Experimental Psychology and Information Processing

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Preface

When I began teaching courses in Experimental Psychology and Information Processing at the University of Wisconsin, Madison, four years ago, the tradition in the experimental course here, as in most universities, was to teach methodology relatively independent of content and theory. This seemed to me to be an impossible task, so I set out to integrate methodology, content, and theory in teaching the course. An information-processing approach was utilized because it provided a framework for work in all of the areas of experimental psychology. With this framework, one did not need entirely different conceptualizations to study such varied topics as perception, memory, and decision-making. The potential contribution of the information-processing approach promised an exciting adventure. My goal was to define and develop an information-processing framework for experimental psychology and to communicate it to my students and colleagues. This volume is the outcome of that venture.

The goal here is to articulate a paradigm for experimental psychology. The paradigm, consisting of metaphysical, conceptual, theoretical, and methodological commitments, defines a set of standards for scientific exploration into the human mind. Calling the paradigm "information processing" is not as important as the articulation of the paradigm itself. The success of the present articulation will not only be evaluated by the reader, but will be tested against the development of experimental psychology.

The development of the first half of the book proceeds from the experimental course, which deals with more traditional areas of research such as reaction times, psychophysics, and visual sensation and perception. Most of the second half of the book is based on an undergraduate course called human information processing. The topics here concern attention, visual information processing, auditory information processing, short-term memory, long-term memory, and learning. The organization is not necessarily front-to-back or middle-to-back sequence. Rather, sections and even chapters can be read independently. If the reader finds that some earlier development is necessary, the table of contents and indices should be sufficient to direct him to the necessary material. Also, cross-references across chapters are included throughout the text. Further study of each topic should be facilitated by the suggested readings given at the end of the book.

This volume is meant to be basic and yet advanced. It is basic because the level of material covered is exactly that taught to sophomores and juniors. Undergraduates have no more trouble dealing with contemporary concepts than they have with traditional concepts. For example, there is nothing inherently more difficult in the method of signal detection theory than in the method of constant stimuli. At the same time, it is advanced because it represents the current state of the art in Experimental Psychology and Information Processing. My belief is that this book is appropriate for courses in Experimental Psychology, Perception, Memory and Attention, Information Processing, and Cognitive Psychology.

It is difficult to say whose assistance was most crucial in a project of this sort. The abstract goal of writing such a book developed into a concrete commitment because of Howard Leventhal. I appreciate the comments and helpful reactions of Peter W. Frey, Andrew Goldman, and Harold L. Hawkins. Their ability to react to the material as would students, teachers, and scientists improved the book considerably. Finally, Michael Olson provided good feedback from the undergraduate point of view.

Susan Case enthusiastically and energetically transcribed my sixty or seventy lectures and helped organize the book. Marion Masse has been a most dependable secretary, and Lynne Heinneman and Kathy Schmit also contributed to the typing. Peter Lang kindly provided the brain waves shown in Figure 1.2, Michael Cohen contributed many of the spectrograms in the auditory information-processing section, and Wendy Idson proofread many of the typed chapters. Karen T. Massaro photographed the Roman mosaics shown on the opening pages of Sections I, III, and V, and the Borromini colonnade. Finally, Bob Erhart, Charlotte Iglarsh, and Jenny Gilbertson at Rand McNally aided in the materialization of the book.

Some of my research reported in the book was supported financially by the Wisconsin Alumni Research Foundation and the National Institute of Mental Health. The final version was written while I was a John Simon Guggenheim Memorial Foundation Fellow. Their support and that of the Wisconsin Alumni Research Foundation allowed me to spend the year in a way that such work could materialize. In this regard, I would like to thank the people at the Institute of Psychology of the Central Research Council in Rome for their hospitality.

I am obliged to the many scientists who gave their permission to reproduce findings from their work. Thanks also are due to the artists, museums, and collectors who permitted reproduction of their works of art.

D. W. M.

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Experimental Psychology and Information Processing

Overview

Mind is a mass of tangled processes. Our problem is to dissect this complex, and to discover if we can, its plan of arrangement.
—Edward B. Titchener (1899)

The goal of this book is to present the current state of the art in *Experimental Psychology*. By experimental is meant scientific; by psychology is meant the study of psychological phenomena. We focus, therefore, on the scientific study of psychological phenomena. As has been traditional in Experimental Psychology since Woodworth's (1938) book of the same title, the study of abnormal, developmental, and social psychology is not included. We further limit ourselves to the study of human psychology. Our focus is on the scientific study of sensation, perception, memory, decision-making, psychophysics, attention, imagination, and learning. These topics concern the ways in which the individual derives knowledge, that is, information, from his environment. We assume that psychological functions or processes intervene between the stimulus environment and the knowledge the subject finally realizes. Therefore, we consider the study of experimental psychology equivalent to the study of information processing—the processes that allow the individual to take the potential information from the environment to its utilization by that individual.

The central assumption of this book is that psychological functions, operations, or processes intervene between stimulus and response. As psychologists, we study what these processes do, rather than what they are. The question of what psychological processes are is a metaphysical one, which cannot be answered experimentally. The problem of the nature of psychological events is known in philosophy as the mind-body problem. The solutions to this problem are analyzed in Chapter 1 and one solution is developed as the metaphysical basis for the information-processing approach.

Chapter 2 discusses the role of theory and method in experimental research. One observation that is made throughout this book concerns how experimental method follows theoretical development. The information-processing approach also prescribes a particular methodology since its goal is to provide information about the sequence of processes that intervene between stimulus and response. This methodology follows directly from the development of the experimental method in psychology during the last one hundred years. After covering the foundation of experimental method in Chapter 2, we develop its utilization in psychological research throughout the book.

The information-processing approach is illustrated nicely in the methods that have been developed to measure the time it takes for psychological operations (see Chapter 3). The goal of this procedure, established by Donders in the 1860's, is to measure the exact time it takes to perform certain psychological events, such as selecting the appropriate response from a set of alternatives. Although there are certain problems with Donders' exact method, a modification, the additive-factor method, can be used to study the nature of psychological processing. As an example, in one task discussed in Chapter 4, a subject is given a short list of target items and then presented with a given test item. His task is to indicate whether the test item was contained in the target set. For example, if the target set was 4, 9, 7, 2 and the test item 8, the answer would be "no." The dependent variable is the time it takes the observer to make his decision. By manipulating a number of independent variables and analyzing the data appropriately, this paradigm illuminates the nature of certain psychological operations.

Psychophysics, or the relationship between the physical and the psychological worlds, is one of the earliest areas of psychological study (see Chapter 5). Fechner established the experimental study of the relationship between sensation and perception in the middle of the 19th century. Fechner's goal was to describe the subject's response as a direct function of the stimulus. Fechner discovered, however, that there is no one-to-one relationship between stimulus and response. Psychological operations intervene between stimulus and response and these must be accounted for in the psychophysical situation. Chapters 5, 6, and 7 show how two operations occur in a simple psychophysical task in which a subject is asked to interpret a stimulus event; for example, was a stimulus presented? These operations involve a perceptual and a decision process, respectively. The experimenter cannot understand the relationship between stimulus and response unless he accounts for both of these processes. We shall see that the decision process is a

critical stage of information processing and must be accounted for in all experimental tasks.

Visual information processing is discussed in Chapter 8–12. The process of visual detection is introduced in Chapter 8 when we seek the answer to the question: What is the minimal amount of light an observer can detect under optimal conditions? Answering this question requires a knowledge of stimulus, physiological, anatomical, psychological, and mathematical variables in the experimental situation. The study of visual perception in Chapter 9 utilizes works of art in addition to the experimental method to learn how we perceive the visual world. Many art works function as controlled experiments and can be used to demonstrate the rules of visual perception. In Chapter 10 the interaction of theory and research is clearly seen in the study of visual illusions. Illusions in themselves continue to intrigue the scientist and can be utilized to illustrate some of the operations in visual perception.

We perceive a constant three-dimensional world although the stimulus input continually changes over time. A given object is perceived reliably under a wide variety of instances and orientations which drastically change the retinal input. This perceptual constancy has generated much theory and research, some of which is discussed in Chapter 11. We are interested in the operations responsible for veridical perception and the time it takes for these operations to occur.

Chapter 12 concerns the interaction between visual recognition and short-term memory. The research and techniques discussed there make apparent that the simplest recognition experiment requires two stages of information processing: perception and memory. Each of these stages of processing must be accounted for in the task before the experimenter can isolate the rules of processing of any one stage.

The experimental and theoretical study of attention receives our attention in Chapters 13–16. The information-processing approach to the study of attention attempts to answer two questions. First, at what stages of information processing does attention operate? That is to say, at what stages of information processing can a limited processing capacity be utilized for one task at the expense of another? For example, excluding changes in eye movements, can we selectively attend to a given location of a visual display? Second, can processing at one stage influence the processing capacity available for another stage of information processing? Does an increased memory requirement decrease the efficiency of the recognition process?

The rules of the visual recognition process in reading are

studied in Chapters 17–19. We assume that the visual stimulus is transformed by the visual receptor system and a preperceptual representation of the stimulus is stored in preperceptual visual storage. The visual recognition process transforms the preperceptual representation into a synthesized visual percept which corresponds to the phenomenological experience of seeing. The time needed for the visual recognition process as well as methods for its study are discussed in detail in Chapters 17 and 18. We also use these methods to define the properties of preperceptual visual storage.

The information necessary for visual recognition is in the nature of the figure-ground contrast of the visual image. This stimulus does not change continuously in time, but is held in a relatively steady-state form during every eye fixation between saccadic eye movements. During this time, we assume that the light wave pattern is held in preperceptual visual storage. The visual recognition stage involves a readout of the information in the preperceptual visual image. An analysis of the visual information available in the image takes time and it is assumed that the preperceptual visual image holds the information for recognition to take place. Recognition of a visual pattern produces a synthesized percept in synthesized visual memory, which holds this information long enough to allow us to see more than just the visual input from one eye fixation.

The characteristics of the auditory stimulus are discussed in Chapter 20 as preparation for our study of auditory information processing. The production and characteristics of speech stimuli is included, since we also study the perception of speech. The auditory recognition process is studied in Chapters 21–23. Auditory information processing is assumed to be exactly analogous to visual information processing. The auditory stimulus is transformed by the auditory receptor system into a representation held in preperceptual auditory storage. The auditory recognition process involves a transformation of the preperceptual representation into a synthesized auditory percept.

The information necessary for auditory recognition is in the nature of the temporal changes of sound pressure over time. The process of recognition requires an analysis of the acoustic information available in the sound pattern. This analysis cannot take place while the stimulus is occurring, since a complete sound pattern is necessary for recognition. The preperceptual storage holds the information in the sound pattern so that recognition can occur. Until the sound pattern is complete, recognition cannot begin, since all of the stimulus information is necessary for the recognition process. Recognition of an auditory pattern produces a synthesized percept held in synthesized auditory memory.

Chapters 24–27 examine the properties of immediate or short-

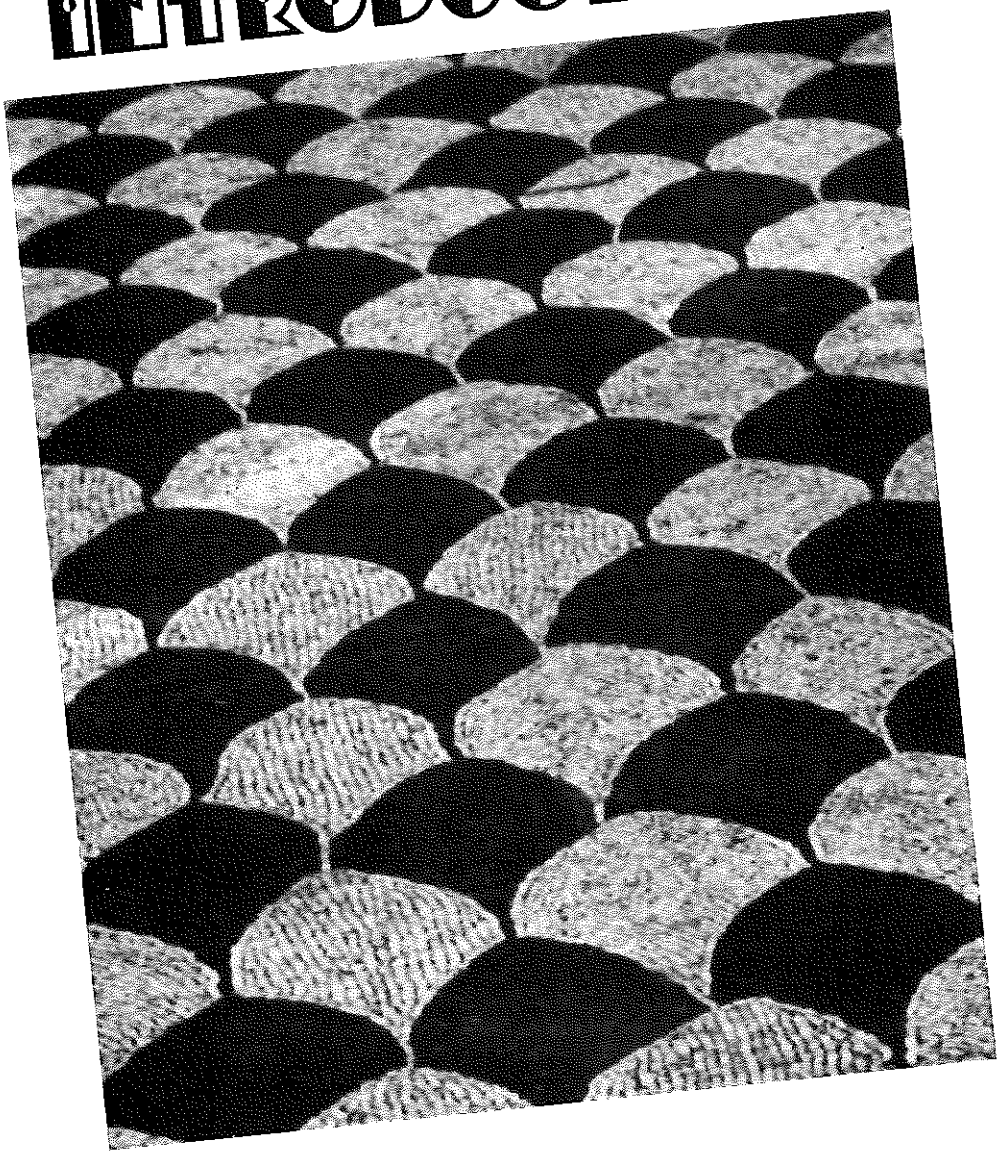
term memory. We divide short-term memory into three structural components: synthesized auditory and visual memory, which are modality-specific, corresponding to the experience of the immediate present, and generated abstract memory, which is not modality-specific, but is in an abstract form. We study the properties of synthesized auditory memory in Chapters 24 and 25 and the properties of synthesized visual memory in Chapter 26.

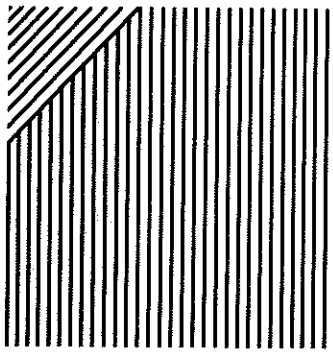
Synthesized memory is made available by the recognition of information in preperceptual storage. This memory is the structure responsible for experience of what we are currently seeing, hearing, or dreaming. Synthesized memory differs from preperceptual information in that preperceptual information is tied to the stimulus, whereas synthesized information is not. Information can be synthesized and experienced without a recent stimulus, such as is the case in dreaming. With little effort, we can silently imagine the sound quality of a friend's voice or what he looks like. The studies discussed in Chapters 24, 25, and 26 demonstrate that synthesized information usually lasts some seconds following stimulus presentation.

Meaning is derived from synthesized auditory and visual memory and is placed in generated abstract memory. This stage of processing corresponds to the processing stage studied by most immediate memory studies. In the model developed in this book, the same structure is used to store meaning derived from auditory, visual, and other sensory stimuli. One structure seems to be sufficient since the information is not modality-specific, but appears to be in a relatively abstract form. The storage and forgetting of information in generated abstract memory are discussed in Chapter 27.

In Chapter 28, we study the structure of long-term memory, our storehouse of knowledge, and discuss methods used to determine how information is stored there and what processes are responsible for its utilization. Chapter 29 presents methods of the study of learning. Learning appears to be made up of all of the component processes discussed in this book. Hence, all of these component processes must be accounted for in the learning task. Finally, we summarize the information-processing model developed in our study.

INTRODUCTION





Psychology: the science of mental life

The mind-body problem
- interactionism
- materialism
- epiphenomenalism
- idealism
- best choice
- monism

Mental operations
- creativity and computers
- information-processing model

Psychology is the Science of Mental Life, both of its phenomena and their conditions.
—William James (1890)

Our study of psychology follows in the tradition of William James, who in 1890 defined psychology as the science of mental life. What James meant by a science of mental life was nothing more or less than understanding the psychological processes of perception, imagination, memory, thinking, and decision-making. These processes seem to be fundamental to man's existence qua man. For example, one important problem in perception is how the reader derives meaning from a page of text. How is he or she able to imagine the theme of Beethoven's ninth symphony? How does a person remember what he was doing one year ago today? Think of a four-letter word that ends in *eny*. Should you continue reading or consider some of the thoughts generated by these questions?

James' definition of the content of psychology appears reasonable and provides a fascinating challenge to the experimental psychologist. Before accepting this challenge, however, we need to explore the assumptions that are implicit in James's definition about the nature of man as the subject of science. The assumptions are first, that mental phenomena exist, and, second, that these phenomena can be subjected to the scrutiny of scientific endeavor. These assumptions have rival assumptions, and although the issue among them cannot be decided with the certainty of science, they can be subjected to rational, critical examination.

MIND-BODY PROBLEM

Early in the history of philosophy the mind was isolated and identified as distinct from the body. Immediately the relationship between mind and body became a central problem of human thought. The ingenuity of generations of philosophers provided various models of man, all starting from the dualism of mind and body. One of the first great thinkers to reflect on this problem was Plato. He observed that whereas the body follows laws embedded in physical events and circumstances, the mind appears to be free from

these events. Building on the mind as the agent of man's incorporeal acts—perceiving, thinking, decision-making, and so on—and on the vague cultural concept of spirit Plato conceived the soul. Immortal and incorporeal, the soul in this life is imprisoned by the body. Its escape is death, when it breaks free of the body's limitations and exists as pure thought. Plato's notion of the soul was adopted by religion, and the concept that the soul or mind is free from the demands and laws to which the body is subject permeated Western culture. This dualism still determines the framework in which most of us think about man: we study him either as biology or as psychology.

Plato's formulation—called Platonic dualism—immediately raised a problem that has exercised philosophers ever since: How can these two distinct entities, with their two distinct sets of functions, be related within one entity? The mind-body problem is a metaphysical one. No experimental paradigm can be set up to solve it, and no final answer is possible with presently available techniques. We can only analyze it carefully and review the answers that philosophers arrived at by using the methods of metaphysical speculation.

Interactionism

About 20 centuries after Plato, Descartes, a Catholic scientist, came up with a famous solution to the problem. As a good scientist, Descartes maintained that the human body, like all physical entities, could be described by mechanical laws. Accordingly, through mechanical laws, we would understand the functioning of the human body as human physical behavior. In this respect, the physical body was no different from other physical objects. As a good Catholic, however, Descartes also maintained that the human soul was not subject to the laws that governed the body. Being spiritual, immortal, and eternal, the soul was free of physical necessity and could not be understood by the laws of science.

Descartes' solution to Plato's problem was to accept that the mind and body must somehow meet, since their operations are in some ways interlinked. For this meeting place Descartes chose the pineal gland; he was drawn to it as the seat of the interaction between mind and body because this gland is not duplicated as are most of the brain structures (one hemisphere of the brain being a mirror image of the other). In the pineal gland, according to Descartes, spiritual fluids interacted with bodily fluids, with the result that some control of the body by mind was possible.

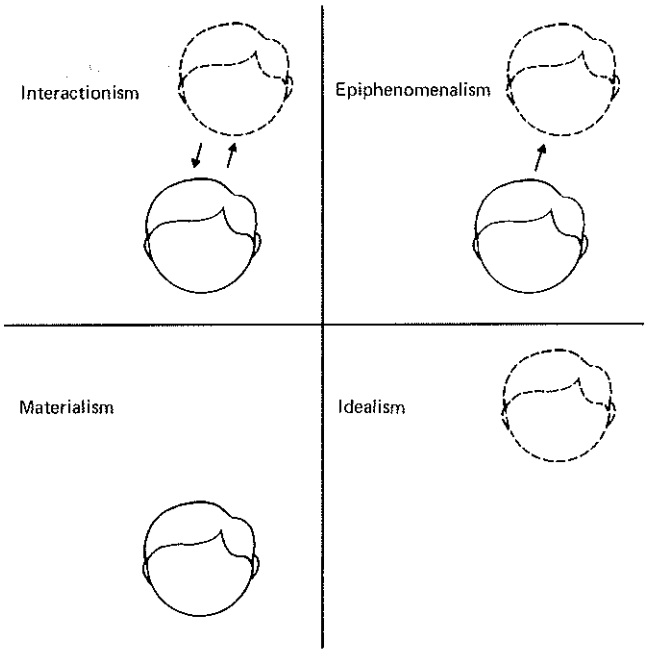
Cartesian interactionism is represented graphically in Figure 1 (upper left), in which we have the human body interacting with the human mind. Cartesian interactionism maintains that a person is

made up of two different things: mind and body. Two things ought to be capable of being thought about independently of each other. For example, this book and a table are separate entities, and one should be able to think about them separately. One can, indeed, think about the book without thinking of the table, and about the table independently of the book. But to attempt to do the same with the two entities of interactionism causes some difficulty. When thinking of the body, thoughts of the mind arise. Thoughts of the mind also give rise to those of the body. The manner of our thinking, therefore, poses a problem for Descartes' theory.

Materialism

Philosophers have been unhappy with the Cartesian proposition that a person is two separate things that somehow interact and have evolved alternative theories. One of the most influential of these is materialism, shown in graphic form at the lower left in Figure 1.

FIGURE 1. Graphic representations of four solutions to the mind-body problem.



Materialism simply denies the existence of the mind. If the mind does not exist, then to understand man we need understand only his behavior. A materialist rejects James' definition of psychology

as the study of mental life. For the materialist, there is no mental life and no need to study it. The proper subject of psychology is, rather, observable behavior; materialism is the metaphysical foundation of behaviorism.

Epiphenomenalism Another solution to the mind-body problem is epiphenomenalism, which holds that consciousness—or mental life—is nothing more than the by-product of material life, an epiphenomenon with no consequence of its own. The mind can be compared to the glow around a lightbulb that in no way influences the behavior of the bulb itself. Epiphenomenalism, then, rejects Descartes' conviction that the mind interacts with the body. Rather, the body controls the functions of the mind without being at all influenced by it. To understand man, therefore, it is not necessary to study his mental life.

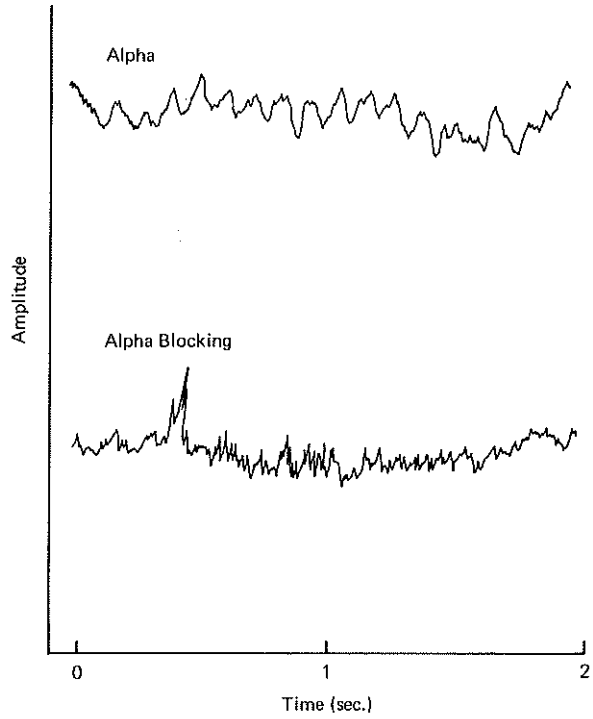
Idealism Do you deny mind? I'll deny matter. Thus said Bishop Berkeley, some time after the age of Descartes, and in so doing formulated the theory of idealism. For Berkeley, the body, as matter, does not exist. Therefore, only the mind need be studied; physical events may be ignored. Samuel Johnson put Berkeley's solution to a unique test; maintaining that there was a material reality, he kicked a stone, thereby hurting his toe and proving, to his own satisfaction at least, the existence of matter.

Best Choice We now have discussed four different theories of the respective roles of mind and body in human life. Today the three most influential theories among scientists are Cartesian interactionism, epiphenomenalism, and materialism. Each of these deserves careful thought, given the consequences of accepting a particular theory. Consider the implications of epiphenomenalism and materialism. If mental phenomena do not influence our behavior or do not even exist, then we need not understand mental life in order to understand behavior. On introspecting, however, we find it difficult to believe that our mental life has no influence on bodily processes. In fact, methods of controlling bodily processes by the mind are now widely used and have become an important part of the psychological study called bio-feedback training.

Employing electronic devices, psychologists are able to record a number of physiological responses, such as heart rate, brain waves, and galvanic skin potentials of human observers. Electrodes can be attached to an observer's head so that the electrical changes

in his brain activity can be monitored. The electrodes pick up these brain waves, take their electrical potential, and put it through an amplifier (analogous to the amplifier of your record player). The amplified signal is then fed into an oscilloscope which, in essence, renders a graphical analysis of the electrical changes in the observer's brain. With an oscilloscope, time is represented along the horizontal axis, and a relative change in electrical current along the vertical axis. Figure 2 presents an oscilloscopic display of two prominent brain waves: the alpha wave and alpha blocking.

FIGURE 2. The alpha wave shown at the top oscillates regularly at about 9 cycles per sec. The wave produced by alpha blocking shown at the bottom oscillates at a much higher frequency in a highly irregular fashion.



An observer with attached electrodes can be seated at the oscilloscope so that he can observe his own brain waves. This touches on the question of whether a mind can look upon itself. Experimental studies indicate that observers *can* control the nature of their brain waves. Indeed, as you may already know, yoga has provided a system of mental exercises allowing the yogi to control his body with his mind. By thinking the right thoughts, the yogi can

change his heart rate and the wave shape of his brain activity. This has great implications for our metaphysical problem, implications that are fortified by data gathered from observers controlling their brain waves in the laboratory.

Different types of brain waves can be distinguished by the amplitude (the height of the wave) and the number of repetitions of the wave per second. The alpha wave is very regular, has a high amplitude, and usually cycles between eight and fourteen times per second. A second wave, alpha blocking, is more irregular, has a smaller amplitude, and repeats at a much higher frequency than the alpha wave. With a little training, an observer finds that he can produce these two brain waves at will. Alpha blocking is produced by attending to an interesting scene, or by forming a visual image if the eyes are closed, or merely by attending to the changes in the brain waves that are appearing on the oscilloscope. The alpha wave state is a meditation state; to produce it, one but maintains a relaxed alertness, thinking about nothing at all, or alternatively, one concentrates on something mundane, like a regular bodily process. An observer concentrating on the steady beating of his heart rate to the exclusion of everything else produces alpha waves.

What does this phenomenon imply for our theories of the relationship between mind and body? The brain pattern constitutes a physical behavior of man; the epiphenomenalist, or behaviorist, should be able to predict it. On the contrary, however, it is the observer alone who can predict which wave shape will come next. He controls the phenomenon, and he may choose, from the point of view of the behaviorist, quite arbitrarily. This creates difficulties for both materialism and epiphenomenalism. Mental processes, say epiphenomenalists, play no part in controlling the body. But here we have an experimental situation in which a mental event does control a behavioral event. Materialists tell us that mental events do not exist. But here they are, controlling the body. In this experiment we can, and must, grasp the real existence of something we call mental processing.

So the mind exists and influences the body. That the body affects the mind is also known. Recalling one's last trip to the dentist should remove any doubt of that; pain hurts. Hurt is a perception, a phenomenon of mind. We seem to have been led back to interactionism, to the theory, originally espoused by Descartes, that mind affects body and body affects mind. Unfortunately the problems in this theory still remain. *How* do body and mind interact? If a spiritual entity can affect a physical one and vice versa, this seems to imply that anything can cause anything. Here are two things, mind and body, which can neither be related to one another satisfactorily, nor thought of separately.

At this point it is necessary to retrospect and ask why mind and body have been postulated as separate and distinct in the first place. The philosophers from whom we inherit this distinction were unable to conceive that a physical entity could be conscious, that is, lead a mental life. They experienced consciousness as altogether other than a corporeal function. Consciousness, they believed, was free of all but its own dictates, whereas the body was subject to the accidents of time and place, the random influence of exterior events, the laws of nature, and death. It was not logical that thought, an incorporeal function, could be caused by, produced by, and be dependent upon a mortal body. Plato had the only possible solution. There must be a second entity, a spiritual being, to do the thinking.

Attributing mental processing to an incorporeal entity does not, however, resolve the problem. The operations of consciousness are not in any sense easier to understand if they are assumed to be independent of the body. Conversely, in the age of computers and other nonhuman information-processing systems, it is much easier to accept the fact that physical things think. Computers, to whose absolute corporeality man can attest since he made them, do perform incorporeal operations with incorporeal results. We ourselves have designed their operations, and can usually understand the rules by which they occur. Many of the internal operations of computers seem to be analogous to the mental operations of man. So it is simply not unreasonable or illogical that some physical things are conscious and can lead a mental life. Nor is it inconceivable any longer that certain physical organisms can perceive, imagine, and remember. Our task is to describe how these physical entities—ourselves—perform these internal operations.

Monism

These observations lead us to a distinctly different alternative solution to the mind-body problem, which is called monism. The term monism is used to describe this solution because the mind and body are not considered to be separate entities whose interaction must be explained. Rather, it is assumed that human beings are highly complex organisms with a number of complex visible attributes such as a complex brain and nervous system. One of the properties of this complex being is that it leads a mental life. To understand man, we must understand these mental processes.

One critical attribute or dimension of the physical entity, man, is consciousness. Throughout history, consciousness has been attributed to a nonphysical entity, the mind or soul. However, it is more logical to conceptualize consciousness as a dimension of human beings in the same way that the thumb and forefinger arrange-

ment represents one of their characteristics. Mental life is the distinguishing feature that qualifies man as the unique subject of psychological study. When we say that the contribution of the mind is critical to understanding man, we are not positing another entity; rather we are referring to a dimension or attribute of man himself. In studying the processes that William James laid down in 1890, we shall be studying neither mind nor body, but the internal mental operations of the whole person.

Psychology was defined here as the science of mental life. To build our metaphysical foundation, it was necessary to determine how our mental life related to our behavioral life: how the mind related to the body. Popular solutions to the mind-body problem were discussed. Materialism and epiphenomenalism were rejected because mental events or processes exist, and these affect our behavioral life. Descartes' interactionism was rejected because it is not logical that the nonphysical should affect the physical. We were left with the monistic solution, which posits that the physical nature of a person possesses the attributes that allow him to lead a mental life.

Mental processes are tied to physical systems but cannot be reduced to physical processes. Man is organized with a conscious awareness that is integrated with the different sense modalities. Visual perception is an example. Input for vision comes by way of our eyes; but they are not sufficient for perceiving. We actively construct and synthesize our view of the world. Later, with no visual input, we can reconstruct what we saw earlier and form a mental image of the scene. This is what is referred to as a mental process. Mental events exist and must be studied to understand human behavior. Accordingly, the subject of psychology as seen here is the study of man's mental processes.

MENTAL OPERATIONS

Earlier researchers assumed that mental processes could be ignored because the stimulus situation alone would be sufficient to predict response. This expectation has not turned out to be the case. For instance, it would have been nice to predict the simple detection response (in which the subject reports whether or not a stimulus was presented), based on the intensity of the stimulus. Indeed, it was long assumed that there existed a threshold of intensity above which the observer would detect a stimulus and below which he would not. On investigation what actually happens is that, although subjects grow increasingly more likely to detect (experience) a stimulus as its intensity is increased, their response

on any given trial is also a function of a decision or a response rule. The response rule governs how often the subject will say "yes" or "no" to a given experience and is influenced by the attitudes and motivations of the subject. Subjects, therefore, may claim to hear a sound that is well below any possible threshold; later they may ignore one that is surely above it. In these experiments it is clear that in some way the subject has acted upon the information derived from the stimulus before he produced the response. He does not constitute a passive reactor, but is himself an agent that influences the final outcome—the response. The response cannot be understood without understanding how the subject acts upon the information in the stimulus.

Some might object that no reliable method exists for studying the mental processes of the subject. This is no longer true. The information-processing approach provides us with a model which has proved extremely fruitful in generating experimental designs for studying the sequence of operations between stimulus and response. Each mental process is looked upon as an operation on the information made available to it by an earlier operation or by the stimulus itself. What this means can be illustrated by an analysis of the creative process in human invention and discovery and also by the sequence of operations performed by a general purpose computer.

Creativity and Computers

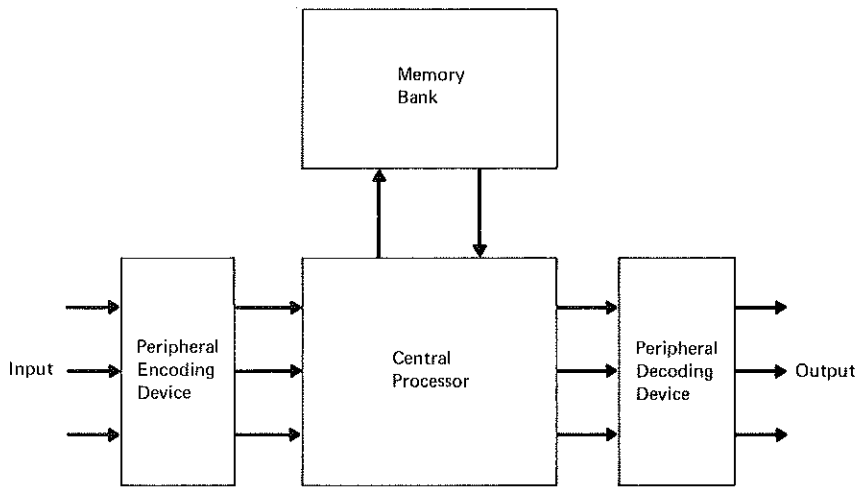
The creative process is a large, ill-defined process at present and as such is not studied by experimental methods, but the data received from introspection can be analyzed in the framework of information processing. Most creative people report that they go through a series of operations or stages of processing from the inception of a project until its publication. The first of these is a preparation stage in which the problem takes shape as such, and relevant information in the person's storehouse of knowledge is called up and sensitized and made available for the solution. This information is now available for the next stage of the creative process, in which the individual stops consciously processing the information. We know nothing about this incubation stage, which is widely reported by creative people, except that the processing taking place here is accomplished at a subconscious level, and that when the problem emerges again into the creative person's consciousness, it has been transformed into a new conceptualization.

Under the new formulation a solution may now be possible. If so, the person experiences an insightful stage of processing. He or she may now see the theoretical revision that will permit a solution, or the link between this and other problems in his area, or the

key piece of knowledge that will furnish a solution. Finally, the creative person must go through the final editing, or mopping-up, stage in which he must validate his insight. The implications of the solution must be worked out to verify its consistency. He may refine it by mapping it into mathematical or logical terms, which are a further check on its validity. Whatever his tests, if his solution passes them it is now ready to be made public.

In each of the stages of creativity a certain amount of information is made available. The operation of a particular stage transforms the information and passes it into the next stage of processing. A computer's operations on a computer program follow the same pattern. Figure 3 illustrates the series of operations between the input of the program and the output of its solution. The series is initiated by an input; the first stage transforms the input into a

FIGURE 3. Computer Behavior: A graphic representation of the sequence of component operations between the input of a program and the output of its solution.



language comprehensible to the computer. After this peripheral encoding, the central processor of the computer routes the information into the memory bank, where it remains available as needed for execution of the program. The central processor executes the program and produces an output which must pass through the peripheral decoding device before it can be communicated to the outside world.

A computer is usually equipped with devices to read cards, paper tape, or magnetic tape; information meant for ears and eyes

is meaningless to it. The input designed to be encoded by a card-reading device arrives in the form of a card punched with holes. The area of the card is arranged in rows and columns so that the location of each hole can be precisely identified. The card reader has a set of photoelectric cells that send light through each hole in the card. The device can therefore move from one position to the next, asking in each location whether or not a light shows through. The presence or absence of light can be transformed into a more useful form, for instance whether or not a particular magnetic core is magnetized. At the end the computer has a set of "yeses" and "nos" or 1s and 0s in the form which it was specifically designed to handle directly.

The central processor now places the information in memory, which is made up of a set of locations. Each location in memory has an address, and the information stored there is its content. Now the central processor can refer to the contents by their addresses only. The central processor can then begin to execute the program. The execution of the program involves performing the sequence of operations listed in the instructions of the program. The outcome of the program is the solution or information wanted by the computer user. In order to communicate the solution, the central processor must translate it into a form that is intelligible to the computer user.

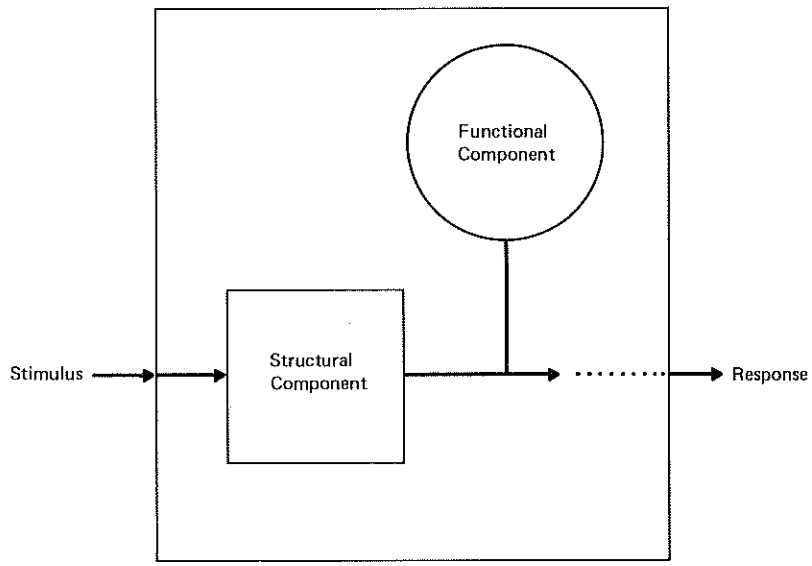
The goal of this book is to present methods of experimental psychology that will enable the experimenter to understand the sequence of operations that occur between stimulus and response. We have noted that to understand the creative process it is necessary to understand the sequence of events that occurred between the inception of the problem (stimulus) and its solution (response). Analogously, to understand a computer's behavior it is necessary to understand the internal set of operations and transformations of information between input and output. The study of man is fundamentally no different. To understand man we must determine and understand the sequence of mental processes that occur between the observed stimulus and response.

Information-Processing Model

The guide we use in our study of psychology is an information-processing model. The central assumption of the model is that a number of mental operations, called processing stages, occur between stimulus and response. A stimulus has potential information and its presentation initiates a sequence of processing stages in which each stage operates on the information available to it.

The operations of a particular stage take time and transform the information in some way, making the transformed information available to the following stage of processing. Two theoretical components or constructs are important in the model. First, the *structural* construct describes or defines the nature of the information at a particular stage of processing. Second, the *functional* component describes the operations of a stage of information processing. Figure 4 illustrates the graphic representation we shall use for the structural and functional components between stimulus and response.

FIGURE 4. Information-Processing Model: A graphic representation of the structural and functional components between stimulus and response.



The information-processing model will be utilized to study sensation, perception, memory, attention, learning, and decision-making. Its main purpose is to formally represent the psychological processes that are important in a given experiment. By delineating the psychological processes, an understanding is obtained that not only clarifies the stimulus-response relationship but also illuminates the processes themselves. Our goal is to understand what the psychological processes do and how they do it. The model functions as a formal representation of our knowledge of these processes and forces us to be consistent in our psychological research. It enables us to study methodological, logical, and theoreti-

cal issues in a consistent and coherent manner. The model also provides a tool we can use to summarize our findings and predict the results of new experimental and real-life situations. Remember that a model is used to represent the phenomena under study as simply as possible; it is not meant to correspond to the phenomena exactly. If it did, it would no longer be a model but would be identical to the phenomena.

Our psychological model is built by a method of successive approximations in order to demonstrate how knowledge is accumulated in science. Chapter 2 begins our study with a short discussion of the development of theory and scientific method in psychology. One of our goals there and throughout the book is to show how the method of experimentation follows from psychological theory, whether or not it is explicitly articulated by the experimenter.

Methods of psychology

No psychologist is likely to make pertinent contributions to the field if he still hesitates to remember that the armchair is the most indispensable piece of hardware we own.
—Rudolf Arnheim (1971)

Given that psychological phenomena exist, how do we go about understanding them? No single set of methods is correct for psychological study in the same way that no single set of rules is followed for proposing marriage. The method used in both cases is critically dependent upon one's perception of the situation and what one wants to know. In most cases, a "yes" or "no" answer is not sufficient; there is concern for other aspects, such as the rationale for the answer. In psychology, the methods we use to study psychological processes can only follow, not precede, the questions we wish to ask. Scientists with different questions or conceptions of the topic to be studied develop different experimental methods. They then use the results of the experiments to argue for the importance of asking just these questions in their particular experimental manner.

Consider the change from the Aristotelean to the Galilean view of motion. Aristotle saw a falling stone as a change of state rather than a process. For him, the relevant dependent measures of motion were the total distance covered and the amount of time elapsed. From these two observations the Aristotelean could compute the average speed or the average distance covered per unit of time. In contrast, Galileo, like some of the men before him, saw the falling of a stone as a process; therefore, it was reasonable to speculate on the operations of this process. One hypothesis put forward was that stones fall with a uniformly accelerated motion. This idea led to new methods of experimentation and data analysis which were unlikely in the conceptual framework of Aristotle's view of motion.

THE ROLE OF THEORY IN RESEARCH: A BRIEF HISTORY

Research in psychology has also been dictated by the theories and conceptual ideas of the investigator. A brief review of some different psychological theories will indicate how the methods of research followed directly from these theories. The British Empiricists (John Locke, George Berkeley, and David Hume) of the 17th and 18th centuries provided a model of human psychology that stimulated the beginning of its systematic study in the 19th century. The empiricists rejected the venerable philosophical notion of innate ideas as the working material for thought to take place. Instead, they postulated that all knowledge is acquired through experience. According to Locke, experience consists of sensation and reflection. Sensation is what we see, hear, feel, or touch. Reflection is a process of the mind and involves building directly on our sense experiences. Accordingly, phenomena such as knowing are a direct consequence of the reflective process operating on our sense experiences. Thus sensation—a phenomenon with observable, tangible properties—becomes the basic unit of human psychology.

Thomas Reid, an 18th-century empiricist, was the first to further refine empirical psychology by distinguishing sensation from perception. Sensation, according to Reid, is the impression that an object makes on the mind; it constitutes the bare content, the raw materials, of the mind. Perception, on the other hand, includes a further step or operation by which that content is supplied with meaning. Perception is the apprehension or recognition of an object; it contains not only the sensation of the object, but a concept of it.

Reid answered the question of how the mind took this step—of applying meaning to the bare sensation and transforming it into a perception—by appealing to the Supreme Being. We need not look so far. The source of the meaning by which the observer transforms the sensed or detected object into the recognized one is his storehouse of knowledge, his memory. William James made this point by stating: "We perceive only that which we preperceive." For example, we hear, or detect, a foreign language as well as we do our native tongue, but very little if any meaning can be attached to the message. Certain syllables may be recognized as corresponding to some that we know in English, but even these do not have the same meaning. The words of the foreign language are not making contact with our semantic memory that continuously provides meaning to the words of our own language.

Introspection

The empiricist theory of knowledge emphasized a process, sensation, that could be observed and measured; and in the 19th century people who had been influenced by the empiricists began to think

of doing so systematically. Wilhelm Wundt set up the first laboratory dedicated to experimental psychology in 1879. Wundt was, at least functionally, a dualist; he believed that the study and description of mental phenomena should differ from that of physical phenomena. Fixed laws could be developed to describe physical phenomena, he believed, but mental phenomena could be characterized only by normative rules. For example, Wundt utilized different methods of study for sensory motor events and cognitive mental events. To study the former, he employed the empiricistic concepts of association and contiguity of events. In studying the latter he relied on developments of Kant and his followers. As an example, he formalized and tested the concept of apperception to describe the focus of attention in which the observer selects and structures his conscious experience.

Given his belief in conscious experience, Wundt proposed to analyze this experience into its elements. In order to do this, he developed the method of introspection. In this method observers were trained to report the elements of their conscious experience. Carefully collecting and systematically analyzing their own and others' reports of mental processes, the introspectionists defined some of the most important areas of psychological investigation, such as attention and the analysis of consciousness. In his best known finding, Wundt claimed that conscious feeling could be described on values on three basic dimensions: pleasant-unpleasant, excitement-calm, and strain-relaxation. Titchener and his students also utilized Wundt's experimental methods but found slightly different results. They argued that there were only two basic dimensions to feeling since Wundt's excitement-calm and strain-relaxation dimensions measure the same psychological experience. Unfortunately, this disagreement grew into a controversy which could not be resolved by the introspective method itself. Accordingly, no advancement in knowledge could occur until psychologists agreed on a new method of analysis within Wundt's general paradigm or until a new paradigm was developed.

Introspective method

Although the introspective method sometimes proves valuable as an adjunct to the experimental method, it does not, by itself, lead to precise and quantitative knowledge. We have all been dissatisfied with someone else's subjective report of some psychological experience. Consider St. Theresa's description of a mystical experience known as the Ecstasy of St. Theresa.

> Beside me on the left hand appeared an angel in bodily form, such as I am not in the habit of seeing except very rarely. Though I often have visions of angels, I do not see them . . .

> He was not tall but short, and very beautiful. . . . In his hands I saw a great golden spear, and at the iron tip there appeared to be a point of fire. This he plunged into my heart several times so that it penetrated to my entrails. When he pulled it out, I felt that he took them with it, and left me utterly consumed by the great love of God. The pain was so severe that it made me utter several moans. The sweetness caused by this intense pain is so extreme that one cannot possibly wish it to cease (from Hibbard's *Bernini*, 1965).

Bernini, in his famous baroque sculpture inspired by this description (see Figure 1), represented the hallucinatory event in as real and concrete a depiction as possible.

To see the uses and limitations of introspection itself, consider the question: "In the house that you lived in two houses ago, was the front doorknob on the right side or the left side of the door?" How do you retrieve this memory? Most likely you will first fix on the house in which you live at present, go back one step to the house before that, and then to the house before that one. In other words, you trace back your history until you have arrived at the correct house, when you gradually recall details that build a picture of the front door. At some point it becomes clear on which side the door opened. In the final step, one person might be picturing himself coming home in the evening after a hard day's work; another might see himself leaving. One might remember the position of his own body as he went through the door; another might remember the door itself as it opened.

The introspective method can tell us a great deal about the psychological processes involved in answering this question. The task is a difficult one and involves a sequence of processing operations or stages between question and answer. Employing the experimental method to study this task would not be informative, due to the complexity of the task. The performance of this task, however, involves the performance of myriad smaller tasks, such as those involved in the perception of a message or in the retrieval of a single item in memory. Some of these processes do not lend themselves to introspection at all, but each of these processes can be studied and evaluated by the experimental methods articulated in this book.

Act psychology

Rather than accepting Wundt's definition of psychology, Franz Brentano argued against focusing the study of psychology on the *contents* of consciousness; instead, psychologists should be concerned with the *acts* of consciousness. In this sense, Brentano saw the importance of mental processes, or psychological functioning

FIGURE 1. Ecstasy of St. Theresa as represented by Bernini.

over time. Freud, a student in Brentano's psychology courses, developed the first systematic psychological theory that emphasized dynamic processes. The critical weakness in Brentano's contribution was that his theoretical development did not include a new method or paradigm for research. Thus, although Wundt em-

phasized the contents or structure of consciousness while Brentano attended to the acts or function of consciousness, both thought in terms of the introspective method.

Behaviorism

John B. Watson (1913), primed with the findings and methods of Pavlov and Thorndike in the study of animal behavior, rejected the methods of Wundt and Brentano. Watson proposed, instead, an entirely objective psychology in which public observable behavior was the focus of study. In his favor, Watson cited the current controversies that grew out of defining psychology as the study of consciousness and the use of the introspective method. He concluded that introspection was an invalid scientific method; hence, because he believed that mental processes were not discoverable in any other way, they were not a proper study for psychology at all. Only behavior, observable, measurable, and controllable, could be studied scientifically.

Watson correctly realized that advancement in any scientific discipline requires methods of study the results of which can be agreed upon by the scientific community. Since introspections were not directly observable, they were open to alternative interpretations, whereas all scientists would agree on some observable behavior, such as whether a rat turned left or right. In this respect, Watson was entirely correct and was following in the methodological development in the physical sciences. However, Watson went beyond arguing for observable behavior as the basic dependent variable, and denied that any theoretical references to consciousness or other mental processes could increase our understanding of behavior. Watson's argument reached its logical consequence with B. F. Skinner's (1950) proposal that psychologists should develop a stimulus-response psychology with no reference to any psychological processes between stimulus and response. Given this framework, proponents of the paradigm set about attempting to define functional stimulus-response relationships without reference to intervening psychological processes.

Watson's and Skinner's elimination of any reference to mental processes in psychological study is not a logical consequence of demanding observable dependent measures. Although two psychologists might agree on *when* a rat turned right or left, they might not agree on *why* the rat turned in a particular direction. In order to explain and to predict the direction of turning, it might be necessary to propose intervening processes which cannot be directly observed. To return to our physical example of motion, Aristotle and Galileo would agree on Aristotle's observation of the relationship between the distance that an object moves and the time taken

for the movement. However, Galileo proposed an unobservable intervening process—uniformly accelerated motion—that predicted the relationship and allowed him to predict results in other experimental situations. Although it may be argued that, with present techniques, a uniformly accelerated motion can be observed directly, it could not at the time of Galileo's proposal. In the physical sciences today, the idea of an unobservable process is not bothersome and is considered essential to theory and accurate prediction.

Gestalt Psychology

Another paradigm of psychology was Gestalt, developed by Max Wertheimer and his students (Koffka, 1935; Kohler, 1929). Wertheimer and his followers objected to the introspective methods of Wundt and Titchener and to Watson's behavioristic approach. Against Watson they maintained that immediate conscious experience was an essential subject for psychology. Against Wundt and Titchener they asserted that experience could not be reduced to the elements of sensation, that indeed the experience cannot be understood through analysis of any of its parts. To illustrate, let us consider the experience of hearing a symphony. The important thing about this act is clearly the mental processes involved. The behavior of the listener is insignificant in comparison and consists for the most part in abstaining from activity in order that something might happen inside his head. At the same time, an introspective analysis, which would have us attend to the quality, intensity, and duration of the experience, says really little more than behaviorism does about the experience of listening to a symphony although it might be an accurate list of its parts. The experience is somehow greater than the sum of its parts.

Gestalt psychologists assumed that the physical universe contains organized information and that we preserve this organization in our perception. Accordingly, the study of psychology should focus on the description of this organization. A series of dots arranged to form a circle appear as a circle, not as an unrelated series of dots. Psychology should develop methods and theories that delineate the rules of our perceptual organization. Although the Gestalt psychologists argued against both the introspective and behavioristic approaches, they shared with them some critical assumptions about the content and method of psychological study. In agreement with the introspectionists, they viewed consciousness as a structure rather than a process, even though they differed in their conceptualization of this structure. Accordingly, they mainly were concerned with rules that describe the structure rather than with processes. In many of their studies, they relied on phenomenological reports similar to the introspective reports util-

ized by Wundt and his followers. In a manner similar to the behaviorists, they refused to postulate intervening psychological processes to account for observed behavior. Rather, their primary assumption was that our nervous system was wired in a certain way to resonate to particular configural stimulus situations in the real world. Similarly, Gibson (1950, 1966) ignores intervening psychological processes given his assumption that perceptual systems respond directly to invariant aspects of the stimulus environment.

The theories of Donders, Fechner, Helmholtz, and Broadbent have also influenced the development of certain methods of psychological study. These theories and methods will be scrutinized in detail in subsequent chapters. We shall also contrast each of these theories to our present information-processing approach. The aim of this brief discussion has been to show how the method of study followed from, not preceded, the psychological theory. In this respect, the methods of experimental psychology can be articulated only in the framework of a psychological theory.

The central assumption of the development of theory and method in this book is that psychological phenomena are conceptualized as processes, not as stimulus-response relationships. In this case we are primarily interested in what psychological events do, even though we may be somewhat foggy about what they are. We address ourselves to the psychological processes that intervene between some stimulus and some response for two central reasons. First, explanation and prediction of stimulus-response relationships fail without prior understanding of the intervening sequence of mental processes. Second, we are interested in developing a psychological explanation of exactly those processes that lead to the response. Our inquiry into psychology is primarily directed at understanding the form of psychological behavior, not at merely predicting simple cause-effect relationships between stimulus and response.

The goal of this book is to illuminate the proper methods of psychological study. However, the illustration of these methods is completely interwoven with the study of the psychological processes themselves. As illustrated above and throughout this book, the methods of psychology cannot be discussed independently of the theory and content of psychology. Also, the knowledge of the proper methods of psychology is acquired by doing science rather than by learning a set of abstract rules for doing it. Accordingly, all of the appropriate experimental techniques are illustrated in the context of specific experiments and theories rather than in isolation.

EXPERIMENTAL METHOD

Throughout this book, the experimental method will be used to study the psychological processes that intervene between stimulus and response. Before beginning these experimental approaches, it is necessary to briefly discuss the experimental method itself. In this method the experimenter manipulates nature, in the form of his independent variable, and looks for the effect of the changes that he makes in the independent variable upon changes in a dependent variable. The dependent variable is the indicator of the psychological event of interest.

For example, an experimenter might be interested in finding out how many letters a subject can perceive in a single eye fixation as a function of the number of items in the visual display. Visual

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Dependent Variables

How does the experimenter find a good dependent variable? Most experimental psychologists agree that a dependent measure should be reliable, valid, and sensitive. Validity refers to how accurately the dependent variable measures the psychological process of interest. If a psychologist is interested in how well an observer detected (experienced) a stimulus, the proportion of times he said he detected it may not be a valid measure. In this case, the psychologist is interested in a psychological process (detection) and the subject's observed behavior may not be a true (valid) index of that process. The validity of dependent measures in psychological experimentation is one of the central themes of this book.

The second criterion, reliability, refers to the desire to have as little random variability in our measure as possible. For example, distance might be measured by counting the number of steps one takes between the two points or by utilizing a yardstick. The first measure would have more variability than the second and although both measures would increase our knowledge about the distance between the points, we use the least variable measure possible in the experiment.

The third criterion, sensitivity, is bound up with validity. Most experimental design books tell us to find a dependent measure which is sensitive to changes in our independent variable. Those that vary most with variations in the independent variable are preferred. However, here our interest is in a dependent variable that reflects the operation of a psychological process. So we look for variables that are sensitive to changes in the psychological process itself. Accordingly, in our approach we look for dependent variables that are (1) valid, reflecting accurately the operations of a psychological process, (2) reliable, fluctuating or changing very little for other reasons, and (3) sensitive, changing with changes in the psychological process they measure.

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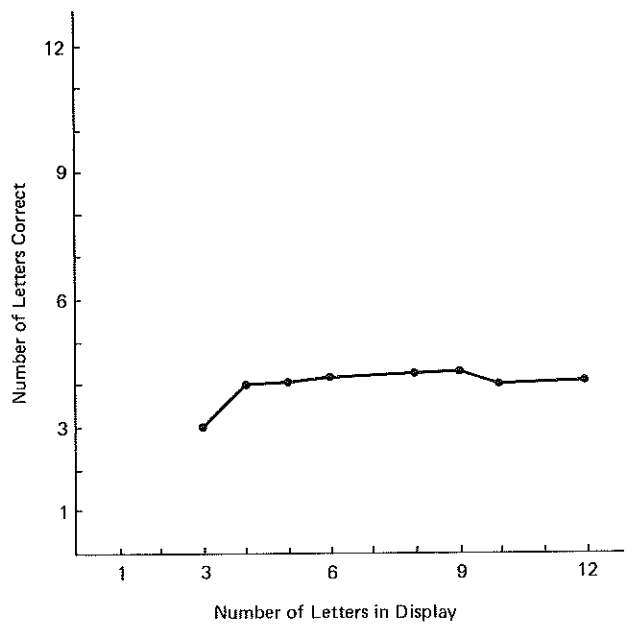
displays can be presented for a very short time, so that their duration does not exceed a single eye fixation. The experimenter presents the subject with a variety of trials containing anywhere from 1 to 9 letters per trial. On each type of trial, he records the number of letters correctly reported. From this data a functional relationship can be plotted between the number of letters reported and the number of letters in the display. The independent variable, that which is under the experimenter's control and manipulated by him, is the number of letters presented on each trial. The dependent variable is the number of letters reported correctly on each trial. Results of this experiment are plotted as a functional relationship in Figure 2. The number of correct letters is plotted on the Y ordinate as a function of the number of letters in the display plotted on the X abscissa.

FIGURE 2. The number of letters correctly reported as a function of the number of letters in the display (after Sperling, 1960).



Experimental Design and Control

In an experimental design, the experimenter seeks to establish a functional relationship between an independent variable and a dependent variable. In order to assure that this relationship is reliable, all other variables must be accounted for in the experimental task. If they are, the experimenter is safe in assuming that changes in the dependent variable were caused by changes in the independent variable. This is only the first step—but a critical one—in de-

fining the experimental task. The experimenter must also account for the sequence of mental processes or processing stages that the task requires before he can understand the functional relationship between stimulus and response. The central theme of this book is the presentation of experimental methods for understanding the processing stages between stimulus and response. Before discussing these methods, however, it is necessary to describe how to establish a proper experiment design for investigation.

Methods of control over experimental design are available to the experimenter. These controls are used to prevent other variables besides the independent variable from influencing or confounding the observed relationship between stimulus and response. A second variable is confounded with the independent variable if it is possible that changes in the second variable are partially responsible for the observed relationship between stimulus and response. Some methods of control are (1) eliminate the variables, (2) hold them constant, (3) counterbalance or randomize their effects in the experimental task.

The experimental question in the sample experiment presented above concerned how many items an observer could recognize in a single glance. This question was answered by varying the number of items in a display and recording the number that the observer recalled correctly. The answer to the question is seen in a functional relationship between the independent variable and the dependent variable. A number of other variables, however, could affect this relationship. These variables must be controlled so that the relationship will reflect the direct influence of the independent variable on the dependent variable.

Some of the variables that can influence the experimental results are (1) how long the observer looks at the display, (2) the nature of the test items, (3) the size of the test field, (4) the acuity of the subject, (5) the figure-ground contrast of the items in the display, (6) the amount of practice, and (7) the opportunity that the subject has for chance guessing. Controlling for these variables should provide the desired functional relationship between the independent and dependent variables, supplying an answer for the experimental question.

Our experimental question requires that subjects get only a single glance at the visual display for recognition. Therefore, the effective duration of display must be controlled to eliminate additional glances. Evidence that will be presented later shows that we cannot take discrete looks at the world faster than about five times per second. To give the subject only one look, then, it is necessary that the display be presented for a duration less than 200 msec. Presenting the display for 50 msec. at each experimental condition will

hold display duration constant and will also eliminate additional looks at the visual display.

The test items chosen must be items that can be recognized; in other words, they must be meaningful to the observer. The letters of the alphabet provide a good population of items for our experiment; since we operationally define test items as letters, it is necessary to prevent the subject from employing other test items in his recognition strategy. For example, if the letters in the display spell words, the subject could possibly treat the whole word as a single item. Accordingly, the experimenter would overestimate the number of items an observer could recognize, since the experimenter counts each letter as a test item. The experimenter can eliminate this possible confounding by making sure that the letters in the visual display do not spell words or wordlike items.

When the experimenter increases the number of items in the visual display it would be only natural to increase the overall size of the visual display. In this case, he has completely confounded the size of the visual display with the number of items in the visual display. This confounding creates a particular problem since the acuity of the observer decreases as letters are removed from the center of the visual display. It is necessary, therefore, to control for the visual display size as the number of items in the display presentation increases. One way to do this is to define a given display size, for example, a 4 x 4 matrix of cells. The subject is instructed to fixate at the center of the matrix. Now on each trial, the experimenter can choose the cells randomly for his item presentation. In this case, even single item displays would contain letter presentations that lie off the center of the display. This procedure randomizes the location of the items in the visual field to eliminate a confounding of display location with the independent variable (the number of items in the display).

Acuity of the subject is an important variable. We can hold this variable constant by testing the same subject under all the experimental conditions. If we tested different subjects under different experimental conditions, the results might differ simply because the subjects differed in acuity (or some other ability), not because of differences in our independent variable. Another solution to this problem would be to test a very large number of subjects at each of the levels of our independent variable in order to average out any differences in the different subjects. Although there are times when such a design is appropriate, we shall see that the best control for individual subject differences is to test each subject at all of the experimental conditions.

Figure-ground contrast (legibility) of the display is also an im-

portant variable that can affect performance. Performance would be positively correlated with the figure-ground contrast of the display. To control for this variable, the experimenter should print the display letters so as to optimize legibility and to maintain the same legibility at all levels of the independent variable.

The amount of practice an observer gets in this task will affect his performance. Observers show some rapid improvement over the first few trials in almost any experimental task. To eliminate this large practice effect, some general practice should be given before the experiment proper is carried out. Also, the experimenter must not confound the order of presentation during the experiment with the levels of the independent variable. The order of presentation in the experiment can be randomized. Assume that there are five levels of the independent variable in the experiment: test displays of 1, 3, 5, 7, and 9 items. The experimenter can, therefore, perform one replication of the experiment every five trials. Each of the five levels must be presented once within the five trials. To do this, the experimenter can have five cards, each of which represents one of the five experimental conditions. He mixes the cards randomly, in a hat, for example, and draws one card for the condition to be presented on each trial. Since he wants to present all five trial types once before he repeats a given trial type, he does not replace the cards into the hat until the hat is empty. This is called sampling without replacement. Sampling with replacement involves replacing the cards into the hat after each draw.

The opportunity that the subject has for chance guessing must also be controlled with changes in display sizes. If subjects were simply required to recall the letters that had been presented on a given trial, they would be more likely to guess correctly an item with large display sizes, since they would feel free to name more items at test. One control for this is to have the subject also indicate the location of the letter in the display. In this case, the subject would write the letters in the appropriate cells in a 4 x 4 response sheet on each trial. A reported letter would be scored as correct only if it were written in the appropriate cell.

As one learns more about this visual information-processing task, other variables in the situation become important. The present design provides a good first approximation to an experiment that answers the question asked. The findings of this particular experiment are discussed in the section on the span of apprehension (Chapter 12). The results are presented there because the number of items that can be recalled in this task defines the span of apprehension, which represents the number of items that subjects can process and hold together simultaneously in short-term memory.

Confounding Processes

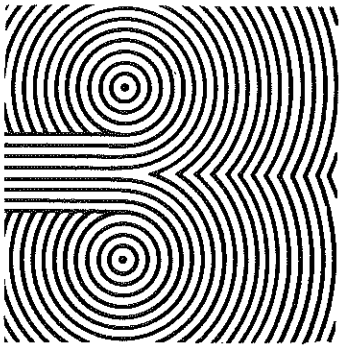
The experimental psychologist has traditionally been interested in the effects of one variable, called his independent variable, on the dependent variable. His goal, in this case, is to eliminate the influence of other irrelevant variables on his dependent measure. When the experiment has failed to adequately control for the effects of an irrelevant variable on his dependent variable, we say he has confounded their effects and his results are invalid. Confounding variables are easily spotted by the experimenter himself or his colleagues so that this is not a major problem in psychology.

The problem of experimental psychology examined in this book is the confounding of psychological processes in an experiment. This confounding invalidates the experiment in the same way as a confounding of variables. Consider the previous question of the effects of the size of the display on perception as measured by the number of items correctly reported from a visual display. We shall see in Chapter 12 that the memory process is a critical one in this task and its effects must be accounted for before any conclusions about perception can be reached. That is to say, increasing the number of items in the display not only affects the perceptual process, but also influences memory so that the results reflect some combination of both of these processes. The experimenter must design his study so that he can isolate the effects of each of these processes before conclusions about either process can be reached. If he fails to pull apart their effects, his dependent measure gives no information about the functioning of psychological processes in this task. Our goal is to discuss designs and analytic methods that can be used to study one psychological process without the confoundings of other processes. We shall find that the traditional experiment which manipulates only one independent variable is usually insufficient to accomplish this.

Scientific Investigation

What characterizes a good scientific investigation of a psychological problem? It is impossible to respond to this question with exactitude because there is no fixed set of rules or properties an experiment must meet. The easiest way to answer the question is in terms of what a psychological experiment does, rather than what it is. The central goal of a psychological experiment is to increase our knowledge about some psychological process. A given experiment may conform to all of the requirements of proper experimental design and control and yet fail to be a good experiment. If it does not increase our knowledge beyond the specific outcome of the experiment itself, it fails. Psychological investigation is an art and requires much more artistry than merely following an experimental psychology cookbook.

Consider an experiment in which an experimenter investigates whether schizophrenics differ from normals; or children from adults; or males from females; or students on the left side of the room from the students on the right. In all these cases, the experimenter will probably find a difference between the groups. But what have we actually learned from the study? Nothing, since it was already highly likely the two groups would differ before the experiment. What the scientist should learn is not simply how well a subject performs in a given experimental test; rather, the results should shed light on the psychological processes required by the test, the rules by which these processes operate, and, finally, the way in which one subject differs from another with respect to one or more of these processes. As can be seen in this example, scientific investigation cannot begin testing between different groups of subjects until something is known about the psychological processes involved. Research in social, clinical, or developmental psychology needs to be concerned with the psychological processes between stimulus and response in the same way that we are in this book.



The duration of mental processes

- Stages of mental processing
  - detection
  - recognition
  - response selection
- Reaction time
  - subtractive method
  - intensity of stimulus
  - simple vs. choice RT tasks
    - visual presentation
    - auditory presentation
  - A, B, and C tasks
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  - naming and button-pushing task

- Stages of information processing
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Would it not be possible to determine the time required for shaping a concept or expressing one's will? For years this question intrigued me.
—Franciscus C. Donders (1869)

An experimental psychologist studying human information processing is concerned with the psychological processes that intervene between stimulus and response. This chapter discusses a technique for studying these processes. The logic of the experimental approach tells us that in order to interpret response data properly, we must ask how many processes occur between a stimulus and a response in an experimental task. How do these processes work? What rules describe the operations of each process? How long does each operation last? What variables influence each of the mental processes?

For example, suppose a student is sitting in a classroom and a fire alarm goes off. The appropriate response would be to leave the room. The siren functions as the stimulus, and walking out of the room would usually be an appropriate response. The amount of time that elapses between the onset of the siren and the onset of walking out of the room is referred to as reaction time (RT) or latency.

STAGES OF MENTAL PROCESSING

Our interest lies in the processes that occur internally between the onset of the stimulus and the onset of the response. We can identify the probable stages of mental processing hypothetically by a logical analysis of the fire alarm scenario. First the observer must certainly become aware that some new stimulus has occurred. This reminds us of the British Empiricists' concept of sensation—the imprinting, as they thought of it, of the stimulus upon the sensory system. Sensation, or detection, is the process that initiates the flow of information through the human processing system. This takes an amount of time which we can call T_d.

Second, before he can act appropriately the observer must recognize the siren and identify it as a symbol indicating that a

Stages of Information Processing

The processes we have identified between stimulus and response in the fire alarm scenario can be clarified in terms of our information-processing analysis. Each process has some information available to it and transforms this information, making the transformed information available to the next processing stage. The information available to the detection process is the stimulus. The detection process transduces the physical signal into a neurological code. At this point in the processing chain, the observer has enough information to report that something has occurred. He cannot, however, say what it is.

The detection process makes available the neurological code to the recognition process. The recognition process must transform this preperceptual information into a perceptual form. There are actually two stages to the recognition of a fire alarm. First, the recognition process must resolve the sound quality so that it can be distinguished from other possible sounds, such as the bell that signals the end of the class period. Second, the observer must know that this particular sound means "fire alarm." For example, if he had never heard a fire alarm before, he may recognize the sound as one of a certain quality but it would have no meaning. In order to recognize its meaning, he must first perceive the sound of the alarm and, second, know that this sound signifies a fire alarm.

The recognition process, therefore, must translate the neurological code given by the detection process into a code that its meaningful to the response selection process. The knowledge that the fire alarm is ringing is the outcome of a successful recognition. This information or symbolic encoding of the sound of the fire alarm is meaningful to the response-selection process. The response-selection process, therefore, receives the information from the recognition stage that the fire alarm is ringing. The response-selection process could have received this information in other ways; a deaf person, for example, could see someone ringing the alarm. The response-selection process must answer the question: Given that there is a fire alarm, what response should be executed?

The response-selection process is similar to the decision process discussed in detail in Chapters 5, 6, and 7. It is influenced by the subject's knowledge of the likelihood that, given a fire alarm, a fire did indeed occur. For example, there may have been a number of false alarms recently, which could lead the response-selection process to wait rather than to execute a "leave the room" command to the response-execution process. Payoffs for different responses also are important for response selection. The situation might be one in which a person could be arrested and fined if he does not leave the building during a fire alarm. In this case, the response-selection process might be biased to leave the room even though a fire is unlikely.

fire, hence danger, may be in the building. The stimulus has now been given a meaning by making contact with some knowledge in memory. If this process does not take place, if the observer experiences the alarm simply as an extraneous event without meaning, then it provides no reason to leave the building. Recognition is similar to the concept of perception used by the British empiricists —the point at which mere sensation has acquired meaning. It also takes a certain amount of time which we will call T_r.

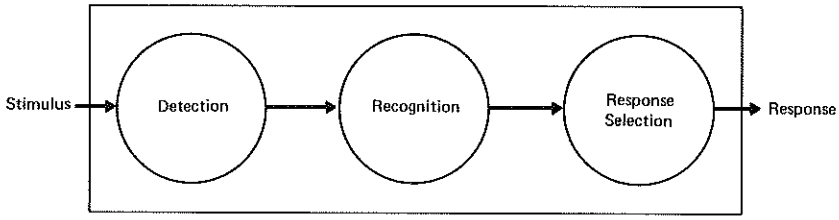
After the observer has recognized the stimulus, he must select a response. He might stand on his head, or jump out the window, or do one of any number of things; we may assume he will pick the response most appropriate to the situation. The choice may be more or less difficult. For instance, if the observer has experienced a number of false fire alarms in the same building and, moreover, is engaged in important work with a deadline to meet, he may hesitate to leave. In any case, selection of the appropriate response also takes some time, which we will abbreviate as $T_{r.s}$.

Finally, the response must be executed after it is selected. In our fire alarm scenario, however, we are not interested in response-execution time per se, but rather in the processing that led up to the execution of the response. Therefore, we measure reaction time from the onset of the stimulus to the onset of the response, so that response-execution time contributes very little to the overall reaction time.

Detection, Recognition, Response Selection

Detection, recognition, and response selection, then, can be identified as three mental processes that would be expected to occur between stimulus and response. We expect also that each of these processes consumes a certain amount of time and the duration of each of these three processes contributes to the total reaction time (RT) from the onset of the stimulus to the onset of the response. The average RT of leaving, given a fire alarm in a classroom, might lie between 2 and 10 seconds, with most of the time taken up by response selection. Detection and recognition of the meaning of the alarm would probably occur in less than 1/2 sec. These mental processes are referred to here as sequential stages in the overall process. Think of a stage as one step in the progression toward the final outcome. Figure 1 presents a flow diagram representation of these stages in the task. Thus, in this example, there are at least three stages between stimulus and response. Of course the observed RT will be longer than the sum of these three times since other events, such as nerve conduction time, will contribute to the overall RT.

FIGURE 1. Three psychological operations or stages of information processing that occur between stimulus and response.



REACTION TIME

The first experimenter to study mental life in terms of stages of processing between stimulus and response was F. C. Donders, a Dutch scientist best known for his work in ophthalmology. Donders described his work in psychology in a paper (1869) entitled "On the Speed of Mental Processes." In this article Donders recalled the pronouncement of physiologist Johannes Müller, twenty-five years before, that the time required for a stimulated nerve to carry its message to the brain and for the brain to activate the muscles was "infinitely short," and that therefore the velocity of nerve conduction could never be measured. Donders pointed out, however, that by 1850, Helmholtz, the famous German scientist, was doing exactly that. Helmholtz worked out a technique for measuring nerve condition velocity in frogs, and subsequently applied the same principles to a series of experiments with humans. The experiment measured the time between the presentation of a stimulus on the skin and an involuntary reflex to the stimulus. Helmholtz compared two conditions of RT. In one, the muscles of the ball of the thumb were stimulated at a point on the wrist (the subject's hand and arm were immobilized). Reaction time was measured between onset of this stimulus and the onset of muscle contraction reflex of the thumb. In the other condition, the same muscles were stimulated at a point just above the fold of the elbow. The RT required for muscle contraction to the stimulus at this point was also measured and was found to be more than in the first condition.

Subtractive Method

The logic of this experiment was founded on the belief that the two RTs should differ only with respect to how far the nerve impulses had to travel between the point of stimulation and the nerve-muscle junction. The basic task did not differ under the two conditions, and therefore the time for all other elements of processing between the stimulation and muscle reflex could be assumed to be

constant. Thus, all Helmholtz had to do in order to arrive at the nerve conduction velocity was to determine the extra time required for the longer distance and divide this time by the difference between the two distances. In this way, Helmholtz was able to estimate human nerve conduction velocity at 100 ft./sec. This result was surprisingly accurate, given the speed of nerve conduction time and the short distance between the two points.

Helmholtz also was able to employ this paradigm with voluntary responses. He stimulated the skin at either of two different distances from the brain. The subject was instructed to respond to the stimulus as rapidly as possible with a movement of the hand. The two conditions, therefore, only differed with respect to how far the nerve impulses had to travel to the brain. All other components of the task were assumed to be constant in the two conditions. Thus the difference in the reaction times provided an estimate of the difference in nerve conduction times for the two distances.

Donders was stimulated by another set of experiments also, those of the French astronomer Hirsch. Hirsch measured the RTs of simple detection responses (moving a hand) to stimuli presented to the eye, ear, and skin, respectively. Hirsch found that stimuli to the eye produced slower RTs than stimuli to the ear, which produced slower RTs than stimuli to the skin. Donders replicated these conditions and found that a reaction to a visual stimulus took 1/5 sec.; to an audio stimulus 1/6 sec.; and to a touch stimulus 1/7 sec. It should be noted that the RTs in these experiments would have been affected by the intensity of the stimuli used, although the investigator did not appear to be aware of this.

Intensity of Stimulus

Today a number of studies have shown that RTs to a stimulus decrease as the intensity of the stimulus increases. Thus, an observer instructed to press a lever as soon as he hears a tone will respond sooner, as the loudness of the tone is increased. Logically, this effect should probably influence the sensation stage, the process of becoming aware of the stimulus. This logical analysis is supported by physiological studies, which have actually shown that nerve conduction time across the synapses on the way to the brain is inversely related to stimulus intensity. Consequently, it appears that stimulus intensity affects the detection or sensation stage in a simple signal detection task. According to a sequential process model, stimulus intensity is unlikely to also affect response selection because response selection occurs after the stimulus is detected and should be relatively independent of stimulus variables (see Chapter 7).

Given Helmholtz's measure of nerve conduction velocity and Hirsch's and Donders' absolute RTs, Donders correctly reasoned that nerve conduction time could only account for a small portion of the total RT. What Donders wanted to know, however, was what process or processes took up the rest of the RT. Although Donders' indicated that there was at least 1/10 sec. consumed by mental processes, his analysis did not allow one to measure the time it took for each mental process.

Helmholtz's experiment had taken the activity of the nerves out of the realm of the unfathomable. Donders was inspired to hope that the same might be done for mental processes. "Would thought also not have the infinite speed usually associated with it?" he asked. Helmholtz's method gave Donders a clue, and in time he devised a method for studying the speed of mental activities, employing the Helmholtz principle of subtraction in his research.

Simple vs. Choice RT Tasks

Donders devised several experimental situations based on this principle. In one paradigm, an electrode was placed on each of the subject's feet and hooked up so that Donders could stimulate either foot as he wished. There were two conditions. In the first, Donders told the subject that he was going to stimulate the left (or the right) foot, and asked the subject to make a response as rapidly as possible with the hand on the same side. Thus, in this condition, the subject knew which foot would be stimulated and was prepared to respond with the correct hand. His task, therefore, was simply to detect that a stimulus occurred and give the predetermined response as fast as possible.

In the second condition, the subject was told that the stimulus might be given to either foot and was instructed to respond with his left hand if his left foot was stimulated, and with his right hand if his right foot was stimulated. Donders would stimulate one or the other foot randomly from trial to trial. In this situation the subject did not know in advance which foot would be stimulated and, therefore, which hand would be the correct one for his response. Thus, two additional operations in the mental processing that occurred between stimulus and response were required in the second task. The subject had to first identify which of his two feet were stimulated and then select the appropriate hand for the response. The first condition is referred to as a simple RT task; the second is called a choice RT task.

Consider at this point what your intuition would predict as the result of the experiment. This can be a helpful tool in analyzing both one's own experiments and those of others. In this case, one

would certainly predict that choice RT would be larger than simple RT. This was indeed true of the data Donders obtained. On the average, choice RT took longer than simple RT by 1/15 sec. (67 msec.).

Donders reasoned that since all other aspects of the experimental situation had been held constant in the two conditions, the additional time necessary for completion of the task in choice RT could only be explained by the presence of the two additional mental processes. He concluded, therefore, that 1/15 sec. or 67 msec. was "the time required for deciding which side had been stimulated and for establishing the action of the will on the right or left side." That is, by comparing two tasks, the second identical to the first except for the addition of a recognition and a response-selection stage, Donders could isolate out and identify the duration of these two stages as 67 msec. He found from this experiment that it requires 67 msec. for an observer to recognize one of two possible stimuli and to choose between two responses when only one response was possible. It also seems reasonable that a larger number of possible stimuli and responses to choose among would take even longer.

Donders' experimental design was such that the subject in the simple RT task, knowing which foot would be stimulated and all prepared to respond, could possibly respond before he actually detected the stimulus. We all jump the gun now and then. The measured RT would be affected, of course. It would no longer accurately reflect the duration of the mental events. Psychologists are careful to remain aware of the possibility that the subject might start to respond before information is sensed or perceived; such responses are called anticipation errors. How could a psychologist check for anticipation errors in the simple RT experiment?

Visual presentation

Donders repeated the same experimental design for the visual modality, using a red and a white light in place of the right-left feet. Again, the first condition required a predetermined response to one of the lights; the second required a choice between the right or left hand, depending on which of the two randomly varied stimuli was perceived. His results averaged over five subjects indicated that the extra time required for choice RT over simple RT was 154 msec. The difference between the simple and choice RT was over twice as long (154 vs. 67) when the stimulation was visual rather than tactile. Why would recognition and/or response selection be more difficult in the visual than in the tactile experiment?

In a third set of experiments, the nature of the response was changed. The stimuli now were two letters of the alphabet, and

the response required was to pronounce aloud the name of the letter presented on each trial, again (as always) as fast as possible. Thus if the subject saw an *E*, for example, his task was to say "*E*" as quickly as he could. Again RTs were observed under two conditions: in one, the subject knew which of the two alternative letters of the experiment would be presented on each trial and thus was ready with his response; in the other, one of the two letters was presented randomly from trial to trial and the subject was not told which letter, so that he could only choose between the two responses after the stimulus was presented and correctly recognized. The extra processing in the choice task required an average of 166 msec. longer than the simple RT task.

Auditory presentation

Donders' stage-process model implied that insertion of additional stages would increase reaction time for all the sensory modalities, and he therefore took care to demonstrate that the results of an experiment using one modality could also be replicated for another. Thus the above visual experiment was also done with auditory stimuli. Subjects were presented with vowel sounds and asked to respond as soon as possible by repeating the sound presented. For example, the two-alternative experiment was done using the vowel sounds /e/ and /i/. In the choice reaction condition either of two vowel sounds, /e/ and /i/, could be presented on a given trial, and the subject had to distinguish the sound and repeat back the vowel. This condition was compared with the simple reaction condition in which the subject knew in advance which vowel sound would be presented and repeated the sound as quickly as possible.

Insertion of the recognition and response-selection stages also added to reaction time with auditory presentations, but the amount of additional time was greater in the visual task (166 msec.) than in the auditory task (56 msec.). Either recognition, or response selection, or both, was easier in the auditory task with spoken vowel stimuli, than in the visual task with printed symbols. Donders believed that the differences in the two tasks must be due to the recognition stage rather than the response-selection stage since response selection is the same in the two tasks. To account for the results, Donders actually presented a detailed description of how the auditory identification of a vowel sound was not as complex as the visual identification of a vowel symbol.

Donders was aware that choice RT tasks differed from the simple detection task with respect to two processes: stimulus recognition and response selection. So he devised another series of experiments to isolate the contributions of each of these stages. To determine the time for the recognition stage, Donders set up two

experimental conditions. In the first condition, a subject would be required to push a button as rapidly as possible when he saw a light go on. In another condition, the light could be one of two colors, and the subject was instructed to respond only when one of the lights came on. In this case, the subject had to identify the color of the light after he had detected it in order to insure that he would only respond to the indicated light. Thus the second condition required a second stage, recognition, in addition to the detection stage required by both conditions. Donders considered that he had held the detection stage constant and that response selection did not occur in the two conditions. He believed that when only one response was required, the subject could select this response before the stimulus was presented. Therefore, any difference in RTs would represent the time required for the recognition stage inserted in the second condition.

To determine the time for response selection between two alternatives, Donders devised another experimental comparison. The subject would be required to recognize the stimulus in both conditions, but should have to select a response in only one. In the first condition, the subject could be presented with either of two signals but was required to respond to only one. In this case, the subject could conceivably select the response before the stimulus is presented. In the second condition, the subject is required to respond differentially to both stimuli; therefore, he could not select his response in advance. Hence, the second condition requires all the processing of the first, plus the time for response selection. It follows that the difference in RTs between the two conditions represents the time for response selection.

A, B, and C Tasks

In order to estimate the time for mental processes, Donders' classic comparisons involve three different experimental conditions, A, B, and C: the detection task, the detection-identification-response selection task, and the detection-identification task, respectively. In Condition A, the subject is told that a certain stimulus, let us say the letter X, will appear on every trial and he is instructed to pronounce the letter X as soon as he sees it. Once he has detected the presence of a stimulus, he can execute the appropriate response immediately. The stimulus does not have to be identified and a response does not have to be selected, since it has been chosen in advance.

In Condition B, the subject knows that the stimulus will be one of two letters, say X and O, and he must respond appropriately to both stimuli. Therefore, he must detect the presence of the stimulus, identify it as either one or the other, and select his response. Although the subject knows the stimulus must be one of two alter-

natives, it must be identified on every trial. Similarly, although he can narrow his response down in advance to the two alternatives, he cannot select a response until identification is complete. Therefore, in Condition B, the subject is required to identify the stimulus and select the appropriate response after the stimulus is recognized. In this case, detection, recognition, and response selection contribute to the RT.

In Condition C, either X or O can be presented on any trial, but the subject has been told to respond only when one of them, say X, is present. Therefore, he must detect the presence of the stimulus, identify it as either X or O, and if it is X, respond by pronouncing "X." Donders believed that the response-selection stage in this task was equivalent to the same stage in the simple detection task; that is, there is only one correct response, which the subject can prepare in advance and have ready whenever the stimulus is presented. Accordingly, response-selection time should not contribute to the overall RT in Condition C.

If Donders' analysis is correct, the time for the identification process should equal the difference in RT between conditions C and A. Similarly, the RT difference between conditions B and C estimates the time for response selection. Donders' original results employing these three conditions were very promising. The RTs were ordered as predicted by the stage analysis. In one study reported, with vowel sounds Donders found reaction times of 201, 284, and 237 msec. for Conditions A, B, and C, respectively. Using the subtractive method, he was able to estimate the time for recognition or identification as 237 minus 201, or 36 msec., and the time for response selection as 284 minus 237, or 47 msec. Of course, the time for detection cannot be estimated, since other events contribute to the reaction time in the task. That is to say, the RT in the simple RT task does not simply represent the time for detection.

Criticism of Donders' methods

Donders believed that he could insert a stage of processing in an experimental task and estimate its time using the subtractive method. For example, the difference in reaction time between Conditions B and C was assumed to represent the time for response selection. It is assumed that Condition B contains response selection, whereas Condition C does not. But we can look at Condition C in a slightly different manner; there are two stimuli, X and O, and there are two responses, "X" and silence. That is, after identifying the stimulus as either X or O, the subject must decide whether the appropriate response is now to say "X" or not to say anything. Indeed, there is a sense in which the subject can be said always to have to select a response; that is, he must always decide whether to respond or not, even in a simple detection task. Accordingly, we

cannot say that the response selection stage was present in Condition B and not present in Condition C. Condition C required the subject to select between responding and not responding, depending on the stimulus presented. In Condition B he was required to respond to both stimuli, but to select a response depending upon the stimulus presented.

It appears then, that rather than inserting or deleting a stage of processing in the task, the different conditions changed the nature of the response selection process. Donders' assumption that the experimenter could devise two experimental tasks which differed only with respect to an additional stage of processing is, therefore, untenable, and without this assumption his results cannot be used to estimate the duration of a processing stage. Indeed, it is difficult to see what meaning his results would have even if the method of insertion were a valid one. Even if we knew the duration of each stage, we would still be in the dark about how these mental processes operate. Donders' work, having proved at least that perception and cognition were not instantaneous, failed to open further doors and lent itself to criticisms that undermined what little it had seemed to achieve.

At the turn of the century, Külpe and his coworkers criticized the central assumption of Donders' subtractive method: the additivity of the times for mental events. They asserted that stages cannot be added in a task without affecting the time to complete other stages. Their central argument was that typical tasks compared in the subtractive method differ by more than one or two stages: rather, the overall quality or gestalt of the tasks differ. Accordingly, the subtractive method cannot indicate the duration of a particular stage of mental processing. Being introspectionists, they did not present any RT evidence supporting this criticism of the Donderian subtractive method. Rather, they relied on the introspective reports of the observers. After this criticism, investigators lost interest in Donders' insertion method as a tool for studying mental processes.

Sternberg's modification

Donders' stage model of mental life remained dormant along with his techniques until the 1960s, when it was revived by Saul Sternberg (1969a,b). Sternberg accepted as valid the conclusions of Donders' critics that one cannot insert one stage without affecting the operations of other stages, and that the new reaction time will confound the duration of the new stage with changes in the duration of the original stages. The method he devised avoided this problem while capitalizing on the possibilities in the stage notion. Sternberg's idea was to introduce changes in the experimental situation that affected the amount of processing or the number of

operations required within a single stage, rather than the number of stages present in the task.

For instance, using Sternberg's principle we might set up an identification experiment in which the subject was asked to push a button to a red light. In one condition, we would randomly mix red light presentations with blue light presentations. In the other condition we would randomize red light trials with pink light trials. Therefore, the task remains exactly the same in both conditions—respond only to red—but the colors are more similar to each other in the second condition than in the first. We can test whether this variable might affect the time needed to complete the recognition stage; it seems logical that the observer would find it harder to discriminate between very similar stimuli than between very dissimilar stimuli. The detection stage, however, in which the subject in either case notices that something is out there, should not be affected; nor would we expect the variable to affect the response-selection stage, which in both cases, given one of two identifications, requires deciding on one of two possible responses.

To test these expectations, the experimenter must choose other independent variables that would be expected to affect other processing stages of the task. He assumes that the color of the stimuli does not affect response-selection time, but he could vary an independent variable that is expected to influence this stage of processing. The experimenter might vary response compatibility in the task, since this is expected to influence response-selection time, but not recognition time. In our task, for example, we can also have the subject respond verbally with the word "red" when it is presented under the red-pink and red-blue conditions. Hence, we have four experimental conditions and measure the RT in each condition.

We expect significant differences in RT as a function of both of our independent variables. Reaction time should be larger in the red-pink condition than the red-blue conditions and button pushing might take longer than verbal reaction. More importantly, if the two variables affect two independent processes (stages) in the RT task, their effects on RT should be additive. That is to say, the effect of the red-pink variable would be the same under each response compatibility condition and, analogously, the effect of response compatibility should be the same under both color conditions.

Thus, if our results show that it takes 50 msec. longer to respond when the alternative stimuli are red and pink than when they are red and blue under both response compatibility conditions, we have evidence that indicates it is more difficult to distinguish red from pink than red from blue. We still do not know

the absolute identification times in either case. Rather, the 50 msec. is a measure of the increased difficulty of the recognition stage in the red-pink relative to the red-blue condition. By choosing other stimulus pairs according to increasing or decreasing color similarity, we should be able to determine the psychophysical similarity of the colors, using reaction times as our dependent measure.

Donders assumed that it was possible to introduce an entire stage without affecting the difficulty of the other stages. Sternberg assumes that one can introduce a variable that will selectively increase or decrease the difficulty and, thus, the time to complete a single stage without affecting the others. He has formalized a method to validate the assumption that a given variable selectively affects the processing of only one stage. This procedure, known as the additive-factor method, will be discussed in detail (see below).

With Sternberg's method we have indeed abandoned Donders' hope of obtaining the absolute time to complete mental stages of processing. Donders was searching for some sort of platonic ideal of each stage, even if it were only quantitative: he wanted to be able to state that recognition takes 100 msec., detection 50 msec., and so on. As the example just described demonstrates, however, recognition time fluctuates from one condition to another, making the platonic ideal of recognition time a meaningless concept. Rather, it is the fluctuation itself that will interest us, not only because it alone can be studied, but also because it is far more useful information than the absolute time required for identification in any particular task. Sternberg's paradigm, by allowing us to understand how variables affect the duration of mental processes, informs us about the nature of those processes themselves, an accomplishment which lay beyond the hope of Donders.

ADDITIVE-FACTOR METHOD

In Sternberg's formalized method of study, called the additive-factor method, each experimental task can be analyzed logically to determine the number of stages involved in the task. The experimenter then chooses an independent variable that is expected to affect the processing or operation of a particular stage. For example, the experimenter could choose two levels of stimulus discriminability (red-blue, red-pink) as a variable that affects recognition time. By pairing each level of this variable with levels of another variable that is expected to affect another stage, the experimenter can provide a test of his experimental assumption that the two variables affect different stages of processing. In our example, we

Factorial Designs

The design of the tone detection experiment is typical of experiments using the additive factor method. It is called a factorial design because each level of one independent variable is crossed with every level of the other independent variable. The two independent variables are stimulus intensity and response compatibility, with two levels of each variable, which gives $2 \times 2 = 4$ experimental conditions. It will become apparent that the additive-factor method could not be used if the experiment was not a factorial one.

In this experiment, as in most of the experiments in this book, the subject goes through all of the experimental conditions. Accordingly, the experimenter must present the different conditions in such a way that the condition is not confounded with the temporal order of presentation. One way to do this is to first practice the subject sufficiently under all experimental conditions, say, for example, one hour. Then the subject is required to participate for four additional days. The conditions could be presented in the following order. On each day, we present all four conditions so that each experimental condition is presented once at each of the 4 possible temporal orders. This counterbalances for any possible learning or fatigue effects that may be present on each day. For a second subject, the experimental conditions can be presented in an entirely different sequence, but with the same counterbalancing constraints, and so on for the different subjects. This counterbalancing technique, although completely straightforward, is an important one in this kind of psychological experimentation.

	Order			
	1st	2nd	3rd	4th
Day 2	a	b	c	d
Day 3	b	c	d	a
Day 4	c	d	a	b
Day 5	d	a	b	c

Each condition is preceded with a number of practice trials under that condition. For example, we might have 25 practice trials before each condition, followed by 100 experimental trials. Also, the experimenter should not tell the subject which are practice trials, since the subject might be likely to treat these trials differently. The subject should be precisely instructed in the task and reminded to keep a constant motivation throughout the study.

chose a second variable—response compatibility—that is believed to affect response selection time. If the two variables affect two independent stages in the RT task, their effects on RT should be additive. If not, their effects would most likely combine in a non-additive fashion, that is, they would interact.

The method of studying mental processes, in which the effects of two or more independent variables are evaluated, is an important one. We shall, therefore, analyze yet another task, in which the subject has to respond to a stimulus as soon as he detects it, using the additive-factor method. In this task there are two stages; first, the subject must detect the stimulus, which will take up a certain amount of time. Then he must select his response; he must remember which of the innumerable actions possible to him at the moment is the correct one, given the information put out by the detection stage. This selection also takes some finite time; the two times should contribute to the total RT of the task.

Now we choose two independent variables to study in this task, asking whether each one affects only one or both stages. Stimulus loudness, it would seem, is a variable that should affect only the detection stage. The more intense the stimulus, the easier it is to detect; we shall be surprised, on the other hand, if the more intense stimulus results in a shorter response selection time. We might choose response compatibility as the second variable, requiring subjects to use their dominant hand in one condition and their nondominant hand in the other, pushing a button with the index finger in each case. People are able to respond much more rapidly with their dominant hand than with their nondominant hand, and thus we can expect RT to be longer in the nondominant than in the dominant case. Response compatibility should affect the response selection stage, but again, we will be surprised if it affects the detection stage. Logically, it should not be easier to detect a signal simply because the appropriate response is easier to make.

The experiment will thus have four separate conditions:

1. A tone of the intensity of a whisper; subject required to respond with his dominant hand.
2. A louder tone, of normal speaking intensity; subject required to respond with his dominant hand.
3. The soft tone of condition 1; subject required to respond with his nondominant hand.
4. The loud tone of condition 2; subject required to respond with his nondominant hand.

This experiment can be represented by a 2 x 2 matrix, shown in Figure 2.

FIGURE 2. An experiment that covaries two levels of two independent variables: stimulus intensity and response compatibility. The numbers refer to the experimental conditions described in the text; t_i, where $i = 1,2,3$, or 4, represents the RT for each condition.

		Response Compatibility: dominant hand	Response Compatibility: nondominant hand
Stimulus Intensity	soft	(1) t_1	(3) t_3
	loud	(2) t_2	(4) t_4

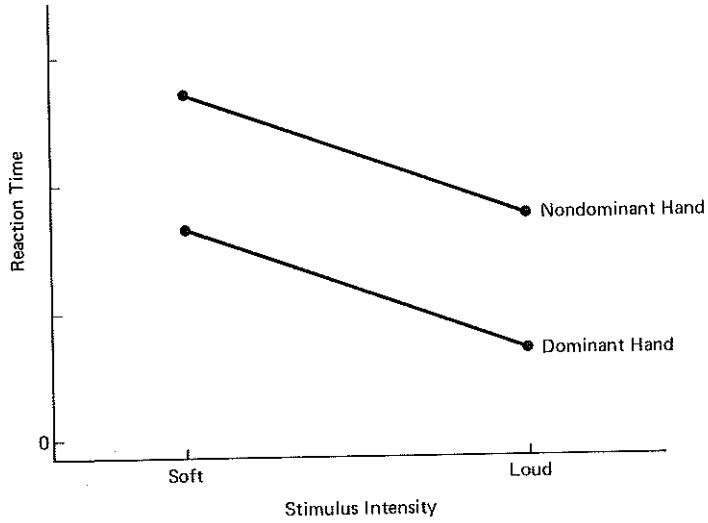
The experimenter runs many trials under each experimental condition and records the reaction time. The dependent variable in the experiment would be the mean RT under each experimental condition. This RT is assumed to be the sum of the duration of the two stages plus the time taken up by other internal events. It should be stressed that the time taken for the other internal events, called t_o, is assumed to be the same at each condition. If one variable only affects one stage, and the second affects the other stage, then the effects of two independent variables, each of which affects the duration of only one stage, should be additive. That is, there is a time required for detection of a soft tone and another time required for detection of a loud tone; there is a time for selecting a response with the dominant hand and a different time for selecting a response with the nondominant hand. In Condition (1) the total reaction time should include the time it takes to detect a soft tone, plus the time to respond with the dominant hand. In Condition (2) reaction time includes the time for detection of a loud tone, plus the time for selecting a response with the dominant hand. Reaction time in Conditions (3) and (4) will contain the time required for detection of the soft and the loud tones, respectively, plus the time needed to respond with the nondominant hand.

If the additive factor holds, that is, if the independent variables affect different stages, the sum of the RTs of Conditions (2) and (3) will be equal to the sum of the RTs of Conditions (1) and (4). The contribution of t_o can be ignored, since it is assumed to be constant under all experimental conditions.

$$t_2 + t_3 = t_1 + t_4 \tag{1}$$

If the assumptions are correct, the RTs will take on a definite form. If we plot RT as a function of stimulus intensity and response compatibility, the two curves will be parallel as seen in Figure 3.

FIGURE 3. Predicted RTs if stimulus intensity and response compatibility only affect the detection and response-selection stages, respectively.



Assume, however, that stimulus intensity affects not only the time it takes to detect the stimulus, but also the time it takes to select a response. In this case, the two curves probably would not be parallel because a decrease in stimulus intensity will change both detection time and response-selection time. Since response compatibility affects response-selection time, both of our variables affect response-selection time, and it is unlikely that their effects would be additive since they are in some sense compounded.

As an example of this case, assume that response-selection time takes 100 and 150 msec., respectively, for the dominant and nondominant responses with a loud tone. If the loudness of the tone also affects response-selection time, we can expect that it might have a larger effect with the nondominant than with the dominant hand. Therefore, the soft tone may slow down the dominant response by only 50 msec. and the nondominant response by 100 msec. Accordingly, the results would not be additive but would interact, since response selection time would have the following times under the four experimental conditions.

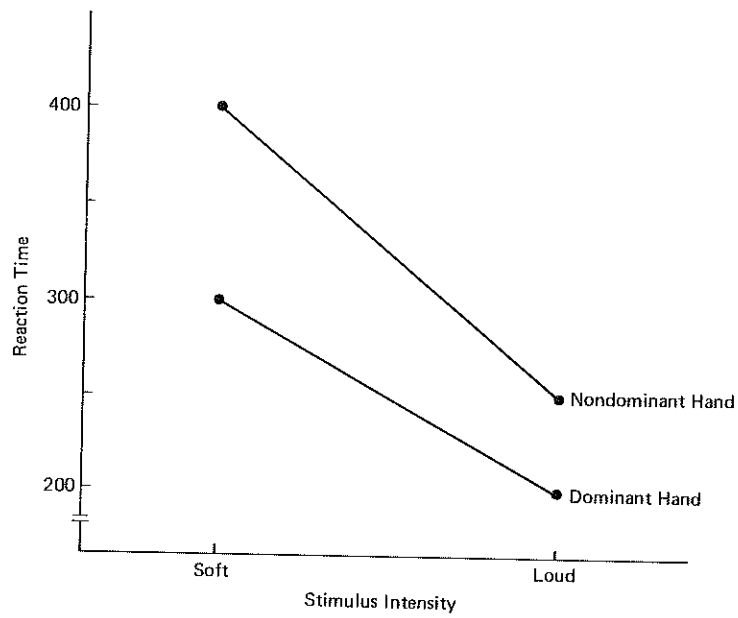
		Response Compatibility	
		Dominant	*Nondominant*
Intensity	Loud	100	150
	Soft	150	250

Now if loudness affected detection so that detection time was 100 and 150 msec., respectively, for the loud and soft tones, the sum of the times of the two processes would be

		Response Compatibility	
		Dominant	*Nondominant*
Intensity	Loud	200	250
	Soft	300	400

Therefore, if t_o were constant these conditions would give results that were not additive, but interacted. Plotting these results gives the curves shown in Figure 4.

FIGURE 4. Predicted RTs if an increase in stimulus intensity shortens both detection and response-selection stages of processing.



The concept of two variables affecting the same stage of processing and leading to an interaction is a difficult one and deserves another example. Although the additive-factor method was developed for RTs, the concept of interaction is easily seen in an example using 'percentage correct' as a dependent measure.

Consider two variables that affect legibility of printed text: lighting and letter size. First, make the task 20 percent more difficult by decreasing the lighting from an optimal level until the reader is performing 20 percent poorer. Now return to the optimal

lighting and decrease the letter size until the reader again performs 20 percent poorer. Then combine the lower levels of lighting and letter size found in the previous two conditions and measure performance. Since both lighting and letter size affect legibility, the task should be much more difficult than the 40 percent below optimal performance predicted by additivity of the two effects of our variables. The foregoing example supports the notion that if decreases in stimulus intensity slow down both detection time and response-selection time, the curves will appear as in Figure 4. Therefore, if the results show diverging curves, one possibility is that the two independent variables interact. That is to say, at least one variable in the task affects two stages of processing.

SUBTRACTIVE METHOD AND ADDITIVE-FACTOR METHOD COMPARED

To see how the additive-factor method improves on Donders' method of subtraction, let us consider an experiment by Donders and discuss its limitations. Then we can continue his study in the framework of the logic of the additive-factor method. Recall Donders' comparison of simple and choice RT tasks in naming visually presented letters. Donders found that the choice RT experiment took an average of 166 msec. longer than the simple RT task.

To this experiment, Donders added one more condition, testing the effect of enlarging the number of alternative responses in the choice reaction time task. The subject was instructed as before to pronounce the name of the letter as rapidly as possible on each trial. This time, however, there were five possible test letters instead of only two. Donders expected that this task would be harder than the two-choice RT tasks and, therefore, would require more time for identification and response selection.

Donders saw that the difference between the two- and five-choice RT experiments measured the processing time difference for at least two stages, identification and response selection. If Donders found that the five-choice reaction time experiment gave longer RTs than the two-choice experiment, he would not know whether the increased time was required because the subject must prepare himself for five possible responses instead of two, or because identification among five alternatives requires finer discrimination and therefore more time than between two. Where the response was to be one of a number of known alternatives, a subject could prepare these responses in advance and select among them when the time came. Obviously, it would be easier to select between two than among five. The subject could use an analogous strategy for identification as well. In the two-alternative case, he might say to himself on any trial that the stimulus out there has to be either X or O, and identify it by means of a single distinguishing

characteristic or feature. In this case, a curved or straight line would be sufficient to discriminate between the two letters. To use the same strategy among five alternatives, the subject would have to consider a larger number of distinguishing features, for example, if the alternatives Y, Q, and M were added.

Naming and Button-pushing Task

What Donders didn't realize, however, was that manipulation of this independent variable—number of alternatives—could be covaried with a second independent variable to isolate the contributions of stimulus recognition and response selection. As was mentioned above, increasing the number of alternatives could conceivably affect stimulus recognition and/or response selection. However, logically, we should be able to find independent variables that affect only one of these stages. For example, Donders required his subject to respond by naming the letter symbol on each trial. Response selection in this case would involve determining the appropriate response and executing the necessary articulatory commands to name the stimulus. As a second condition, Donders could also have required his subjects to push a button for their response. In this case, the number of different button responses would increase with increases in the number of alternatives.

This manipulation of the nature of the response should affect response-selection time. Button pushing would probably take longer than naming, since naming a letter symbol is an overlearned response, whereas button pushing is not. The subject in the choice RT task would find it much more difficult to keep track of the appropriate stimulus-button pairings than the stimulus-name pairings. Moreover, the difficulty of the response-selection task would increase much more rapidly with increases in the number of alternatives in the button-pushing task relative to the naming task.

Whether the subject names or pushes the appropriate button to give a letter alternative, however, should not affect stimulus recognition time. The stage model of the task is a sequential one. Stimulus recognition occurs before response selection and its duration cannot be affected by the duration of mental events that follow it. Therefore, it is logical to assume that the type of response should not affect stimulus identification time. In the fire alarm example, the time to identify the warning siren was independent of the difficulty of selecting the appropriate response.

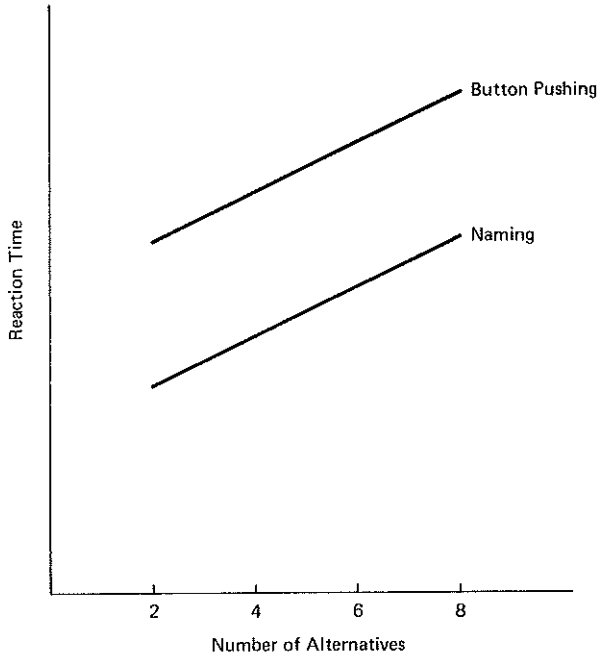
Our experiment would accordingly manipulate the number of alternatives and the nature of the response in a reaction time task. For example, we could choose 2-, 4-, or 8-letter alternatives and have the subject name or push the appropriate button to each

stimulus. Reaction time would be measured from the onset of the stimulus to the onset of the response. This design gives six experimental conditions. Each subject would go through all conditions. The order of the conditions across different subjects could be counterbalanced to control for order effects in the task. In each of the six sessions, the subject would be told the stimulus alternatives and the appropriate response to each alternative. Some practice should be given at each experimental condition before the experimenter records the results.

The results of the experiment could be presented graphically, plotting mean RT on the Y ordinate as a function of the number of alternatives on the X abscissa. Two curves would be plotted; one for each response condition. Some hypothetical results of the experiment are presented in Figures 5 and 6.

Recall that the experimental question was whether the increase in RT with increases in the number of alternatives was due to stimulus identification time, response selection time, or both. If this increase was due only to stimulus identification time, the increase should be independent of the nature of the response. If the increase was due only to response selection time, the increase should be directly related to the difficulty of the response. The

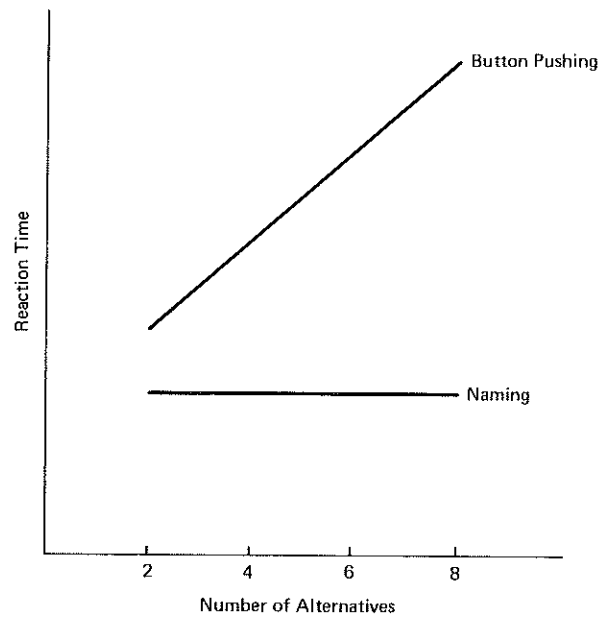
FIGURE 5. Hypothetical results of an experiment in which increasing the number of alternatives affects only the stimulus recognition stage.



hypothetical results in Figure 5 show that the increase in RT with increases in the number of alternatives was the same for the naming and button-pushing tasks. These results would indicate that increasing the number of alternatives increases stimulus-identification time and does not appear to influence response-selection time. Button pushing is more difficult than naming, but this difficulty does not interact (change) with changes in the number of alternatives.

Figure 6 plots another set of hypothetical results where the increase in RT with increases in the number of alternatives is flat between 2 and 8 alternatives in the naming case, but increases sharply in the button-pushing task. What mental process accounts for the increase in RT with increases in the number of alternatives? The results in Figure 6 indicate that response-selection time can account for all of the increase in RT from 2 to 8 alternatives. This follows from the fact that the naming function between 2 and 8 alternatives is flat. If the response is an overlearned one, increasing the number of alternatives does not increase overall RT. Requiring a button-pushing task instead of naming should not change stimulus-identification time since the button-pushing condition simply changes the response selection process, not the identification process. Accordingly, the increase in RT with increases in the

FIGURE 6. Hypothetical results in which response-selection time accounts for the increase in RT with increases in the number of alternatives in the button-pushing condition.

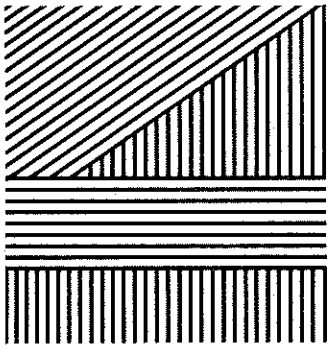


number of alternatives in the button-pushing task cannot be accounted for by stimulus-identification time, but is due to response selection time. When this experiment is carried out, the results actually correspond to those shown in Figure 6 (Theios, 1973).

The simple RT condition was not included in this experiment since this condition changes the overall nature of the task by eliminating the identification stage. Accordingly, we would expect RT to increase in both the naming and button-pushing tasks from a simple to a two-choice situation. If the subject is faced with two or more alternatives, stimulus identification is necessary for the response to be given. In the simple RT task, stimulus detection is sufficient for response selection to begin. We can see that the overall nature or quality of the task changed in going from the choice to the simple task. Therefore, RT will be shorter in the simple than in the two-choice task for both the naming and the button-pushing conditions. This result indicates that stimulus-identification time must be different in the two cases. However, response-selection time also differs since the subject can prepare his response exactly in one task but not in the other. Therefore, the comparison between the one- and two-alternative conditions does not illuminate the operations of stimulus identification and response selection processes.

The experimental conditions from 2 to 8 alternatives are illuminating in our modification of Donders' experiment. If the alternatives are overlearned stimuli such as letters, it appears that stimulus-identification time is independent of the number of alternatives larger than two. Response-selection time is also independent of the number of alternatives larger than two if the responses are highly compatible and overlearned, as in the naming condition. If, however, the responses are not compatible and overlearned, response-selection time is a direct function of the number of alternatives in the experimental task.

In summary, covarying two independent variables using the additive-factor method can illuminate the nature of psychological processing. In this paradigm, the experimenter does not attempt to insert a stage of processing but simply to influence the amount of processing at a given stage. In the choice RT task with two or more alternatives, a stage of processing was not inserted when the number of alternatives was increased. Rather, the experiment tested whether the operations of each stage, as reflected in the time to complete each stage, differed with changes in the independent variables. This experiment, therefore, makes transparent some of the operations of the recognition and response-selection processes, whereas the Donders method of insertion does not.



Operations of mental processes

Memory search
- stages of processing
- serial search: self-terminating
- serial search: exhaustive
- content-addressable search
- memory set size
- quality of test stimulus

Visual scanning
- differences between Sternberg and Neisser tasks
  - specific practice

Models
Analysis of variance

We may be able in the future to use "brain waves" as indicators of the beginning and end of a mental process; but in general it has seemed necessary to let the timed process start with a sensory stimulus and terminate in a muscular response.
—Robert S. Woodworth (1938)

This chapter discusses the techniques of decomposing RTs to study the operations of mental processes. One psychological process that can be studied very easily using RTs is memory search. To answer the question, where would you like to eat dinner? involves some form of memory search. We search in memory for restaurants we know about and test their qualities against our current appetite, budget, and whatever other considerations we deem important. The main concern of this chapter will be to see how the time it takes to search memory illuminates the nature of the memory search process.

MEMORY SEARCH

Sternberg (1966, 1967) used the additive-factor method to design a series of experiments for studying memory search processes. The experimental task is slightly more involved than the tasks Donders employed. The subject is told that the experimenter is going to present a target list of digits of a certain size, say 4 digits. He will then present some sort of warning signal—a buzz perhaps—and finally one more digit, the test digit. The task of the observer is to respond "yes" by pushing one lever if the test digit was one of the digits in the preceding list, and to respond "no" by pushing another lever if it was not. Thus the subject might hear 9, 2, 6, 7, buzz, 6. The correct response would be "yes," since the test digit was equal to one of the memory list digits. Had the test digit been "3," the correct response would be "no."

Given this paradigm, Sternberg could vary the difficulty of the search task by varying the number of digits in the memory list. Thus the independent variable in this task is the number of digits in the list; the dependent variable is the reaction time measured

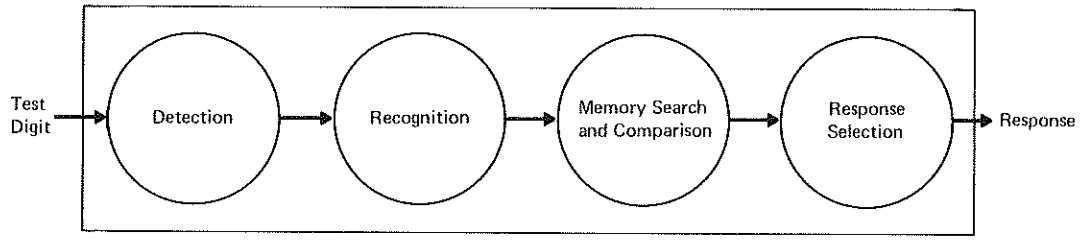
from the onset of the test digit to the onset of the subject's response, pushing the appropriate lever. All other factors can be held constant, such as the rate at which the digits are presented (usually at 1 test digit/sec.).

Stages of Processing

What stages of psychological processing does this task involve? First, it is clear that a good deal of processing goes on both before and after the test digit presentation. To respond correctly, the subject must first learn and remember the target list of digits. This requires accurate recognition and memory of the target set. Recognition and storage of each target item may take from 250 to 500 msec. In the typical memory task in which the items are presented at 1/sec., we can assume that the processing is complete before the test item is presented. Therefore, the time it takes to perform this processing does not affect the RT to the test item.

Processing and responding appropriately to the test item determines RT in this task. First, the subject must detect and recognize the test item. To determine whether the test item was a member of the target set, the subject must perform some sort of search and comparison of the test item with the target items in memory. The outcome of the search and comparison provides the necessary information for the response-selection process. We can discern, then, detection, recognition, memory search and comparison, and response selection as the processing stages in this task. Figure 1 presents a flow diagram of these stages of information processing in the memory search task.

FIGURE 1. A flow diagram of the intervening stages of information processing between presentation of the test digit and execution of the appropriate response.



Which of these stages will be affected by the independent variable—changes in the number of items in the target list? The detection stage clearly would not be, nor should recognition of the test digit be affected by the number of preceding target items. Undoubtedly, however, a change in the number of items in the target

set is going to affect the difficulty of the memory search and comparison. Once the search is performed, on the other hand, and the observer knows whether or not the test item was present in the target set, the nature of the response selection task should still be the same: given that the item was or was not present in the list, is the appropriate response pushing the left or right lever?

Analysis of the task, then, allows us to test the assumption that changes in the independent variable (number of items in the target list) affects only the memory search and comparison stage. If this assumption is correct, if RTs change as set size is increased or decreased, it can tell us a good deal about the nature of the memory search process. For instance, we can hypothesize a search algorithm, a sequence of operations that might be used to perform the memory task and determine the expected changes in RT as a function of increase in memory set size. Two very different algorithms, or strategies, will be analyzed for their prediction of how RT will change as a function of change in the independent variable. The experiment, then, can provide a test of these two hypotheses. If the actual results match the function predicted by one of them, the results will support the assumptions about the processing stages in the task, and provide evidence that a particular algorithm was used. If, however, the results match neither prediction, the results imply that either the assumptions about the processing stages were incorrect or that a different search algorithm was used.

One source of hypotheses concerning the strategies of human subjects is provided by the general purpose digital computer. Computers are characterized by three distinct structures: The most critical is the central processing unit, which is the workhorse of the machine. The second is the computer's memory, which holds both

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Models

In studying memory search and comparison operations, we use the computer program as a model of the psychological processing of humans. Models are useful in scientific study because they provide a description of a process that helps make it understandable. When we ask how a human does something, any answer is essentially in the form of an analogy; he acts as if he were doing the following. Models not only make psychological processes understandable, but they also are useful as a guide or heuristic to further research and theorizing. The model that the scientist uses is his reality; he sees the psychological process in this form. Other models are not as understandable or as meaningful to him in his search.

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the computer programs and any necessary data information. The third structure contains the communication links to the computer user. The central processor can communicate with both the memory and the communication links referred to as input/output devices. The memory bank contains a set of locations each of which has a specified address and contents. The central processor can read the commands or data coming over an input device and can also execute instructions to present information over output devices. A teletype similar to an electric typewriter usually functions as both an input and output device for computers.

Computers can be programmed to perform Sternberg's task and, of course, these programs are known in full detail. There are two basic search algorithms that can be employed using a digital computer. The search algorithm is in the form of a computer program which lists a sequence of operations. Each operation takes a certain amount of time so that the RT of the computer can also be used as an index of a particular search strategy. If we perform the task analogous to a particular computer program, the number of operations the program executes is taken as a relative index of the time it takes us to perform the task. Therefore, we can analyze each program and compare the predicted results with the results obtained from humans.

Serial Search: Self-terminating

The programs specify how the central processor of the computer stores the target list in memory and how this list is searched, given the test item. The first strategy considered is a serial search. Initially, the central processor assigns a location in memory, the address TARGET LIST. The first item in the target list is recognized and is stored in the contents of TARGET LIST. When the second item is recognized, it is stored in the next adjacent location, called TARGET LIST + 1. The third digit goes into TARGET LIST + 2 and so on, until each item in the list is entered into memory in serial order. The computer has to be informed that it has come to the end of the list, so the programmer instructs it to enter some code such as "end" in the next location when the buzz is presented. Table 1 presents an outline of the computer program which stores the target items in serial order.

Now the central processor is ready for the test item, which comes in, is recognized, and is stored in location TEST. The central processor takes TEST and compares its contents to the contents of TARGET LIST, then TARGET LIST + 1, and so on in serial order. At each comparison the program asks first whether the contents of the target location are equal to "end"; if so, the search is terminated and the program moves on to the next stage of processing. If the

contents do not contain "end," the central processor compares it to the contents of TEST. If the TEST and TARGET LIST + x are equal, the central processor places a "yes" in the contents of ANSWER. At this point the program instructs the central processor to terminate the search. The program then determines the contents of ANSWER and selects the appropriate response. Table 1 presents the program for this algorithm, which is referred to as a serial self-terminating search. The search is self-terminating because no further comparisons are made once a match has been found.

TABLE 1

Outline of a computer program specifying the processing of the target list and the test item for a serial self-terminating search of the target items in memory. (Each instruction or step in the program is executed before going to the next instruction.)

Processing the target list

1. make the variable x equal to zero
2. wait for input; when input detected, go to step 3
3. recognize input; if not target digit or buzz, go back to step 2
4. if input is buzz, go to step 8
5. if input is digit, store it at location TARGET LIST + x
6. increment the variable x by 1
7. go to step 2
8. store the symbol "end" at location TARGET LIST + x
9. make the variable x equal to zero

Processing the test digit——serial self-terminating search

10. wait for input; when input detected, go to step 11
11. recognize input; if not test digit, go back to step 10
12. store test digit at location TEST
13. determine contents of TARGET LIST + x
14. if it is the symbol "end," go to step 20
15. if it is equal to the test digit, go to step 18
16. increment the variable x by 1
17. go to step 13
18. store the symbol "yes" at location ANSWER
19. go to step 21
20. store the symbol "no" at location ANSWER
21. determine the contents of ANSWER
22. type this symbol
23. stop

Serial Search: Exhaustive

By contrast, in a serial-exhaustive search (shown in Table 2), the central processor proceeds to the next comparison and does not output the contents of ANSWER until the list has been exhausted and it has reached "end."

TABLE 2
Outline of a computer program performing a serial-exhaustive search of the target items in memory. (Program for processing the target list before the test item presentation is the same as that given for the serial self-terminating search in Table 1.)

Processing the test digit——serial-exhaustive search

10. store the symbol "no" at location ANSWER
11. wait for input; when input detected, go to step 12
12. recognize input; if not test digit, go back to step 11
13. store test digit at location TEST
14. determine contents of TARGET LIST + x
15. if it is the symbol "end," go to step 21
16. if it is equal to the test digit, go to step 19
17. increment the variable x by 1
18. go to step 14
19. store the symbol "yes" at location ANSWER
20. go to step 17
21. determine the contents of ANSWER
22. type this symbol
23. stop

In a self-terminating search, the number of items actually searched varies, ranging from all items on "no" trials and on trials in which the last digit in the list is equal to the test digit, through one item only on trials in which the first item is equal to the test digit. On the average, the central processor would have to search $\frac{N+1}{2}$ items on "yes" trials, where N is the number of items in the target list. In a serial-exhaustive search, it exhausts the list on "yes" and "no" trials alike.

To demonstrate whether either of these algorithms describes the performance of human subjects in Sternberg's task, we must analyze each one for its predictions regarding changes in reaction times as a function of changes in memory set size. Begin with the processing of the test digit since the RT is measured from its onset. First, the computer program has instructions corresponding to the detection and recognition of the test digit and the response-selection stage. We can see that these instructions and the number of times they are executed do not vary with changes in the size of the target list. The memory search and comparison stage, however, is affected by target list size: the more items to be searched, the larger the number of instructions to be executed and the longer the search should take. Looking only at "no" trials, which would be the same whether the search was exhaustive or self-terminating, the number of instructions to search each target location is the

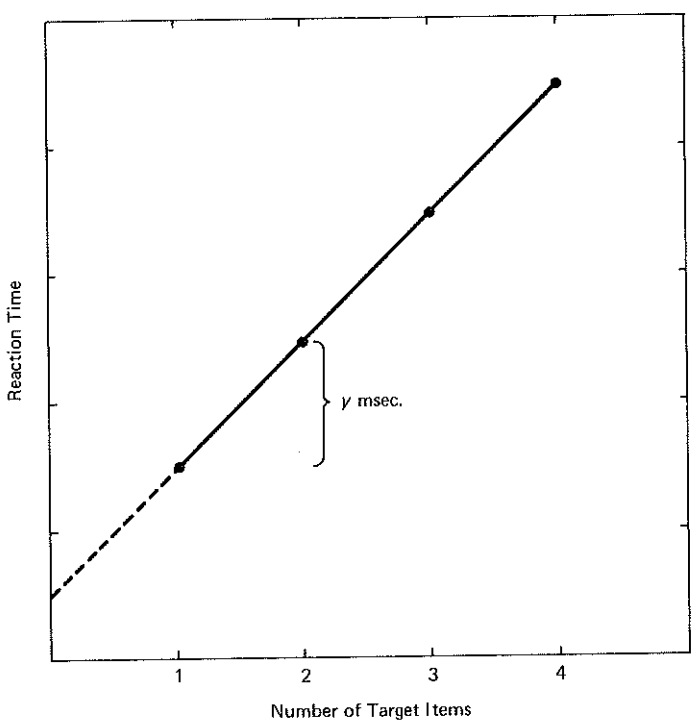
same; therefore, the time required to search each item is equal. Each additional item in the target set will add a constant increment to the reaction time. Thus, if detection plus recognition time equals x, memory search and comparison per item equals y, and response-selection time equals z, then the total RT to say "no" will be equal to

$$RT = x + yN + z + o \tag{1}$$

where N is the number of items in the target set, and o is equal to the time for other events necessary in the memory search tasks.

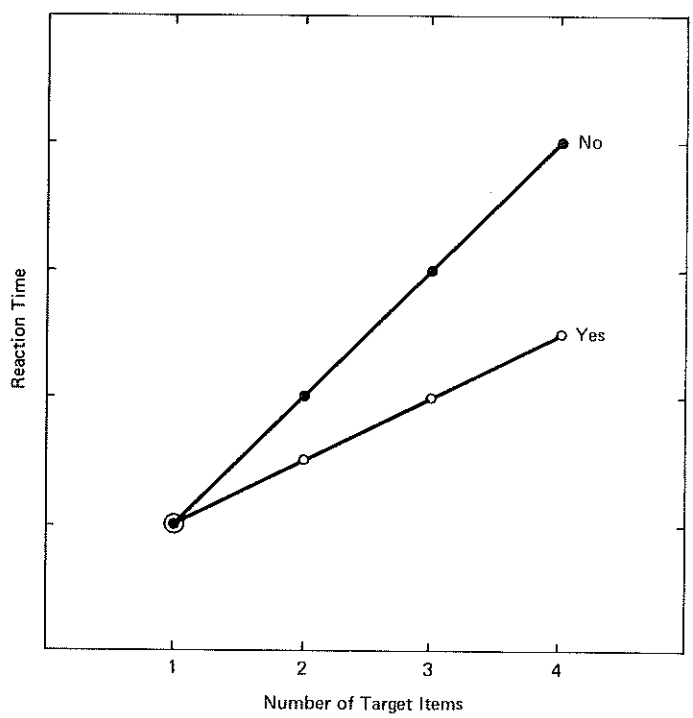
Figure 2 plots "no" RT as a function of target set size according to Equation 1. With one item in the target set, $RT = x + y + z + o$. With two items in the target set, $N = 2$, $RT = x + 2y + z + o$. The results, when plotted, give a linear function, intercepting the Y ordinate at $x + z + o$, with a y msec. increase in reaction time for every increase in target set size.

FIGURE 2. Predicted reaction time function for "no" responses for both the serial self-terminating and serial-exhaustive searches of the target list.



In the serial-exhaustive search, the slope of the function will be the same for "yes" and "no" responses. The slope of the function will not be the same, however, for trials in which ANSWER equals "yes," when the program instructs the central processor to terminate the search whenever it finds a match. In the case of the self-terminating search, on each "yes" trial the central processor searches some proportion of the list. If the test digit is equally likely to occur at any serial position on "yes" trials, it will search $\frac{N+1}{2}$ items on the average, whereas on "no" trials it will search the entire list. If the strategy is a serial self-terminating search, therefore, we can expect the rate of increase in reaction time as a function of target set size to be 1/2 that of "no" trials. Figure 3 presents the curves for "yes" and "no" responses under the assumption of a serial self-terminating memory search. If, on the other hand, the entire list is searched on both kinds of trials, it follows that the function will be the same for both "yes" and "no" trials. Therefore, the "yes" and "no" curves will be parallel when the search algorithm is a serial-exhaustive one.

FIGURE 3. Predicted reaction time functions for "yes" and "no" responses for a serial self-terminating search of the target list.



Content-Addressable Search

The computer can also be programmed to use a different search algorithm, called a content-addressable search, to perform this task. In this strategy, somewhat more processing of the target list makes possible a shorter search time, so that a different reaction time function is obtained. The program tells the computer that in this task any of the digits 0 through 9 may be fed into its memory, and instructs it to set aside 10 locations, assigned the names TARGET LIST, through TARGET LIST + 9. All 10 locations are assigned the contents "no." As each digit in the target list comes in, the central processor goes to the location with the address of the target digit and changes its contents from "no" to "yes." For example, if the digits in the list are 3, 7, and 2, the central processor changes the contents of TARGET LIST + 3, TARGET LIST + 7, and TARGET LIST + 2, respectively. Thus, in this example, at the end of this operation there are three locations containing "yes" and seven containing "no." At test, the test digit is recognized and the program instructs a search of TARGET LIST plus the value of the test digit. If the test digit was contained in the target list, that location should contain a "yes"; otherwise, it would contain a "no." This program is shown in Table 3.

TABLE 3

Outline of a computer program specifying the processing of target list and test item for a content-addressable search of target items in memory.

Processing the target list

1. make the variable *x* equal to zero
2. store the symbol "no" in TARGET LIST + *x*
3. increment the variable *x* by 1
4. if the variable *x* is equal to 10, go to step 6
5. go to step 2
6. wait for input; when input is detected, go to step 7
7. recognize input; if not target digit or buzz, go back to step 6
8. if input is buzz, go to step 12
9. if input is digit, make variable *x* equal to this value
10. store the symbol "yes" at location TARGET LIST + *x*
11. go to step 6

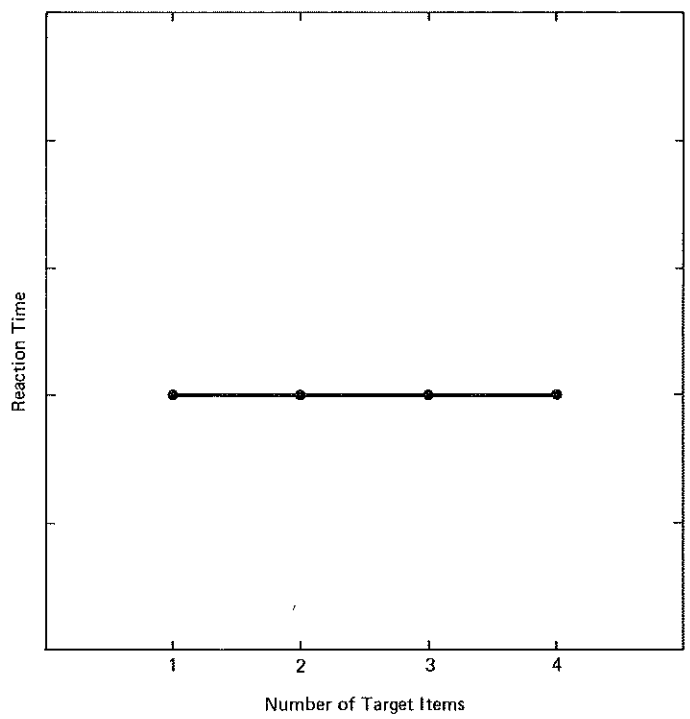
Processing the test digit——content-addressable search

12. wait for input; when input is detected, go to step 13
13. recognize input; if not test digit, go back to step 12
14. make variable *x* equal to test digit
15. determine the contents of TARGET LIST + *x*
16. store it at ANSWER
17. determine the contents of ANSWER
18. type this symbol
19. stop

In this strategy, changes in the number of items in memory will affect the amount of processing before the onset of the search operation. A larger number of items will require a longer time for the storing of the digits in their proper memory locations. No matter how many digits are in memory, however, once they are stored and the test digit is presented, the operations are always exactly the same; the central processor reads the test digit, addresses the location TARGET LIST plus test digit, and reads its contents. Since RT in this task is measured from onset of the test digit to the onset of the response, the slope of the RT function with increases in target set size given this strategy would be zero; it would be plotted as a horizontal line (see Figure 4). The horizontal function would be obtained for both "yes" and "no" responses.

The major difference between the serial search and content-addressable search is the way target items are retrieved from memory. In the first case, the subject has the names of the target items in a particular part of memory and he searches those locations for a target item equal to the test item. In the second case, the target items are not restricted to one area of memory, rather, all digits are

FIGURE 4. Predicted reaction time function for "yes" and "no" responses for a content-addressable search of the target list.



represented in memory and the subject simply inquires about the status of the test digit. In the serial search, the target items must be systematically retrieved from memory, whereas in the content-addressable search the only retrieval is that of the contents or status of the test item itself. Therefore, RT is dependent upon the number of target items in the serial search but is unaffected by this variable in the content-addressable search.

These two search strategies are probably utilized at different times in normal cognitive functioning. If you are asked whether there is a given number—for example, "one"—in your telephone number, you will probably use a serial search. A content-addressable search seems unlikely since it is improbable that contents of the memory location of "one" would have information about whether or not it is contained in your telephone number. Rather, you must go to the location or address of your telephone number and inquire there whether a "one" is represented. In contrast, when asked if you keep your butter in the refrigerator, you do not search through all the foods you have stored in memory under refrigerator. Rather, the concept of butter is enough to tell you whether you store it in the refrigerator. Therefore, the time to answer this question should be independent of the number of foods kept in the house.

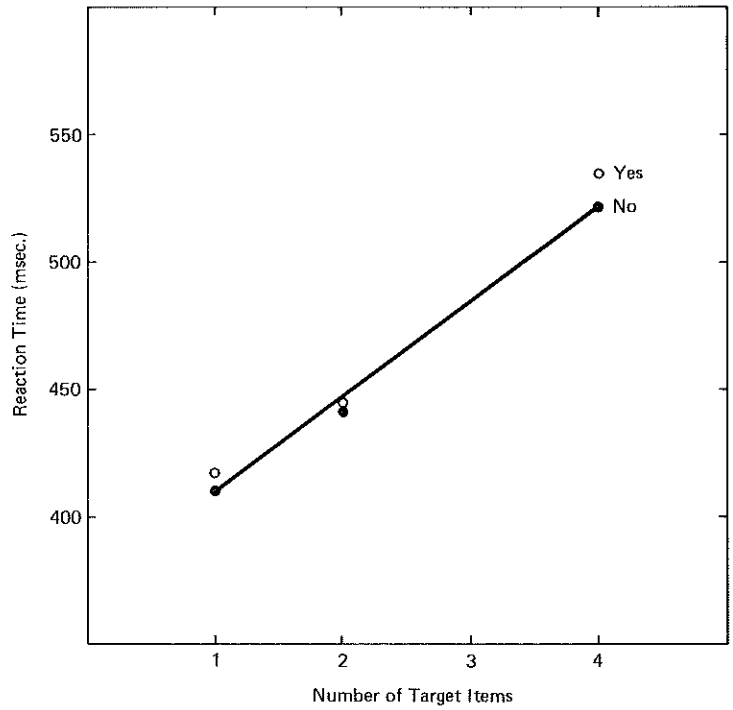
Memory Set Size

Here, then, are two hypothetical strategies that generate two different reaction time functions across changes in memory set size. These predicted functions can be compared to the function obtained in the actual experiment with humans. If the latter is a horizontal line, we have evidence that humans use something analogous to a content-addressable strategy in this task. If the results show a linearly increasing function, the serial search algorithm is supported. One other possibility is some combination of the two, perhaps a flat line up to 3 or 4 items in memory, followed by a linear increase; this would imply that at a memory list size of 3 or 4, subjects changed from a content-addressable to a serial search strategy.

In fact, Sternberg's results plotted in Figure 5 showed a linear increase in reaction time as a function of memory set size, supporting the hypothesis that humans perform this task by employing a serial search strategy. Moreover, the function was the same for both "yes" and "no" responses, indicating that the subject exhausted the memory list on "yes" trials. The results, then, support the serial-exhaustive search algorithm.

It might be hypothesized that this search and comparison operation is performed during subvocal rehearsal that subjects em-

FIGURE 5. Observed "yes' and "no" reaction times in the memory search task as a function of the number of items in the target list (after Sternberg, 1969).



ploy in the task. Subjects report reciting the numbers to themselves in order to keep them fixed in memory. This hypothesis would predict that each additional item in the target set would require at least an additional 160 msec. for search and comparison, since the rate of implicit speech is about 6 items per second. Sternberg's results, however, show the increment of additional time for each additional item to be about 40 msec., demonstrating that the serial search and comparison cannot take place at the level of subvocal speech.

The additive-factor method can be used to clarify further the operations of the search process in the search task. Simultaneously, this method can be used to substantiate the independence of the processing stages. Consider the three stages—recognition, memory search and comparison, and response selection—and independent variables that might affect each stage. The recognition process is dependent on the clarity of the test digit; if we present the test digit in degraded form, it should take the subject longer to recognize the test digit but should not necessarily affect the time to complete the following processing stages. We have seen how the number of items in the target set appears to affect only the memory search

and comparison stage. Finally, the response selection stage might be affected by the contents of ANSWER. The subject may find it more or less difficult to select a "yes" than a "no" response.

Quality of Test Stimulus

This armchair analysis leads to further experiments which simultaneously vary these three independent variables. In one experiment, Sternberg (1967) manipulated the visual quality of the test digit, presenting it in degraded form on half the trials, and intact on the remaining trials. The stimulus was degraded by placing a masking screen of dots over the test digit. In this study, subjects were given a fixed target set for a whole block of trials. For example, the subjects might be given the target list containing the digits 4 and 7. Then each trial would be initiated with the onset of the test digit. After a series of trials, the subjects would be given a new target list followed by a block of trials. The quality of the test digit was also varied between trial blocks. (Work out a counterbalancing scheme for this factorial experiment of four levels of target size and two levels of visual quality.)

In this study, Sternberg covaried two independent variables. The test digit appeared either intact, or was embedded in the visual noise and the number of items in the target set was varied. The reaction time function under the intact condition was compared to the reaction time function in the degraded condition. Logically, one would predict that the case in which the test stimulus was embedded in noise would take longer than the intact stimulus case. In particular, one would expect that recognition of the test digit would be more difficult. Thus, the overall reaction time function would be higher than the typical function found with intact stimuli. One might expect, however, that the slope of the function would not change, that is, that the stimulus quality manipulation would not affect the difficulty of the memory search process. It seems reasonable to suppose that once the recognition stage has given the test digit a label, however easy or difficult it may have been to do so, the rate of memory search would be the same. If this is the case, the slopes of the two functions will be parallel. If not, if changes in stimulus quality *do* affect the memory comparison stage, the results of the experiment will show diverging lines.

Thus, we can expect one of two alternative functions, both of which would be informative. In Figure 6, the two independent variables have additive effects, the degraded function is parallel to the intact function, and we can conclude that the two variables affect different stages. If the two variables interact, their effects will be compounded, resulting in the interaction presented in Figure 7. This result might imply that the subjects employ some

Analysis of Variance

The analysis of variance is the best statistical tool to analyze experiments with two or more independent variables that are combined in a factorial fashion, as is required by the additive-factor method. The analysis essentially evaluates the treatment effect against the chance variability found in the experiment. Consider an experiment with two levels of an independent variable in which we test the subject 3 different times under each level so that we have 3 scores at each level. Assume that in two different experiments the scores are those given in the table below, where I_1 and I_2 are the two levels of the independent variable.

Experiment 1		*Experiment 2*	
I_1	I_2	I_1	I_2
80	100	73	87
60	90	70	90
70	80	67	93

In both experiments, the subject averaged 70 at I_1 and 90 at I_2. However, we have more confidence in the difference between I_1 and I_2 in the second experiment than in the first. In the first experiment, the difference (20) between I_1 and I_2 is not any larger than the difference between the 3 scores at the same level of I_1 or I_2. The differences between the scores at the same level of our independent variable must be attributed to chance variability since there is nothing the experimenter can point to as a causal factor. Since chance variability was so much larger in the first experiment than the second, we have more faith in the significance of the results in the second experiment than the first. However, statistical significance itself is not the major issue and our analysis is focused on the psychological significance of a given result.

The analysis of variance provides the experimenter with an index of the size of the treatment effect measured against the chance variability in his experiment. In a two-factor design—an experiment with two independent variables—the analysis of variance provides this index for the effect of each of the independent variables and their interaction. The experimenter should design his experiment as carefully as possible to keep chance variability to a minimum. After the experiment, he computes the statistical significance using the analysis of variance. His task then is to evaluate the size of these effects and what these effects say about psychological processes and current models or theories of the processes. Our knowledge comes from evaluating the meaningfulness of the effects of independent variables rather than simply from their statistical significance.

FIGURE 6. Predicted reaction time functions if the quality of the stimulus affects only the recognition stage of processing in the search task.

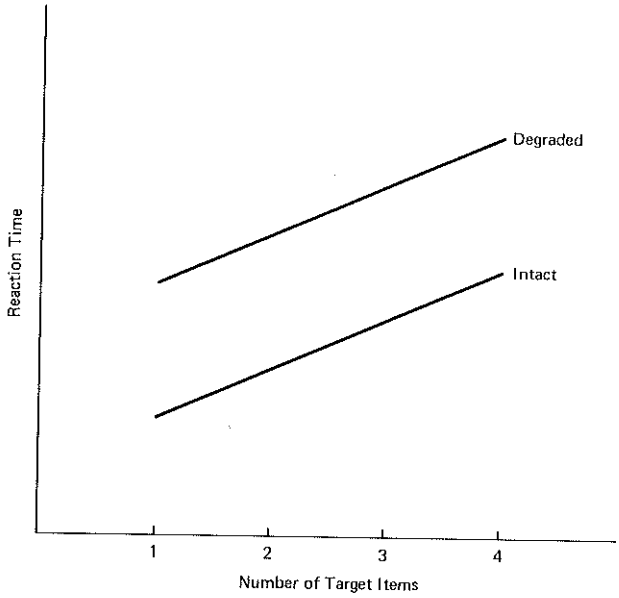
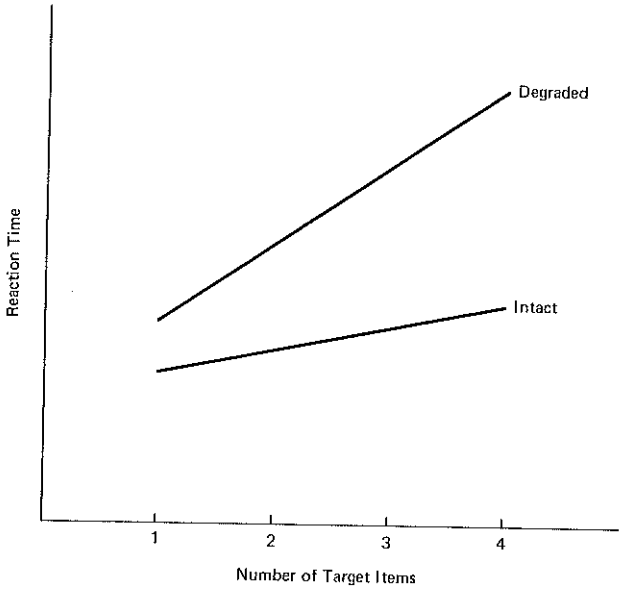


FIGURE 7. Predicted reaction time functions if the quality of the test stimulus affects both the recognition stage and the memory search and comparison stage of processing in the search task.



direct representation of the test digit in the memory search and comparison so that the degraded digit not only increases recognition time but slows down the rate of memory search.

On the second day of the experiment, Sternberg found that the RT function in the degraded condition described a straight line above and parallel to the function of the intact condition, supporting the hypothesis that stimulus quality affected only the recognition stage. This result tells us something about the connections between the stage of recognition and the stage of memory search and comparison. If degrading the stimulus had affected the reaction time of the memory search stage, then that would imply that the information in the recognition is handed over raw to the memory search and comparison stage. Sternberg's results, however, tell us that the recognition stage transforms the degraded information to produce an unequivocal digit value for the memory search stage. This lends credence to the information-processing model, in which stages of processing are seen as producing successive transformations upon the information as it moves through them.

Note that Sternberg designed his experiment so that either result would have been informative. A good experimenter first asks: What are the possible outcomes of the experiment? What theories can be rejected or supported by the study? If the results do not distinguish between theories, they are not informative in the sense of reducing uncertainty about the psychological processes responsible for the results. The psychologist is primarily interested in what the experiment can indicate about psychological processing; behavioral data are not sufficient in and of themselves. He, therefore, designs the experiments so that every possible outcome will be informative with respect to psychological functioning.

VISUAL SCANNING

About the time that Sternberg was doing his memory search experiments, Neisser and his colleagues devised another paradigm that approached the study of memory search from a different direction (Neisser, 1963, 1964; Neisser, Novick, & Lazar, 1963). In Neisser's task, the subject was given a target item, perhaps a letter of the alphabet, and told to find this item in a list of letters that he was then given. The list contained a column of letters with usually 4 or 6 letters per row. Upon presentation of the list the subject read (scanned) the list from the top and pushed a lever as soon as he found the target letter. On each trial, then, he was presented with a list of, say, 50 rows of 6 letters each, which he searched for the target item. As soon as he found it, the subject pushed a button.

Reaction time was measured from the presentation of the list to the onset of the response.

Sternberg's additive-factor method allows us to determine the time for memory search by accounting for the times of other processes in the task. The slope of the function relating reaction time to the number of items in the target set provides an index of memory search and comparison time. Neisser estimated memory search and comparison time in a similar fashion. The independent variable in Neisser's task is the location of the target letter in the test list. Reaction time should be a direct function of what row in the list contains the target letter. Since the subjects begin scanning at the top of the list, we would expect RT to increase as the target letter is placed lower down in the test list. Logically, each letter in the test list requires the same amount of processing until the subject finds the target letter. For example, if the subject is looking for the letter *K*, we would expect that his search rate through the list would be constant. That is to say, the time to process the test letters should be independent of their serial position in the test list. Since the response selection time should also be independent of where the subject finds the letter in the list, we would expect that reaction time should be a linear function of the serial position of the target letter.

The results of Neisser's experiment, shown in Figure 8, support the logical analysis. Reaction time is well described by a linearly increasing function of position of the target letter in the test list. The fact that the intercept of the function is close to 0 sec. shows that other processes such as response-execution time account for very little of the reaction time. The slope of the function provides an index of the time it takes the subject to recognize, to compare, and to select a response for each letter. That is to say, for the subject to perform the task correctly, he must process each letter to the degree that he knows enough about whether it is or is not the test letter and must select the appropriate response given this information. If it is not the target letter, he goes on to the next letter; if it is, he pushes the lever.

Neisser's paradigm is very similar to the experimental task used by Sternberg. The target item in Neisser's task is analogous to the target set in Sternberg's task; Neisser's test list is analogous to Sternberg's test item. Given Sternberg's results, we might expect subjects to perform Neisser's task by comparing each item on the presentation list to the target item in memory. Since they are instructed to start at the top of the list, they could proceed in serial order until a match is found.

In Sternberg's task, the subject has several items in memory

and one test item to be recognized and compared serially to the items in memory. In Neisser's task, the subject has one item in memory, and up to 50 rows of letters to be compared to it. Reaction time in Neisser's task should vary, therefore, not as a function of the number of target items, which is constant, but rather as a function of the position of the target item in the list; that is to say, RT should vary as a function of the number of test items that must be searched before the subject reaches the one that corresponds to the item in memory. This function should be linear, as in Sternberg's task, i.e., each item to be searched should add a constant increment to the reaction time. In fact, Neisser's results confirm this prediction, indicating a linear increase in RT as the target item is moved further and further down the list. Up to this point, Neisser's and Sternberg's experiments confirm each other nicely.

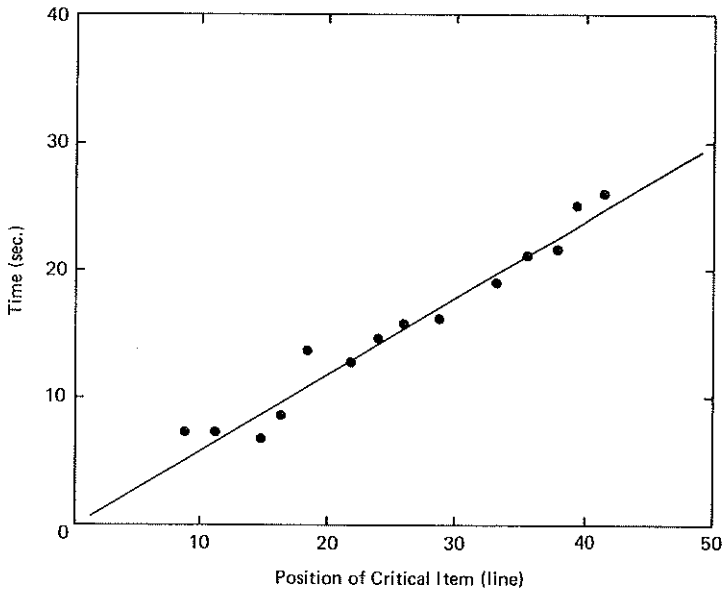
Having established the reaction time function in the case of one target, Neisser presented subjects with a larger number of target items. For example, the subject would be given two targets, perhaps *K* and *O*, and told to respond as soon as he found either one in the list. We would expect, according to what both Sternberg and Neisser have shown so far about how subjects perform this sort of task, that each item in the list would be matched against one target letter first and then against the other, proceeding serially down the list, and generating a linear function that would have a steeper slope than the function with the same list and only one of the targets. That is, twice as many comparisons will have to be made for the same number of test items, since now the subject has to check each test item against two targets instead of just one.

This is not what Neisser found with practiced subjects. Although RT was a linear function of the position of the target item in the test list, it did not vary at all as a function of the number of targets in memory. A target that was 1 out of 10 was found as quickly as the same target when it was the only one the subject was looking for. Subjects could search the test list for 8 letters and 2 numbers as quickly as they could search for the letter *K* alone. This means that the rate of memory search and comparison was independent of the number of target items in memory.

Neisser's results can be described by a slight variation on the content-addressable search algorithm discussed earlier. Subjects would ticket only the target items in advance; negative items would remain unmarked. Therefore, each test item would take the search process to a specific location in memory corresponding to that test item. If it was ticketed, it would be a positive (target) item and the subject should push the lever. If it was unticketed the subject could reliably conclude that it was a negative (nontarget) item and proceed to the next test item. In this way, reaction time would not be

dependent upon the number of target items in memory. All that is required is a check of the status of each test item without referring to the target items at all.

FIGURE 8. Reaction time as a function of the serial position of the target item in the test list (after Neisser, 1967).



Differences Between Sternberg and Neisser Tasks

The difference in the way the subjects performed these two tasks must reflect differences in the two experimental paradigms. Unlike Sternberg's subjects, Neisser's were practiced and highly motivated. They returned day after day, and were able to decrease their overall reaction time remarkably. Moreover, the targets which they had to keep in memory while searching the lists did not vary. A subject would be given 10 target letters; on one day he might look for 5 of these, and on another day he might look for all 10. Over time he learned the targets quite thoroughly. Sternberg's subjects, on the other hand, came in once for a few hours. They had little practice with the search operation, and very little opportunity to rehearse the target items. In addition, Sternberg emphasized perfect performance with his subjects, keeping the rate of errors down to about 2 or 3 percent. Neisser, on the contrary, allowed his subjects to make many errors, about 25 percent; the emphasis in his experiment was on speed of reaction.

Neisser compared the performance of his subjects to that of employees in news-clipping services, who contract with clients

to search the newspapers for any mention of clients' names. The people who perform this work learn to scan newspapers at astonishing rates. They report they do not need to read the material in any sense. Somehow the clients' names just pop out at them. In the same way, Neisser's subjects reported that after practice, the target letters just leaped out at them from the list. According to our content-addressable search model, ticketing the target items has the phenomenological consequence of these items popping out, whereas unticketed items do not. With the content-addressable search, it was not necessary to compare each letter in the test list to the target items in memory. Rather, the necessary information was present in the test item itself.

Specific practice

An experiment performed by Graboi (1971) demonstrated the critical effect of specific practice on memory search. Graboi used Neisser's paradigm and English surnames as target and list items. Subjects were given such names as Hicks, James, Blake, Klein, Allan, Brown, and Joyce to find in a list of similar names; the number of target names could vary from 1 to 7.

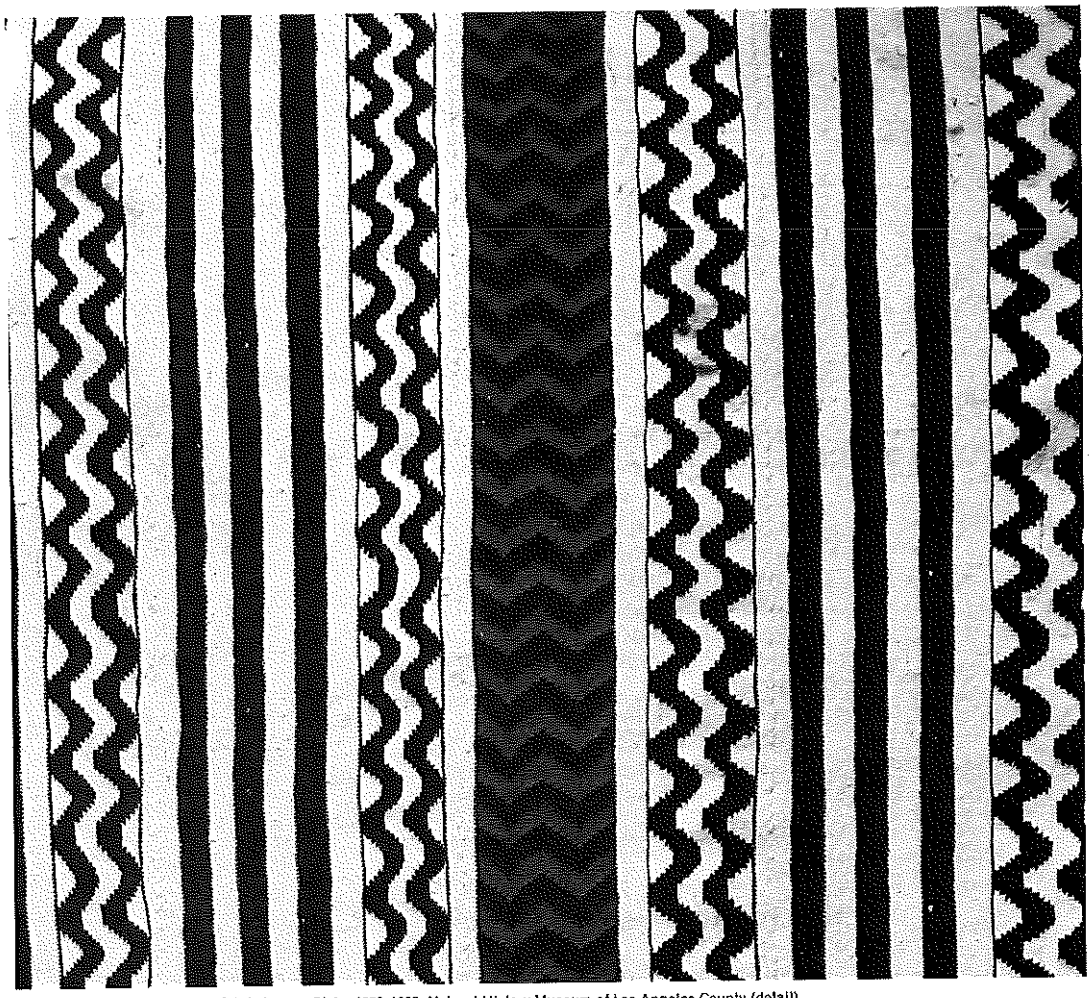
Graboi first allowed his subjects to become very practiced with the same 7 names. Each subject had 7 targets which he searched for in combinations from 1 to all 7 in list after list, until he was highly practiced with these targets. Measuring reaction time as a function of target list size, Graboi found that there was some increase in time, but this increase was not a linear function. Subjects took longer to search with 3 targets than with 1, but beyond 3 targets reaction time did not increase. Seven targets took no longer than 3; finding James in a list took no longer if the possible targets were Hicks, James, Brown, Jones, Klein, Blake, and Joyce, than if they were Hicks, James, and Brown.

Subjects all reported that this was a skill they had learned. After so much practice, they felt they no longer gave the list the active attention they had at the beginning of the experiment; rather, they seemed to need only glance through the list, thinking of nothing in particular, to have the relevant names pop out at them.

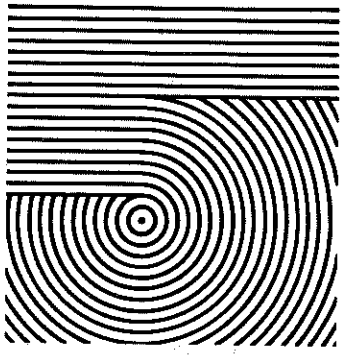
Now Graboi gave subjects a new set of target names and 15 minutes in which to study them. When the same subjects performed the same task with a different set of names, the reaction time was found to increase sharply with increases in the number of items in memory. Subjects who had had much practice in the task and who had learned to search for one set of targets according to a content-addressable search fell back on a serial search when presented with a new set of targets. This study demonstrates that practice affects the type of search algorithm used. Humans probably choose one of a number of search algorithms depending upon the conditions and

requirements of the task at hand. If subjects are highly practiced with the target set and errors are not critical, something analogous to a content-addressable search can be used. If accuracy is critical and the subjects are unpracticed, a serial search seems more appropriate.

SENSATION



Los Angeles County Museum of Art, Serape Style, 1850–1865, Natural History Museum of Los Angeles County (detail).



Psychophysics

Classical psychophysics
Fechner's psychophysical methods
- method of limits
- method of adjustment
- method of constant stimuli
- choice of stimulus levels

The threshold and Fechner's psychophysical law
- variability of the threshold
- attitudes of the observer
  - modifications to keep observer honest
  - motivation of observer

Logarithms
Dynes
Normal distributions and ogive curves
Stars
Subliminal perception

Psychophysics should be understood here as an exact theory of the functionally dependent relations of body and soul or, more generally, of the material and the mental, of the physical and the psychological worlds.
—Gustav T. Fechner (1860)

The methods developed by Donders and Sternberg have allowed us to partition the time between stimulus and response into a series of psychological processing stages. We now begin to study how these processes operate in more detail. The initial stage of processing is what we call detection and is very similar to the British Empiricists' concept of sensation. The outcome of the detection process provides information about whether or not a stimulus was presented. Traditionally, the study of the relationship between stimulus and sensation has been called psychophysics. The goal of this research has been to describe and understand the relationship between the physical stimulus signal and the psychological experience it creates.

Given the current advanced state of technology, the experimental psychologist is now able to control and measure the stimulus signal exactly. In contrast, the psychological sensation of the observer remains unobservable and the experimentalist must resort to asking the observer about his experience. From his answer, the experimenter must be able to derive a measure of the observer's sensation. The development of experimental and analytical techniques for deriving a measurement of sensation based on the response of the subject has gone hand in hand with theoretical advances, so that today the experimenter is able to measure the unobservable psychological experience of the observer.

CLASSICAL PSYCHOPHYSICS

In the mid-19th century, Gustav T. Fechner, a physicist recovering from a nervous breakdown, took up the study of philosophy. At that time the fashion in metaphysics was materialism, but Fechner was not convinced by it. He rejected the notion that the mind was forever closed to the scientific explorations that had been devel-

oped for the study of the physical universe. On the contrary, it seemed to him certain that mind and matter were two aspects of one world. The mind was only a different sort of manifestation of the same universe (completely separated and different in kind, but in constant correspondence with the body). Thus, internal psychological experience should correspond directly to changes in the physical environment. These beliefs correspond to the epiphenomenalists' solution to the mind-body problem (see Chapter 1). It followed that internal experience could be studied through manipulation of the environment. Changes made in a stimulus under carefully controlled experimental conditions should be reflected directly in changes in sensation. Sensation, a mental event, could thus be an object for scientific study on the same level and under the same scientific constraints as physical phenomena.

Fechner inaugurated the study of psychophysics, whose goal was to determine the laws of correspondence between the outer world and inner experience. For example, the sensory threshold seemed a clear case of the link between mental and physical phenomena. Since the time of the ancient Greeks it had been taken as self-evident that for each individual there is some value on a given stimulus dimension—sound intensity, for instance—such that stimuli above this value produce a sensation, whereas stimuli below it do not. A sound that is one unit more intense than the individual's threshold would be heard, and a sound that is one unit less intense goes unnoticed. No one had ever subjected the assumption of a sensory threshold to experimental study; the threshold for sound intensity, or indeed for any other stimulus dimension, had never been determined for any individual. Yet here was a clear instance of the direct relationship between mental and physical events, one that could be observed and measured under controlled conditions.

Accordingly, Fechner set about studying individual threshold values. His first problem in this new science was to devise experimental methods for measuring the correspondence between the physical and mental worlds. The three experimental methods that he employed, (1) the method of limits, (2) the method of constant stimuli, and (3) the method of adjustment, were carefully described along with his results in the treatise *Element der Psychophysik,* published in 1860. These three methods continued to be used in all psychophysical research as recently as fifteen or twenty years ago, when their inadequacies began to emerge and better methods were introduced. Indeed, Fechner's methods are still favored by some researchers and are assumed to be valid in some practical applications. These experimental methods will be discussed in some detail, showing in just what way they fail to provide the experimenter with a reliable measure of the observer's sensation. Follow-

ing this discussion of classical psychophysics, a more recent and sophisticated psychophysical experiment will be presented. In the two chapters following, we shall discuss and evaluate alternative models of the psychological processes involved in the psychophysical task.

FECHNER'S PSYCHOPHYSICAL METHODS

To determine the threshold value along a given stimulus dimension, Fechner and his successors in classical psychophysics presented the subject with a stimulus and asked him to report whether or not he detected it. The independent variable in this simple experimental design is the intensity of the stimulus; the dependent variable is the subject's response. Fechner's three methods represent three different ways of presenting the stimuli and measuring the response.

Method of Limits

In the method of limits, subjects are tested by presenting stimuli in an ascending or descending series of intensities. For example, an experimenter can choose a tone of a certain frequency and vary its intensity from trial to trial within a range that is both well above and well below what is known to be audible. On each trial, subjects are asked to say whether or not they heard the tone during a certain interval, and their answers are recorded. Somewhere on the continuum of intensities the subject's response should change. In an ascending series, the tone is presented at a weak enough intensity to assure that the subject will respond "no." Then, the tone is incremented by a small amount on each successive trial until the subject says "yes." In a descending series, the first tone is intense enough so that it is consistently detected and then made slightly less intense on each successive trial until the subject reports "no." Each series is always started at a different intensity so that the subject will not become accustomed to always changing his response at a given serial position in the series.

If the classical threshold model of sensation is correct, there will be a stimulus value along the continuum of values where the subject's response changes from "yes" to "no" or from "no" to "yes." This value should, therefore, correspond to the sensory threshold of the subject, the point at which he ceases to hear nothing and begins to hear something. Fechner's original threshold model predicted that this value would be definite and unconditional.

Table 1 presents the results of a hypothetical experiment employing the method of limits to measure the detectability of a tone as a function of its intensity. As Fechner and all other experiment-

TABLE 1
Determination of the Detectability of a Tone as a Function of its Intensity by the Method of Limits

Stimulus intensity (arbitrary units)	*Alternating descending and ascending series*									
−5					N					
−4			N		N				N	
−3	N		N		N		N		N	
−2	N		N		N		N		Y	
−1	Y		N		Y		N			
0		N	Y				Y	N		
1		Y				N		Y		N
2		Y		N		Y		Y		Y
3		Y		Y		Y		Y		Y
4		Y		Y						Y
5		Y								Y

ers using this method have found, no point exists in these data at which the response consistently changes from one category to the other. Instead, the transition point differs for the ascending and descending series and also varies from series to series within a particular type of series. Faced with this variance, Fechner and later experimenters have usually averaged the transition values and defined the threshold as the mean of all of the transition values. Clearly, these results indicate that the classical concept of a threshold will require modification.

Method of Adjustment

In the method of adjustment, the intensity of the stimulus is under the subject's control and he is required to maintain it at a barely detectable level. In the popular Békésy audiometer application of this method, the observer sits listening to a tone whose intensity is slowly decreasing. He controls a button which increases the intensity of the tone as he presses it. The subject's task is to maintain the tone at a barely audible level. Thus, he presses the button as soon as the tone becomes inaudible and holds it down until it is audible again, at which point he releases the button and the tone is allowed to decrease again. The subject is actually engaged in tracking a certain intensity, corresponding to the limits of his hearing. The experimenter can calculate the intensity that the subject attempts to maintain and thus arrive at an estimate of the subject's threshold.

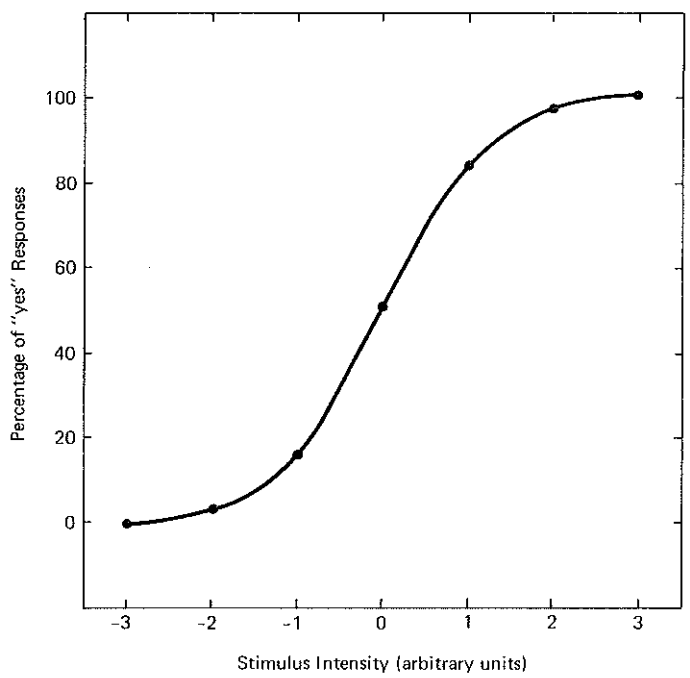
Method of Constant Stimuli

In the method of constant stimuli, the experimenter chooses a population of stimuli that differ in intensity around the limits of audibility. The subject is then given a series of trials in which the stimulus for each trial is chosen randomly from this set. (Although this stimulus set corresponds to the set of stimuli used in the method of limits, the constant stimuli method usually requires more trials than does the method of limits, since the experimenter can terminate the series after a response transition in the method of limits.) The experimenter records the responses to each stimulus and the dependent variable is the proportion of "yes" responses. As shown in Figure 1, the proportion of "yes" responses in a typical experiment rises continuously with increases in intensity. There is no precise threshold level; the subject is more and more likely to say "yes" as the intensity increases, but there is no clearly defined transition between "yes" and "no" responses.

Choice of Stimulus Levels

In these psychophysical methods, the experimenter must attend carefully to the levels of intensities of his independent variable. The

FIGURE 1. The percentage of "yes" responses as a function of the stimulus intensity of a tonal signal utilizing the method of constant stimuli procedure.



series of intensities must be neither too close to one another nor too distant. Consider an experiment using the method of limits, for example. If the intensities are chosen so that they are very close to one another, no change will occur in the subject's response with changes in intensity. By contrast, if the intensities are chosen so that they are too distant, the change in the subject's response with a change in intensity will not be informative. In this case, the experimenter cannot interpolate—speculate on the responses for the intervening intensities—between the observed responses. Therefore, in this task, as in most psychological experiments, the experimenter must choose the levels of his independent variable cautiously.

Choosing the appropriate stimulus levels usually requires a series of miniature experiments. For example, in the method of constant stimuli, the experimenter might choose seven levels of intensity, the extremes of which are known to be well above and well below threshold. The experimenter presents these levels in random order and records the responses to each stimulus. The experimenter could easily find that the subject consistently responded "yes" to some of the stimulus levels and "no" to the other levels. Since the response of the subject changed in an all-or-none manner, does this result support Fechner's idea of a threshold? Not necessarily; the

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Logarithms

Consider the case in which each of the successive levels of an independent variable is 10 times the value of the preceding level. If the first level was 1 unit, the following six levels would be 10, 100, 1000, 10,000, 100,000, and 1,000,000 units, respectively. Rather than dealing with these large numbers, they are more easily expressed as logarithms to the base 10. The seven levels (X) of our independent variable are easily expressed in terms of 10 raised to the appropriate power Y.

$$X = 10^Y.$$

The seven levels would be 10^0, 10^1, 10^2, 10^3, 10^4, 10^5, 10^6, respectively. The logarithms of our values X are the respective powers Y of the value 10. In this way we define Y as the logarithm of X to the base 10 as

$$Y = \log_{10} X.$$

Then the logarithm Y of X to the base 10 is the power to which we must raise 10 to get X. In other areas of psychological study, it is useful to use logarithms to the other bases besides 10. The same general principles hold, so that Y is the logarithm of X to the base b.

$$Y = \log_b X.$$

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intensity levels may have been too far apart, with the result that some of the stimuli were too far above and the other stimuli too far below the limits of audibility. The experimenter should now choose seven new levels between the two levels at which the subject changed from "yes" to "no" responses in the first experiment. If he repeats the experiment and continues in this manner, he will eventually find the appropriate levels that allow him to provide a valid test of Fechner's all-or-none threshold concept.

THE THRESHOLD AND FECHNER'S PSYCHOPHYSICAL LAW

Fechner had centered his study of the relationship between stimulus and sensation on the sensory threshold concept. Below the threshold, changes in stimulation do not effect changes in sensation; sensation does not occur at all. Above the threshold value, Fechner assumed that the magnitude of the sensation increases with increases in the absolute intensity of the stimulus. This central assumption was represented by Fechner's equation:

$$S = K \log_{10} I, \tag{1}$$

where S measures the magnitude of the sensation, I the intensity of the stimulus, and K is a constant of proportionality. The stimulus intensity I is measured with the threshold value as the unit of measurement. Accordingly, the value I, substituted in Equation 1, is a ratio of the absolute intensity of the stimulus to the threshold value. For example, if the threshold of sound intensity for a subject corresponds to a sound pressure of .0002 dynes/cm^2, each value of I is obtained by dividing the sound pressure value of the stimulus by .0002 dynes/cm^2. Therefore, when the stimulus presented is at threshold value:

$$S = K \log \frac{.0002 \text{ dynes/cm}^2}{.0002 \text{ dynes/cm}^2}, \tag{2}$$

$$S = K \log 1 = 0.$$

Dynes

A dyne is a measure of force or pressure, and dynes/cm^2 measures the amount of pressure per square centimeter. One dyne of force applied to a mass of 1 gram for 1 sec. will move it at a velocity of 1 cm. per sec.

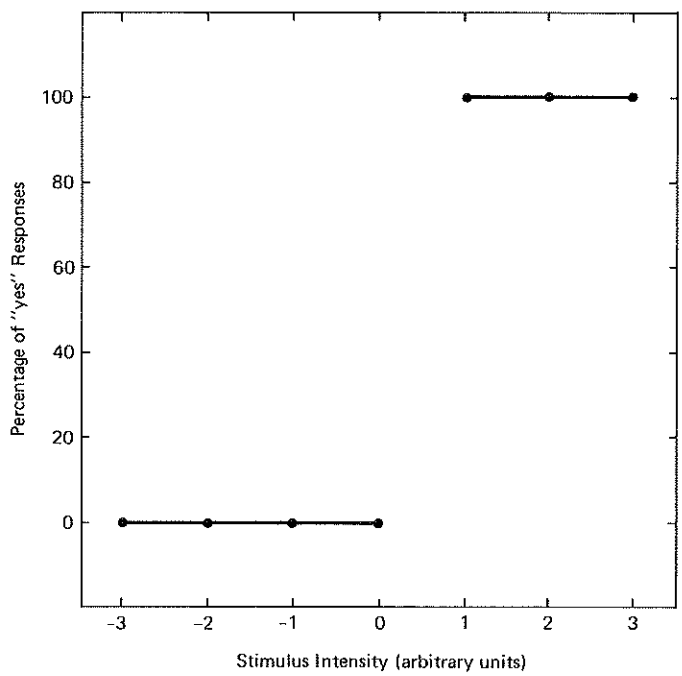
The value .0002 dynes/cm^2 is equal to the atmospheric sound pressure of a 1000 Hz. tone that is barely detectable. Sixty dB with a reference source pressure of .0002 dynes/cm^2 would be equal to 1000 × .0002 dynes/cm, or .2 dynes/cm, which is roughly equivalent to conversational speech at a distance of 3 ft.

That is, when the stimulus is at threshold, no sensation occurs, since $S = 0$. As stimulus intensity increases over this threshold value by the smallest amount, S is immediately greater than zero, and a noticeable sensation occurs.

According to this model, data from an experiment in detection should correspond to the curve shown in Figure 2. First, note that we have transformed our measure of sound pressure from dynes/cm^2 to decibels. A decibel is a unit that describes the sound pressure of a sound wave relative to some other sound pressure value. The decibel, therefore, refers to a sound pressure ratio and is equal to 20 times the logarithm to the base 10 of that ratio. Accordingly, 100 times the sound pressure is equivalent to 40 dB since 20 times $\log_{10}100$ equals 40. A doubling of sound pressure gives an increase of 6 dB since 20 times $\log_{10}2 = 6$. The reference sound pressure level is usually taken to be .0002 dynes/cm^2, since this value approximates the limits of audibility.

As noted above, Fechner's actual results looked rather different from those predicted in Figure 2. The results presented in Table 1 and Figure 1 show that subjects are not completely consistent in the psychophysical task; they do not give the same response to the same stimulus trial after trial. However, the results in Figure 1 indicate that the observers have a higher probability of saying

FIGURE 2. Predicted results of a detection experiment according to a simple threshold model.



Normal Distributions and Ogive Curves

The normal distribution is a frequently encountered distribution in psychology and other scientific disciplines. If we set a radio dial between stations, we hear static, referred to as white noise. If we took isolated samples of this static —for example, recording 100 msec. segments on a tape recorder—and measured the sound pressure level (SPL), we would find that the different samples differed. A frequency distribution of the SPL for each sample could then be plotted. If we took a very large number of samples and converted our frequency histogram to a probability distribution, this distribution would approximate a normal curve. The curve would be symmetrical and would have the shape shown in Figure 3. If the probabilities of the normal curve from left to right were cumulated, we would produce the ogive curve shown in Figure 1.

"yes" to the more intense than to the less intense stimuli. The graph of this data actually approximates an ogive curve; the increase in percentage "yes" responses is less at the high and low values of sound pressure than in the middle.

If Fechner was disappointed to find that the sensation of an observer cannot be exactly predicted by knowledge of the intensity of the stimulus, the results he obtained were nevertheless reassuringly orderly and systematic. The probability that a stimulus exceeded threshold was directly related to the intensity of the stimulus. Thus, although his data did not support the assumption of his original model, that for each sensory system there is an absolute threshold of detection, the threshold concept could be applied if modified from the all-or-none to a probabilistic model.

Variability of the Threshold

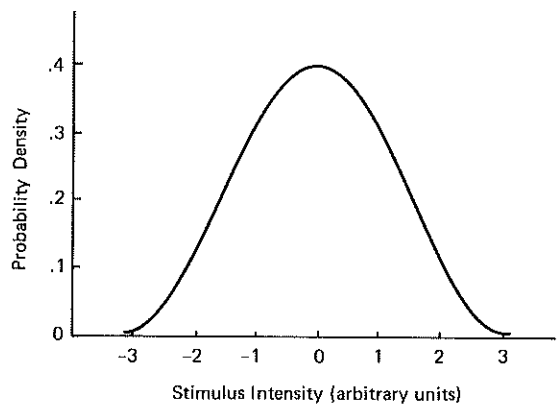
After looking at the results, Fechner defined the threshold as that point at which the observer detects the stimulus 50 percent of the time. This definition maintains the concept of a threshold but assumes that the threshold value varies from trial to trial. With this assumption, the results indicated that the threshold value varies in a very specific fashion. The function in Figure 1 shows that the variation is symmetrical; the momentary value of the threshold is just as likely to be above as below the defined 50 percent threshold value. The ogive curve actually implies that the threshold value follows a normal distribution, with a mean at the 50 percent value. Figure 3 represents graphically the distribution of threshold values that will predict the results shown in Figure 1.

Noise in the sensory system might account for the variability in the threshold values that Fechner observed. Noise is a concept that will be used continuously throughout our psychological study.

Stars

Although Fechner's original model did not predict the results of his detection experiments accurately, his Equation 1 did capture an important relationship between stimulus intensity and the magnitude of sensation. Equation 1 specifies a logarithmic relationship between the magnitude of the sensation and the intensity of the stimulus. This means that it takes a much larger increase in the intensity of a bright light than of a dim light to give the same increase in the magnitude of the sensation. The subjective classification of the brightness of the stars by the ancient astronomer, Hipparchus, illustrates this fact. Wishing to describe the brightness of stars, Hipparchus placed the stars in six or seven categories based on their apparent brightness. The first category contained the stars that were barely visible and each succeeding category contained stars that were perceived to be one order of magnitude brighter than the stars in the previous category. When precise measurement became possible, it was found that the physical intensity of the stars in each category was about 2 1/2 times more intense than the intensity of the stars in the preceding category. If the physical intensity of the stars in the first category is arbitrarily defined as 1 unit, then the stars in the second category would be 2 1/2 units in brightness. The stars in the third category would be 2 1/2 x 2 1/2 or 6 1/4 units and so on. This means that, as described by Equation 1, equal increments in sensation required equal ratios between the stimulus intensities.

FIGURE 3. The probability distribution of momentary threshold values that will predict the results shown in Figure 1.



It is not unlikely that the momentary state of the sensory system would fluctuate rather than remain exactly constant. That is to say, although the subject is in a quiet room in the experiment, we can expect there to be a certain amount of background noise, for example, from the heating and ventilating system or the lights, etc. This noise would most likely fluctuate according to a normal distribu-

tion. That there is internal noise in the sensory system is also likely. Our receptors are continuously firing at a low level even though no stimulus is present. The number of receptors firing could also vary randomly from moment to moment. Therefore, it seems probable that existing external and internal noise in the experimental situation will make itself visible in the results of the experimental situation. We shall see in Chapter 7 that the concept of noise is an important one in the most recent approach to the study of sensation and detection.

Attitude of Observer

A far more serious problem was posed for Fechner's model by his discovery that the probabilistic threshold could be affected by the attitude of the observer. The results he obtained from his wife seemed to be entirely different from those of his next-door neighbor; furthermore, he found that he could raise or lower the threshold of the same observer by instructions affecting his attitude. If he instructed one group of observers that they were to respond positively only when they were absolutely certain that they had detected the tone, he would find a much higher threshold than that from a group not so instructed.

Although noise in the sensory system could account for the variability in the threshold that led to Fechner's probabilistic modification, nothing in Fechner's model could account for the effect of attitude on the subject's response. According to this model, the threshold of detectability is wired into the sensory system. Whether or not a stimulus is detected can be determined only by the limits of that system and by variables that affect the sensory system. How could changes in attitude affect the measured sensitivity of the sensory system?

But since attitude could affect the observed threshold value, Fechner faced the problem that this measure could not be a valid index of the sensitivity of the sensory system. Logically, the sensory system probably does operate independently of the observer's attitudes and motivations. But the decision or response of the subject in a psychophysical task does not. What Fechner needed was an index of the attitude of the observer so that he could correct his data to account for this attitude and get an independent measure of the sensitivity or detectability of the sensory system under study. The experimental methods that Fechner employed, however, could not provide such an index.

Consider for instance the fact that Fechner presented a stimulus on every trial. Some of his stimuli were assumed to be audible and some were not, but even on those trials in which no subject ever detected a stimulus, a stimulus was in fact presented. Very likely most subjects were aware of this or, if not, would sooner or

later become aware of this circumstance as the experiment progressed. Perhaps they just might realize that there was a higher probability that a stimulus was present than that it was not. Intuitively we would all expect a subtle change in the subject's response pattern given this knowledge. Even without reference to such an influence, however, there is the undeniable possibility that subjects could lie in this task. Knowing that a stimulus was always present, they could say that they detected it, when in fact they had not.

Modifications to keep observer honest

A partial solution to the problem of the effect of attitude on the observer's performance, therefore, is to include no-signal trials in the experiment on which no stimulus is presented. The subject's task remains the same; he simply reports whether he detected a stimulus. If 50 percent of the trials are "blank" and if signal and no-signal trials are randomly presented, the subject has no cue to the presence or absence of the signal other than the sensitivity of his sensory system. A 2 x 2 confusion matrix, shown in Figure 4, is used to analyze performance in this task. The criterion of performance changes from "trials on which the stimulus is detected" in the classical methods to "trials on which subject's response correctly reflects the real state of the world" in the new psychophysical method with blank trials.

FIGURE 4. A two-by-two confusion matrix used to analyze performance in the yes-no signal detection task.

		Response: yes	Response: no
Stimulus	signal	hit $P(\text{yes} \mid \text{signal})$	miss $P(\text{no} \mid \text{signal})$
	no signal	false alarm $P(\text{yes} \mid \text{no signal})$	correct rejection $P(\text{no} \mid \text{no signal})$

$$P(\text{yes} \mid \text{signal}) + P(\text{no} \mid \text{signal}) = 1$$
$$P(\text{yes} \mid \text{no signal}) + P(\text{no} \mid \text{no signal}) = 1$$

There are, therefore, two kinds of correct trials: those in which a signal is present and the subject says "yes," called "hit trials," and those in which a signal is not present and the subject says "no." Incorrect trials are those in which a signal is present but the subject says "no"—equivalent to Fechner's missed trials—and those on which no stimulus is present but the subject says "yes," called "false alarm trials." The experimenter tabulates the frequency of each of these four possibilities and computes the probability for each cell. As the figure shows, only two of the probabilities are independent of each other: the two probabilities that come from

different stimulus trials. The standard data analysis of this task employs the proportion of times the observer said "yes" given that a signal was present, $P(\text{yes}|\text{signal})$, and the proportion of times he said "yes" given that no signal was present, $P(\text{yes}|\text{no-signal})$. These are the two probabilities we will be concerned with; the results in the confusion matrix can be represented completely by these two alone, since each of the remaining two can be generated from these.

Consider an experimental situation in which the subject says "yes" on most trials, not because he actually hears the stimulus, but for other reasons; for example, he decides that the experimenter will present a stimulus on most trials. His hit rate—the probability of "yes" given signal—will be very high. But so will his false alarm rate—the probability that he says "yes" given no signal. By contrast, if another subject actually heard the stimulus trials and responded "yes" to these trials and "no" to the blank trials, his hit rate would be high but his false alarm rate would be low. We can see that the correct measure of performance in this task must include some analysis of the relationship between these two probabilities. A high hit rate means one thing when the false alarm rate is low, and another when the false alarm rate is high.

Motivation of observer

Consider, for example, an experiment of 100 trials in which subjects are awarded 5¢ for every correct "yes" response and 1¢ for every correct "no" response. The signal is presented on one-half the trials, and the subjects know this. If these subjects simply disregard the sensory information entirely and say "yes" on every trial, they will get every signal trial correct and receive $2.50. At the same time, every no-signal trial will be a false alarm, and they will not collect for any of these trials. The no-signal trials are worth only 1¢, however; if they got all of them correct, they would receive only 50¢. Obviously, it is better to bias one's response in this situation in favor of "yes," since a correct "yes" is worth more than a correct "no." Indeed, if they attempt to respond simply on the basis of sensory information, then their unbiased performance must be 84 percent correct in order to earn slightly more than the amount they can earn by simply saying "yes" on every trial.

Since the experimenter controls the difficulty of the detection experiment, and since it is he who will have to pay, it seems the wisest choice might very well be to say "yes" on every trial. The hit rate of a subject who so chooses—the probability that he says "yes" given the presence of a signal—will be 100 percent. Fechner would wish to conclude that the subject therefore detected the signal on every trial in which it was present. But we know that this is not the case because the false alarm rate is also 100 percent. Neither of these figures alone—the 100 percent hit rate nor the