Attentional Processing

The Brain's Art of Mindfulness

DAVID LABERGE

HARVARD UNIVERSITY PRESS
CAMBRIDGE, MASSACHUSETTS
LONDON, ENGLAND
1995

Printed in the United States of America

This book is printed on acid-free paper, and its binding materials have been chosen for strength and durability.

Library of Congress Cataloging-in-Publication Data

LaBerge, David.
Attentional processing : the brain's art of mindfulness / David LaBerge.
p. cm. — (Perspectives in cognitive neuroscience)
Includes bibliographical references and index.
ISBN 0-674-05268-4
1. Attention. 2. Neuropsychology. I. Title. II. Series.
QP405.L33 1995
153.7'33—dc20 94-38071

Acknowledgments

When Steve Kosslyn invited me to write on attention for the Perspectives in Cognitive Neuroscience series with Harvard University Press, I had already begun to outline the kind of book appropriate for the series: a synthesis of what the diverse fields of psychology, computer science, and neurobiology were saying about attentional processing. This book could not have been written without the support and encouragement of many people.

Over numerous years the University of Minnesota and the University of California, Irvine, generously provided the means to carry out my research on attention. Research support has also been provided by grants from the National Science Foundation, Joseph L. Young, Program Director, and from the Office of Naval Research, Harold Hawkins, Program Director. Much of the writing was done on sabbatical leave in the Berkshires of Massachusetts, and the library at nearby Simon's Rock College provided many needed references. For these library privileges I thank the Vice President of the College, Bernard Rodgers, the Head of the Library, Joan Goodkind, and the Reference Librarian, Russell Miller.

The research from my laboratory reported here was done in collaboration with my graduate students Blynn Bunney, Robert Carlson, Marc Carter, and John Williams, and in particular Vincent Brown. The work of our research group benefited from the contributions of Professor Alan Hartley of Scripps College.

I am greatly indebted to several colleagues for stimulating discussions of ideas that have found their way into this book: Aric Agmon, Monte Buchsbaum, Mary Baird Carlsen, Peter Fox, Michael Gazzaniga, Michael Goldberg, Patricia Goldman-Rakic, Richard Haier, Steven Hillyard, Herbert Killackey, Christof Koch, John Lawry, Mario Liotti, Duncan Luce, David McCormick, Steven Petersen, Michael Posner, Steven Potkin, Murray Sherman, James Swanson, Sharon Wigal, Tim Wigal, Marty Woldorff and Joseph Wu. I especially thank James Carlsen for many valuable discussions of attention and expectancy in music, John Compton for tenaciously emphasizing the importance of attention's experiential aspects, William K. Estes for his encouragement and inspiring example of clarity in thinking, Ted Jones for generously providing his expertise on matters of the thalamus, and Stephen M. Kosslyn, general editor of the Perspectives in Cognitive Neuroscience series, for his thorough and valuable critique of the manuscript.

I am very grateful to my editors at Harvard University Press: Kate Schmit, who clarified obscure sentences, smoothed out lumpy syntax, and cheerfully moved me through the final stages of preparation, and Angela Von der Lippe, who guided and encouraged my efforts throughout the writing of the book.

Finally, I thank my wife, Janice Lawry, who found the words for the book's subtitle and provided inspiration, support, and patience over years of writing.

Contents

1

Introduction

Our mental experience can be described as a stream of activities that includes perceptions, memories, feelings, intentions, images, beliefs, and desires. Several of these activities may be going on at the same time, as when we read a quotation in the newspaper, recognize it as a line from Shakespeare, kindle the meanings of the words as they are read, and experience the feelings that they arouse in us. On many occasions, however, one particular mental activity seems to ''fill the mind,'' if only for a brief moment of time. Tasting a good cup of coffee in the morning, remembering a discussion with a friend, considering that the economy is on an upswing and wishing that it would continue—these experiences may each take a turn at occupying one's mind. Imagine an individual's ongoing experience as a river containing several currents of distinctive colors, and giving attention to one current expands its width as it flows along; if we could observe the river in a thin cross-section at this point of ''mindfulness,'' it would seem to have only the one color.

This informal impression of the enhancing or magnifying property of attention, with which we are all familiar from private experience, appears to be borne out when the ''mind,'' or mental processing, is observed by the objective methods of the psychological and neurobiological laboratories.

The term *mind* points to a variety of functions of the brain—thinking, feeling, intending, perceiving, judging, and so on—whereas the term *mindfulness* or *attention* points to the characteristic way in which any of these functions can move to center stage (or can move other functions off stage) at any given moment. But the emphasis conferred on a particular mental activity as we attend to it or become mindful of it can vary continuously from a high intensity, when the mind seems completely occupied by that process, to a zero intensity, when that process is carried out automatically. When we first learn to read, we give all our attention to the perception of individual words, but with practice the identification of words requires less attentional emphasis and more attention can be directed to understanding what we are reading. This book is about how this ''mental emphasis'' is useful to the individual, and about how the brain is constructed to enable such emphasis to take place.

My approach here incorporates two assumptions: attention can be expressed in many pathways of the brain, particularly in areas of the cerebral cortex that serve specific cognitive activities such as reading words or understanding sentences, and attentional activity in each of these pathways can be intensified to varying degrees by signals arising from a structure of the brain called the thalamus.

One function of the thalamus during waking appears to be the enhancement or elevation of localized brain activities corresponding to mental functions. Anatomical details are postponed to later sections of this book, but a few general observations about the relation of the thalamus to the cerebral cortex are appropriate at this point. The thalamus is about the size of the end segment of the little finger and is located in the interior region of the brain. From this central position in the brain, the thalamus connects directly with virtually all areas of the cortex, the thin, surface layer of the brain that is rich in circuits that serve cognitive computations. The circuitry of the thalamus is apparently capable of enhancing activity in a restricted set of cortical neurons. For example, it can elevate activity in sets of cells that code a green object while activities in neighboring cells that code blue objects remain at a lower level; or it may enhance activity in cells that code the spatial location of a particular letter of a printed word while the activities in cells that code neighboring letter locations remain at a lower level.

The elevation of activity in cortical neurons coding for a particular item (whether it be the color green or a baby's cry from the nursery or the perfect word to describe your mood) above the activity in neurons coding for similar or neighboring items is assumed in this book to express the way that attention selects one object or idea when a group of objects or ideas is presented to our senses or to our cognitive consideration. As a general rule, attention is intensified when an item (an object or an idea) is accompanied by other items, particularly when the neighboring items are similar to the target item. We are familiar with experiencing an elevated concentration of attention when we reach for a pencil on a desk cluttered with other objects, and when we attempt to identify a face in a room crowded with other faces.

The process of attending to things, like breathing, is ever present in our waking lives. As noted over a hundred years ago by William James, ''Every one knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought'' (James, 1890, p. 403). Such familiarity, however, has not conferred a scientific understanding of how attention works. Among psychologists, attention has been characterized by a broad array of metaphors: a filter (Broadbent, 1958), effort (Kahneman, 1973), resources (Shaw and Shaw, 1978), a control process of short-term memory (Shiffrin and Schneider, 1977), orienting (Posner, 1980), conjoining object features (Treisman and Gelade, 1980), a spotlight that moves (Tsal, 1983), a gate (Reeves and Sperling, 1986), a zoom lens (Eriksen and St. James, 1986), and both a selective channel and a preparatory activity distribution (LaBerge and Brown, 1989). The existence of so many diverse views of attention among researchers in the field highlights the daunting mystery of how to describe the way attention works, regardless of how intimately acquainted we are with using it.

A Multidisciplinary Approach

Some aspects of human biology, such as respiration and circulation, have yielded rather easily to our understanding, because access to the relevant anatomical structures and physiological functions is relatively direct. Others, such as perception, learning, decision-making, and attention, are much more difficult to investigate because the underlying anatomical structures are difficult to observe; neural structures, by which these activities operate, are very small, and physiological indicators of neural activity often produce ambiguous results, owing to the difficulty of isolating one cognitive activity from another.

Breathing is as familiar to us as attention, but what has given the researcher of breathing a massive head start over the researcher of attention is a clear conception of the way that breathing is expressed in bodily structures. Until recent times, researchers of a cognitive process such as attention or learning had no more than speculations of how the process might be expressed in brain structures, if they ventured to pose this question at all. We know that breathing is expressed as the movement of air into and out of the lungs (the goal being the exchange of O_2 and CO_2 gases), and circulation is expressed as the movement of fluid through the blood vessels of the body (the goal being the pickup and delivery of substances). With these concepts at hand, researchers could then move directly and easily to the discovery of the bellows-like mechanism responsible for respiration and the pump-like mechanism responsible for circulation, which led to an understanding of how these processes work.

Currently, an increasing number of researchers of cognitive activities are asking how these processes are expressed in the underlying biological hardware. In the field of learning, for example, it is now generally known that one kind of learning that occurs in the hippocampus (among other brain sites), long-term potentiation (LTP), is expressed as a change (reduction) in the number of discharges arriving at the input of a neuron needed to produce a discharge at the output of a neuron. (''Discharges'' are transient electrical signals by which neurons communicate with other cells and send messages from one part of a cell to another.) A good deal of current research activity in the field of learning is now devoted to determining the mechanism that produces this expression of learning.

An important part of the approach to attention described in this book is the attempt to discover the way or ways in which attention is expressed in the brain. One way to move effectively toward this discovery is to ask what goals attention is expected to achieve for the system, or, put otherwise, what problems it is expected to solve to make the system more adaptable to its environment. Often answers to these questions are given in behavioral or cognitive terms and lead to the design of effective psychological tasks necessary for the testing of hypotheses concerning attention, or to the design of appropriate attention tasks to be carried out while physiological measures (such as positron emission tomography, or PET, scans) are taken. But it is also particularly helpful to answer these questions in terms of the types of computations needed to solve specific problems and then search the myriad kinds of activities expressed in brain pathways for these computation types.

Once the expression of attention in brain pathways is ascertained, the next step is to discover what mechanism or mechanisms produce the expression of attention. That is, the expression of attention in the brain is assumed to be produced by some mechanism that embodies or instantiates an appropriate algorithm whose output is the expression of attention in neural tissue. Having computational descriptions of attentional expression in hand can greatly reduce the number of candidate mechanisms.

But the cognitive-neuroscience story of attention, like the biological story of respiration and circulation, also requires a specification of what regulates or controls the mechanism that produces the immediate expression of the activity. Thus, the present approach to attention consists of four considerations: its *goals* (preferably stated in computational terms), its *expression(s)* in brain pathways, its *mechanism(s),* and its sources of *control.*

Given these various parts of the problem, understanding the dismaying complexity of attention seems out of the reach of a single scientific discipline. Psychological research reveals ''what is done'' by attention as individuals respond adaptively to cognitive and behavioral task demands, but the history of psychology has not produced a single attentional metaphor or even a small set of interrelated metaphors on which most experts in the field agree. Philosophical considerations of ''what it is like'' experientially to be paying attention to something, which began this chapter, are usually framed in the context of the more general and probably more complex problem of consciousness, which has eluded our understanding for centuries.

On the other hand, neurobiological methods cannot be expected to reveal ''how attention operates'' if we have no idea of what sort of activity to look for, that is, what activity enables the system to solve the class of problems regarded as attentional. Furthermore, the computational approach of thinking up abstract algorithms (effective procedures) that describe ''what is being computed'' while paying attention could generate an endless list of possibilities if we were ignorant of the range of computations available to the brain and the kinds of behavioral problems attention solves for the individual.

In reaction to this state of affairs, many researchers of attention are beginning to combine some of the foregoing methodologies, in particular the methods of cognitive psychology, computer science, and neuroscience. Psychological tasks evoke attentional processing and can demonstrate its adaptive advantage in performing behavioral and cognitive tasks, while analyses of information input and output show what problems attention needs to solve to achieve these adaptive advantages. Together the psychological and computational analyses can guide the neuroscientist's search for brain areas and brain processes that implement attentional computations. Researchers who combine these methodologies in various ways have spawned the new interdisciplinary fields of inquiry of cognitive neuroscience, computational neuroscience, and cognitive science. This book attempts to combine cognitive, computational, and neuroscience research methods to build a testable theory of attention. At the same time, it uses the more experiential analyses of some philosophical approaches to ferret out important examples of attentional processing and to help maintain a synoptic view of attention in the face of highly detailed psychological and neurobiological data.

Combining methodologies and data from cognitive and biological sciences is, of course, not a new phenomenon among researchers. William James, whose work in cognitive psychology leaned heavily toward philosophy throughout his career, trained for and obtained the M.D. degree and laced his *Principles of Psychology* with references to "currents among the cells and fibers of his brain" (1890; see, e.g., vol. 2, p. 527). Since that time many psychological researchers have called themselves psychophysiologists.

Today, computational neuroscientists seek to explain how electrical and chemical signals are used in the brain to process information. Information is a well-defined notion for the computer: it is measured precisely in units of "bits" according to Shannon's logarithmic formula

$$I(s) = \log_2 \frac{1}{p(s)}$$

where $p(s)$ is the probability that a particular signal or event, s, will occur and $I(s)$ is the amount of information transmitted in bits when that signal or event occurs (Shannon and Weaver, 1949). The label of the information unit, *bit,* is a contraction of the words *binary digit,* and the expression of information units in binary form is made explicit in the equation by the use of the base-2 logarithm.

While the information in computers can be regarded as symbolic "representations" of messages or events, it is not clear that information in the nervous system "represents" something in the same sense (Freeman, 1975; see also Rumelhart and McClelland, 1986, on the notion of neural information processing as "subsymbolic"). Furthermore, psychological studies have shown that some human limitation in processing may be defined more appropriately in terms of "chunks" rather than bits (e.g., Miller, 1955); for example, humans can briefly remember about seven randomly presented letters, but if a very long sequence of letters is chunked into familiar words (e.g., appletablewindowtelevision), then humans in effect can remember a great many more letters. Computers, in contrast, have strict limits on the number of bits that can be stored in hardware and therefore cannot compress many bits into a single chunk in the way that humans do.

Although the nature of information processed by the nervous system may be fundamentally different from the "Shannon-information" processed by computers, both kinds of information are based on a form of signaling that, among other things, is independent of the energy level of the signal event. In general, a yes-or-no message conveys the same amount of information to a human whether it is whispered or shouted, and the same amount of information to a computer whether it is typed in with a weak or strong hand at the keyboard.

Information, however defined, is transferred within and between neurons by electrochemical events. The spatial and temporal patterns of these signal-like events are assumed to constitute computational processing just as the spatial and temporal coincidences of electrical pulses instantiate computations within an electrical computer.

The information that forms the ingredients of these computations is embodied in the sequence of signals conveyed along pathways within the computer and the brain. It turns out that the measure of Shannon-information in a sequence of signals in a specific computer pathway can almost always be precisely related to the general input-output functions of the computer (one misspelled word can prevent a program from running), while a Shannon-information measure of the sequence of discharges in a specific brain pathway rarely has so direct a relationship with human cognitive or behavioral outcomes (a misspelled word often goes undetected while a person reads a novel). One can easily sympathize with the neuroscientist who awaits a definition of neural information that could provide the kind of powerful predictive and explanatory link between local signal sequences and global system functions that is enjoyed by computer scientists as they work with artificial information-processing systems.

Cognitive neuroscientists may go beyond considerations of neural information processing to address the cognitive and behavioral consequences of the brain's computations, such as attending, believing, desiring, judging, deciding, finding food, or escaping a predator, all of which are generally useful to the individual's survival. While these cognitive and behavioral products of brain signaling can in principle be programmed into computer hardware of the appropriate design, other mental phenomena are believed to lie outside of the domain of the computer at the present time. Examples of mental activities that are believed to resist duplication in programming are understanding (e.g., Searle, 1980) and mental qualities, or "qualia," for example, perceived colors and aromas and feelings (Nagel, 1986; McGinn, 1991); others oppose this position (e.g., Churchland, 1986; Dennett, 1991).

The psychological approach to understanding attention, viewed here in terms of the question of "what is done" by attention to give the individual an adaptive advantage, leads one toward the topic of the goals of attention. In the following sections I describe both the adaptive goals served by attention and the manifestations of attention, or what it is that attention does that allows the individual to meet these goals.

The Goals of Attention

Being able to pay attention has three major benefits for an individual: accuracy, speed, and maintenance of mental processing. These are defined in behavioral and cognitive terms, and in what follows

I frame the definitions in a general manner in order to encompass most of the attentional goals implied in the research literature.

Accurate perceptual judgments and actions. Accuracy in making a perceptual judgment or categorizing an object—correctly identifying an object, judging its aesthetic quality, and categorizing its color, orientation, size, distance away, or velocity of movement—is ordinarily not a problem for the individual when the object is the only item in the visual field. Difficulties sharply increase when other objects are in the vicinity, because information arising from distractors can confuse one's judgment of the target object, particularly when the distractors share features with the target. There is a large literature on the perceptual difficulties of searching for a target object in a visual display containing varying numbers of distractors of varying similarity to the target (e.g., Treisman and Gelade, 1980; Duncan and Humphreys, 1989). When objects are examined one by one in search tasks, it is assumed that attention restricts the range of incoming sensory information so that the information that is to be judged or identified arises from only the target object.

The accurate planning and performing of an action, whether that action be an external response or an internal mental operation, runs into difficulties when other, similar actions are available to the individual and when several separable actions or operations must be coordinated (e.g., Allport, 1989; Duncan, 1994; Pashler, 1992). When an individual is processing action information, attention may promote performance accuracy by preventing cross-talk between brain areas responsible for similar actions as an intended action is executed; this is similar to restricting sensory information when the goal of attention is increasing accuracy in perceptual judgments. Another goal, which currently is generating an increasing amount of research, is the organization of neural activity (e.g., Allport, 1989; Duncan, 1994) involved in the planning of actions.

When a mental process requires the organization or coordination of activities of more than one action component, attention is assumed to select an image of some kind (an image, e.g., of a goal of the action) to serve as an anchor around which the action components are organized or coordinated. An example of what might be called "organization anchoring" in planning to take an action is keeping in one's mind a sensorimotor image of how one would hold three large bags in two arms, or focusing on an intended meaning as one coordinated a sequence of words into an effective sentence. At the same time, attending to the goals of holding three bags or expressing an intended meaning protects the anchoring images from the interfering influences of related thoughts or actions (such as wondering which bag contains the milk you've just bought or writing key words concerning your talk on a blackboard). In view of these considerations, it would seem plausible to assume that attentional enhancement of an organizational anchor also contributes to the effectiveness of performance.

Thus, attention can increase the accuracy of perceptual judgments by selecting information flow on the input side of cognitive processing, and attention can increase the accuracy of actions on the output side of cognitive processing by selecting information flow in the organizing and planning of both internal and external actions.

Speeded perceptual judgments and actions. Attention increases the speed with which perceptual judgments and the planning/performance of actions takes place. When a stimulus is expected to occur, the expectation can direct attention to elevate activity at relevant brain sites prior to the actual occurrence of the stimulus, so that when the stimulus appears perceptual processing takes less time than it would had the stimulus not been expected. A driver can make a quicker start by anticipating a green light, and someone waiting for the phone to ring will be the first to answer it. In a somewhat similar manner, when an action is expected to be performed, this expectation can direct attention to elevate activity in brain sites that code the particular action, so that when the action is triggered it is performed more rapidly. For example, the accelerator pedal of an automobile will be depressed more quickly and with more force at the onset of a green light when the driver is attending to the feeling of tension in his or her foot. For more complex actions, the assembling of several action components can occur more quickly when an appropriate organizational anchor is brought to attention in advance. Examples are preparing to open a locked door with a key and preparing to reply to a lengthy question. As one prepares to use a key, an organizational anchor might be the composite image of the door moving inward as the right hand is turning the inserted key and the left hand turns and pushes the door knob. For someone about to compose a reply to a question, the organizational anchor