundt, Liepmann, Sherington, and Thorndike actively pursued the topic of action and motor performance. With the rise of cognitive psychology, the focus shifted. . . . Perhaps motor performance was considered too simple to be interesting, or perhaps it did not have the intellectual aroma of topics like concept formation or memory of visual perception. The little research in motor performance was usually relegated to departments of physical education or kinesiology, where it had little contact with mainstream psychology.
>
> (Gentner, 1985, p. 183)

A recent overview of the accomplishments and shortcomings of experimental psychology over the last hundred years (D. G. MacKay, in preparation) argues that the failure to develop general and plausible theories is our main shortcoming, with noncumulative development of facts being one of the main side effects of this shortcoming. Without becoming integrated into a coherent theory, empirical phenomena are frequently set aside and forgotten. The present book can be viewed as an attempt to rescue some of these forgotten phenomena, among them the various manifestations of self-inhibition, including stuttering and the interference with speech production and other skilled behaviors that occur when auditory feedback is amplified and delayed by about 0.2 s.

To some readers, stuttering may seem a somewhat peripheral point on which to end a book entitled *The Organization of Perception and Action*. However, stuttering research illustrates in microcosm some of the more general problems endemic to the field at large, and in this Epilogue, I examine these problems and how to solve them. I then summarize what I feel are some of the major contributions and weaknesses of the book.

Stuttering and Theoretical Psychology

Stuttering is important for theories of normal behavior, because a complete and adequate theory must be capable of explaining all of the ways that an output system will break down, and as a breakdown with a perceptual cause, feedback-induced stuttering is especially important for theories of the relation between perception and action.

The history of stuttering research also carries important implications for the field at large. Current problems in psychology, such as fragmentation of the field, misunderstandings as to the nature of theories, atheoretical approaches with possibly self-perpetuating effects, and ahistoricity or noncumulative development of knowledge (D. G. MacKay, in preparation), are all writ large in the 120-year history of stuttering research (which begins with Wyneken, 1868). I argue here that these problems with stuttering research can be traced to a general "divide-and-conquer" strategy that has been adopted by the field at large.

The Divide-and-Conquer Approach in Stuttering Research

Over the past several decades, psychology has been following what might be called the divide-and-conquer approach to theory construction. Under this approach, a subdomain of the field is segregated on practical or intuitive grounds in order to develop one or more unique empirical approaches and experimental paradigms for generating a (hopefully) coherent body of facts, insights, and "miniature" theories within the subdomain. Given this coherent body of facts and insights, the goal is then to reintegrate the subdomain with the field at large, to the benefit of all concerned.

Stuttering research clearly illustrates the motivation underlying the divide-and-conquer approach. On the one hand, stuttering seems different from any other behavior that psychologists are interested in (see the discussion of differences between stuttering and other speech errors in Chapter 8), and on the other hand, mainstream psychology seems to offer little to researchers who want to understand stuttering and perhaps also to help provide relief for stutterers. As Van Riper (1982) points out after a lifetime of work in this area, psychological theories of speech production with applications to stuttering have been "slow in coming."

Stuttering research also illustrates a successful first step in the divide-and-conquer approach: *division*. Stuttering has been studied as a kingdom apart, by and large independently of what psychology has discovered about normal speech production, and many researchers now consider stuttering a field unto itself, with its own special phenomena, methodology, and theories (D. G. MacKay & MacDonald, 1984).

What about the *conquer* aspect of the divide-and-conquer approach? Has a coherent body of facts and insights about stuttering emerged and become part of the field at large? Absolutely not. Despite the practical and theoretical significance of stuttering, and despite the thousands of empirical studies that have examined stuttering under the divide-and-conquer approach, mainstream psychology and stuttering research have continued to go their separate ways (Garber & Siegel, 1982). As in psychology at large, the divide-and-conquer strategy has also retarded the development of theory. Most theoretical ideas about stuttering have been either descriptive in nature or so vague as to be unhelpful (Bloodstein, 1969). For example, "theories" that call stuttering a perseverative response, a symbolic sucking activity, or a miniature convulsion at best only loosely describe rather than explain it. Similarly, attributing stuttering to conflict, anxiety, stress, or delayed myelinization of cortical neurons is theoretically unhelpful unless a detailed causal explanation can be provided for at least one specific, real-time example of stuttering behavior.

More generally, the problem is that theories developed under the divide-and-conquer approach are at best a stab in the dark and at worst simply not possible. In particular, it is not possible to construct a genuine theory that attempts to explain stuttering independently of the mechanisms for producing error-free speech. Although stuttering is important for mainstream psychology, it is equally true that an understanding of the processes underlying normal behavior is necessary for understanding its disruption in a complex disorder such as stuttering. A genuine theory must simultaneously explain how stutterers speak fluently, when they do, and how fluency breaks down, when it does. A miniature theory that attempts to explain stuttering per se is analogous to a hypothetical theory in physics that applies only to backfires emitted from the exhaust system of a car. One cannot explain backfires independently of the principles of internal combustion underlying the normal functioning of an automobile engine. Similarly, one cannot explain stuttering independently of the mechanisms underlying the production of error-free speech (D. G. MacKay, 1969b; 1970a). Nor is this problem with miniature theories confined to stuttering research. As Lachman, Lachman, and Butterfield (1979) point out, the less than satisfactory nature of miniature theories developed under the divide-and-conquer approach seems to represent a general problem in psychology, which it is important, if possible, to correct (see also D. G. MacKay, in preparation).

In summary, the divide-and-conquer approach to stuttering has *in principle* frustrated the development of theory. No coherent account of stuttering either has emerged or can emerge under the divide-and-conquer strategy, and even though large numbers of findings have been amassed, many have been forgotten. Bridging the longstanding gap created by the divide-and-conquer approach between mainstream psychology and stuttering research is not just desirable but necessary for a solution to the riddle of stuttering. The "deplorable" state of stuttering research (Preus, 1981) can be expected to continue as long as stuttering research remains separate from theoretical psychology at large.

The lesson here, as elsewhere in psychology (D. G. MacKay, in preparation), is that general theories are in order and an approach that limits a field to the accumulation of empirical findings should be abandoned. What is needed in addition to further experiments is a genuinely theoretical psychology for integrating available observations and pointing the way to empircal regularities that are significant and new (see also D. G. MacKay, in preparation).

The Node Structure Theory in Overview

What new and significant regularities does the node structure theory point to? Perhaps the main ones are summarized by the principle of higher level activation. One of the distinctive characteristics of the node structure theory is its differentiation between content nodes (the units representing the basic components of action and perception), sequence nodes (the units that activate and sequence the basic components), and timing nodes (the units that determine when and how rapidly the basic components become activated). The general processing characteristics of these nodes (e.g., priming and activation); their basic structural properties (e.g., hierarchical organization with respect to activation and heterarchical organization with respect to priming), and their long-term memory characteristics (e.g., linkage strength) are not particularly new (Chapter 1). However, the precise nature of the interactions between these processing characteristics in the theory provide the basis for new theoretical generalizations such as the principle of higher level activation, which summarizes a large number of empirical regularities, from perceptual invariance to perception of the distal stimulus (Chapter 4).

Another not-so-new set of empirical regularities that acquires significance under the node structure theory concerns the asymmetries discussed in Chapter 6 between the potential rate of perception and action (the maximal rate asymmetry); between effects of practice on perception versus production (the listening practice asymmetry); between the ease of learning to recognize versus produce words (the word production asymmetry); and asymmetries between errors in perception versus production.

A final, but again not entirely new set of empirical regularities given significance under the node structure theory concerns the many parallelisms between perception and production (in both units and empirical effects, Chapter 2) and the many interactions (both facilitative and disruptive) between the processes for perception versus production (e.g., in the organization of timing, Chapter 5).

More specific contributions of the theory include new hypotheses concerning the perceptual processes underlying categorical perception and its exceptions, visual dominance and its exceptions, perceptual errors, and the processing of ambiguous inputs. The theory also extends existing perceptual hypotheses about the units of perception and the explanation of right-to-left effects (as in phonological fusions) and left-to-right effects (such as the greater ease of detecting "mispronunciations" at the beginnings than at the ends of words). Other new hypotheses concern constant relative timing, effects of practice on the timing and sequencing of behavior, and regularities in the nature of errors (e.g., speed–accuracy trade-off, the sequential class regularity and its exceptions, and the level-within-a-system effect, which is the fact that higher level units within a system are more prone to error than lower level units within the same system). The theory also develops new hypotheses about the functions of stapedial attenuation, the role of internal and external feedback in detecting and correcting errors (both overt and internally generated), and differences between the perception of self-produced versus other-produced speech (e.g., the size-of-unit effect in the detection of errors and the missing feedback effect in verbal transformation experiments). Finally, the theory provides a detailed and testable account of stuttering and the disruptive effects of delayed and amplified auditory feedback.

Comparisons With Other Current Theories

How does the node structure theory relate to other current theories? As noted in the Introduction, the node structure theory is much broader in scope than other theories and treats perception and action not as separate but as closely interrelated processes involving the same higher level mechanisms and structures (the so-called perception-and-action approach referred to in the Preface). However, like other current theories, the node structure theory participates in the current trend toward a focus on dynamic, on-line, or real-time process issues, in addition to static or structural issues. Like other recent theories (e.g., Grossberg, 1982), the node structure theory also postulates underlying mechanisms and processes that are within the feasibility of simple neuronal or neuronlike circuits. The theory is physiologically plausible or has the potential for mapping psychological constructs onto neuroanatomical constructs (see also D. G. MacKay, 1985; McClelland et al., 1986), an exciting prospect, because, as Ojemann (1983) points out, some such mapping seems essential for cracking the code of the brain. Indeed, the node structure theory may eventually rise or fall depending on physiological evidence for constructs resembling inhibitory satellites, sequence nodes, and domains and systems of content nodes.

Earlier chapters have compared the node structure theory with other recent theories of perception and/or action on a number of more specific dimensions, among them, "mass action" versus central, localized, or local processes and representations, the representation of phonological rules and phonological units in general, representations of ambiguity and "shades of meaning," the representation of conscious versus unconscious processes, the processing of perceptual feedback and its use in error correction and motor control, sequencing principles and parallel versus serial processing in general, sequential rules versus condition–action rules, timing principles or the lack thereof, ways in which action influences perception, top-down effects in perception and bottom-up effects in production, categorical versus noncategorical perception. However, I have not attempted to compare the node structure theory with any other theory overall and in detail. The reason is not just that such an endeavor would double the length of an already lengthy book (which it would if well done). Detailed overall comparisons will only be really useful when the field has developed two or more well-established theories of equivalent scope and precision. Theoretical psychology is nowhere near that point. Like other current theories, the node structure theory is not well established, has obvious strengths and weaknesses, and is in a state of evolution. Much more will be gained by direct attempts to overcome its weaknesses than by soon-to-be-out-of-date comparisons with other theories (including itself: for example, note the many differences between the present theory and D. G. MacKay, 1982, or between McClelland & Elman, 1986, and Elman & McClelland, 1984).

Limitations of the Node Structure Theory

I turn now to the areas where the node structure theory requires further work: formalization and scope.

Formalization of the Theory

D. G. MacKay (in preparation) argues that there is a natural sequence to theory construction that can be seen in the advanced sciences such as physics. Mathematical formalisms normally follow rather than precede the development of intuitively comprehensible theory, and breadth of theory initially takes precedence over precise but paradigm-specific simulations. I have so far simulated only limited aspects of the node structure theory (D. G. MacKay, 1982), but other aspects of the theory seem ready for real-time simulations of the sort described by McClelland and Elman (1986). Computer simulations of predictions derived from the high-interactivity situations discussed in Chapters 3 to 7 are very much needed, but as noted in the Preface, the relative noninteractiveness (locality or self-containedness) of self-inhibition (Chapters 8 to 10) will make the theory's predictions easier to simulate and check against incoming data in that area.

Conceptual Extensions of the Theory

Although the node structure theory is much broader in scope than other theories, it is nevertheless too narrow to apply to much of what goes on in either everyday cognition or laboratory experiments. Unless detailed mechanisms for attention, awareness, creativity, and learning (the formation of connections) are incorporated into the node structure theory, its applicability (simulated or not) to real data and to real behavior will be severely limited. Indeed, one (anonymous) reviewer suggested that the node structure theory will remain pretheoretical until the learnability of its node structures is determined (personal communication, Nov. 1985; but see D. G. MacKay, 1987).

The node structure theory must also represent visually guided behaviors in greater detail to qualify as a *general* theory of perception and action. Although I do discuss behaviors such as piano playing, typing, and the generation of Morse code, the theory is most detailed when it comes to the perception–production of speech. I therefore agree with McClelland and Elman (1986, p. 7), in reference to their own speech-centered theory, that "we would hope that the ways in which it deals with the challenges posed by the speech signal are applicable to other domains." But to argue that the principles of speech perception–production apply more generally to other perception–production systems is not enough; details of the similarities and differences need to be worked out.

The node structure theory is also limited with regard to speech. For example, its upper bound has been the sentence and its lower bound, the phonological feature. It is silent on the complex processes that intervene between sensory receptors (such as the basilar membrane) and the phonological features for speech perception and between phonological features and the muscles for producing speech sounds. It is even silent on the (in some ways more important) processes intervening between linguistic and nonlinguistic representations of the world.

Another limitation of the theory concerns its essentially psychological focus. Its interface with neurophysiology remains largely unexplored. I currently have no solid answer to questions such as "How are timing, sequence and content nodes instantiated in the brain?" The computational adequacy of the theory from a linguistic point of view also remains to be explored. I simply do not know what additional theoretical mechanisms will be required for producing and comprehending all possible naturally spoken sentences in English or any other language.

In view of these weaknesses and the evolving state of the node structure theory (in some ways another weakness, D. G. MacKay, in preparation), perhaps the most enduring contribution of the present book will be its analysis of constraints that future theories of perception and action must explain. These constraints form a relatively cohesive set, including theoretical constraints imposed by the units involved in perception and action, the nature of sequencing and sequencing errors in perception and action, processing asymmetries between perception and action, timing interactions between perception and action, the nature of error detection and correction, and finally, disruptive effects of feedback. New constraints will undoubtedly be discovered in the future, but the set outlined here will remain as a challenge to theoretical psychology for many years to come.

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