1 Psychophysiological Science: Interdisciplinary Approaches to Classic Questions About the Mind

JOHN T. CACIOPPO, LOUIS G. TASSINARY, AND GARY G. BERNTSON

Psychophysiology is an old idea but a new science. It is a likely assumption that ever since man began to experience himself as an object of his own awareness he has had some intuitive notion that bodily changes were, in some measure, related to his moods, his sentiments, his frustrations, his elations. How to relate these dual aspects of human functioning has been a concern of philosopher-scientists throughout the course of intellectual history. (Greenfield & Sternbach, 1972, p. v)

The first *Handbook of Psychophysiology* was published more than three decades ago (Greenfield & Sternbach, 1972). Coverage in that *Handbook* emphasized the peripheral nervous system, an emphasis that many still identify with the term psychophysiology in accord with the history of psychophysiology. As is the case for physiological and other scientific fields, however, psychophysiology has changed dramatically since the appearance of its first *Handbook*. With the advent of new and powerful probes of the central nervous system (e.g., brain imaging techniques), there is an increased emphasis in the field on investigating the brain and central nervous system as they relate to behavior. Investigations of elementary physiological events in normal thinking, feeling, and interacting individuals are commonplace, and new techniques are providing additional windows through which the neural events underlying psychological processes can be viewed unobtrusively. Instrumentation now makes it possible for investigators to explore the selective activation of discrete parts of the brain during particular psychological operations in normal individuals and patients. Transcranial magnetic stimulation has made it possible to stimulate or temporarily disable a region of the brain to study its role in cognitive operations, and studies of patients with lesions are becoming more precise both in their definition of the lesion and in their specification of behavior.

Developments in tissue and blood assays, ambulatory recording devices, non-contact recording instruments, and powerful and mobile computing devices make it possible to measure physiological, endocrinological, and immunological responses in naturalistic as well as laboratory settings. New, powerful assays, including DNA genotyping, are now possible using minimally invasive or noninvasive procedures. With recent developments in molecular biology, behavioral genetics is becoming an important new player in the field. However, the views from these windows are clear only because of the deliberate efforts of knowledgeable investigators. Knowledge and principles of physiological mechanisms, biometric and psychometric properties of the measures, statistical representation and analysis of multivariate data, and the structure of scientific inference are important if veridical information is to be extracted from psychophysiological data. These are among the topics covered in depth in this *Handbook*.

The field of psychophysiology has changed dramatically in other ways as well. Psychophysiology used to be divided into distinct territories, typically defined by organ systems (e.g., the heart, eye blinks), with relatively little integration across these systems. The concept of arousal – the peripheral equivalent of the early notions of the reticular activating system in the brain – dominated the field for the better part of the twentieth century and made the selection of measure a matter of preference rather than a theoretical choice because the responses presumably reflected modulations of arousal regardless of the system one was measuring. Although low correlations among such measures were well recognized, the differences across measures were viewed as less interesting and informative at the time than the confluence of these measures.

Advances in our understanding of the neurophysiological basis of these measures have underscored the importance of the unique patterns of peripheral responses that typically emerge across situations and individuals, and the peripheral and central mechanisms that orchestrate these patterns are active areas of inquiry. As part of these inquiries, animal research, molecular studies, and computational modeling are being embraced in the

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field despite the original definition of psychophysiology in terms of the study of humans rather than nonhuman animals. Moreover, the larger social, cultural, and interpersonal contexts are now recognized as powerful determinants of brain and behavior. Monism has replaced any lingering notions of dualism, as psychological states are more likely to be conceived as represented in and acting through cortical, limbic, and brain stem regions, with influences on autonomic, neuroendocrine, and immune activity, which in turn serve to modulate crucial cellular and molecular processes. Afferent information, in turn, travels from the peripheral to the central nervous system to influence the brain and behavior in social contexts. For instance, interleukin-1β (IL-1β) in the periphery increases in response to the introduction of antigens, and this increase is reflected in the information carried along the vagal afferent nerve to the brain. As a result of these signals from the periphery, IL-1β levels in the brain are increased, producing feelings of illness and fatigue. The notion of embodied cognition has been alive and well in psychophysiology for decades (see review by Cacioppo & Petty, 1981), and the identification of canonical and mirror neurons has renewed interest in this area (Garbarini & Adenzato, 2004).

Rose (2005) noted that there are at least two voluminous scientific literatures on psychological states and physiological events that have not been effectively related to one another: the literature on the CNS mechanisms underlying a variety of psychological processes, and the literature on psychological factors and peripheral biological activities including physical health. These literatures have tended to focus on different psychological processes, but there is an increasing recognition that these two areas of study have much in common. For instance, studies of the brain during exposure to potentially stressful stimuli can be an important tool in studying stress biology and evaluating its impact in various systems (Rose, 2005). Both of these literatures are covered in this *Handbook* and, although much needs to be done to integrate these distinct lines of research, it should be apparent from the chapters in this *Handbook* that this work has begun.

With the dawning of the twenty-first century, recording standards, procedures for signal representation, and powerful techniques for multivariate statistical analyses have been established. Investigators are now as likely to be studying the interrelationships among brain, autonomic, somatic, endocrinologic, immunologic, and/or genetic processes as they are to be studying any of these systems in isolation. Moreover, given that there are many things going on in the brain at any moment in time, only a few of which are relevant to any particular peripheral organ or effect, it is now recognized that the identification of psychological and brain mechanisms that are related to peripheral changes can be advanced significantly by working from the peripheral effects back to central, psychological, and social conditions, just as it can be advanced by the more traditional, complementary approach of manipulating psychological states and observing the subsequent changes in CNS and PNS processes.

Finally, psychophysiology has always had a special appeal in scientific investigations of the mind because it offers tools for mining information about nonconscious and nonreportable states, processes, and events. Psychophysiological studies of attention and cognitive development in neonates, early sensory and attentional processes in schizophrenics, the cognitive operations underlying psychological states, and the study of sleep and dreams in older adults have helped lift the veil from these otherwise difficult-to-gauge behavioral processes.

In sum, psychophysiological research has provided insights into almost every facet of human nature, from the attention and behavior of the neonate to memory and emotions in the elderly. This book is about these insights and advances – what they are, the methods by which they came about, and the conceptualizations that are guiding progress toward future advances in the discipline. Historically, the study of psychophysiological phenomena has been susceptible to "easy generalizations, philosophical pitfalls, and influences from extrascientific quarters" (Harrington, 1987, p. 5). Our objectives in this chapter are to define psychophysiology, briefly review major historical events in the evolution of psychophysiological inference, outline a taxonomy of logical relationships between psychological constructs and physiological events, and specify a scheme for strong inference within each of the specified classes of psychophysiological relationships.

THE CONCEPTUALIZATION OF PSYCHOPHYSIOLOGY

> The body is the medium of experience and the instrument of action. Through its actions we shape and organize our experiences and distinguish our perceptions of the outside world from sensations that arise within the body itself. (Miller, 1978, p. 14)

Anatomy, physiology, and psychophysiology are all branches of science organized around bodily systems with the collective aim of elucidating the structure and function of the parts of, and interrelated systems in, the human body in transactions with the environment. Anatomy is the science of body structure and the relationships among structures.

Physiology concerns the study of bodily function or how the parts of the body work. For both of these disciplines, what constitutes a body part varies with the level of bodily organization, going from the molecular to cellular to tissue to organ to body system to the organism. Thus, the anatomy and physiology of the body are intricately interrelated. Neuroscience, in particular, stands at this intersection.

Psychophysiology is intimately related to anatomy and physiology but is also concerned with psychological phenomena – the experience and behavior of organisms in the physical and social environment. The primary distinctions between psychophysiology and behavioral neuroscience are the focus of the former on higher cognitive processes and the interest in relating these higher cognitive processes to the integration of central and peripheral processes. Among the complexity added when moving from physiology to psychophysiology are the capacity by symbolic systems of representation (e.g., language, mathematics) to communicate and to reflect on history and experience; and social and cultural influences on physiological response and behavior. These factors contribute to plasticity, adaptability, and variability in behavior. Psychology and psychophysiology share the goal of explaining human experience and behavior, and physiological constructs and processes are an explicit and integral component of theoretical thinking in psychophysiology. The subject matter of psychophysiology, after all, is an embodied phenomenon.

The technical obstacles confronting early studies, the importance of understanding the physiological systems underlying observations, and the diverse goals and interests of the early investigators in the field fostered a partitioning of the discipline into physiological/measurement areas. The organization of psychophysiology in terms of underlying physiological systems, or what can be called *systemic psychophysiology*, remains important today for theoretical and pedagogical reasons. Physiological systems provide the foundation for human processes and behavior and are often the target of systematic observation. An understanding of the physiological system(s) under study and the bioelectrical principles underlying the perceptual and output responses being measured contribute to the plausible hypotheses, appropriate operationalizations, laboratory safety, discrimination of signal from artifact, acquisition and analysis of the physiological events, legitimate inferences based on the data, and theoretical advancement.

Like anatomy, physiology, and psychology, however, psychophysiology is a broad science organized in terms of a thematic as well as a systemic focus. The organization of psychophysiology in terms of topical areas of research can be called *thematic psychophysiology*. For instance, cognitive psychophysiology concerns the relationship between elements of human information processing and physiological events. Social psychophysiology concerns the study of the cognitive, emotional, and behavioral effects of human association as related to and revealed by physiological measures, interventions, and consequences including the reciprocal relationship between physiological and social systems. Developmental psychophysiology deals with ontological changes in psychophysiological relationships as well as the study of psychological development and aging using physiological measures. Clinical psychophysiology concerns the study of disorders in the organismic-environmental transactions and ranges from the assessment of disorders to interventions and treatments. Environmental psychophysiology elucidates the vagaries of organism-place interdependencies as well as the health consequences of design through unobtrusive physiological measurements. And applied psychophysiology generally deals with the implementation of psychophysiological principles in practice, such as operant training ("biofeedback"), desensitization, relaxation, and the detection of deception.

In each of these areas, the focus of study draws on, but goes beyond, the description of the structure or function of cells or organs, to investigate the organism in transactions with the physical or sociocultural environment. Some of these areas, such as developmental psychophysiology, have counterparts in anatomy and physiology but refer to complementary empirical domains that focus on human experience and behavior. Others, such as social psychophysiology, have a less direct counterpart in anatomy or physiology because the focus begins beyond that of an organism in isolation; yet the influence of social and cultural factors on physiological structures and functions, and their influence as moderators of the effects of physical stimuli on physiological structures and functions, leaves little doubt as to the relevance of these factors for anatomy and physiology as well as for psychophysiology. Meaney and colleagues (Meaney, Bhatnagar, Larocque, McCormick, Shanks, Smythe, Viau, & Plotsky, 1996), for instance, provide evidence that rat pups who are ignored by their mothers develop a more reactive hypothalamic pituitary adrenocortical (HPA) axis than rat pups who are licked and groomed by their mothers.

Because psychophysiology is intimately related to anatomy and physiology, knowledge of the physiological systems and responses under study contribute to both theoretical and methodological aspects of psychophysiological research. However, knowledge of the physiological systems is logically neither necessary nor sufficient to ascribe psychological meaning to physiological responses. The ascription of psychological meaning to physiological responses ultimately resides in factors such as the quality of the experimental design, the psychometric properties of the measures, and the appropriateness of the data analysis and interpretation. For instance, although numerous aspects of the physiological basis of event-related brain potentials remain uncertain, functional relationships within specific paradigms have been established between elementary cognitive operations and components of these potentials by systematically varying one or more of the former and monitoring changes in the latter.

The point is not that either the physiological or the psychological perspective is preeminent, but rather that both are fundamental to psychophysiological inquiries; more specifically, that physiological and psychological levels of organization are complementary. Inattention to the logic underlying psychophysiological inferences simply because one is dealing with observable physiological events is likely to lead either to simple and restricted descriptions of empirical relationships or to erroneous interpretations of these relationships. Similarly, "an aphysiological attitude, such as is evident in some psychophysiological research, is likely to lead to misinterpretation of the empirical relationships that are found between psychophysiological measures and psychological processes or states" (Coles et al., 1986, ix–x). Thus, whether organized in terms of a systemic or a thematic focus, psychophysiology can be conceptualized as a natural extension of anatomy and physiology in the scientific pursuit of understanding human processes and behavior. It is the joint consideration of physiological and functional perspectives, however, that is thought to improve operationalization, measurement, and inference and therefore to enrich research and theory on cognition, emotion, and behavior.

Early definitions of the field of psychophysiology were of two types. One emphasized the operational aspects of the field such as research in which the polygraph was used, research published by workers in the field, and research on physiological responses to behavioral manipulations (e.g., Ax, 1964b). Other early definitions were designed to differentiate psychophysiology from the older and more established field of physiological psychology or psychobiology. Initially, psychophysiology differed from physiological psychology in the use of human in contrast to animals as participants, the manipulation of psychological or behavioral constructs rather than anatomical structures or physiological processes, and the measurement of physiological rather than behavioral responses (Stern, 1964). Although this heritage can still be found, this distinction is often blurred by the fact that psychophysiologists may modify physiology with drugs or conditioning procedures, and psychobiologists often manipulate psychological or behavioral variables and measure physiological outcomes. Contemporary definitions are more likely to emphasize the mapping of the relationships between and mechanisms underlying psychological and physiological events (e.g., Hudgahl, 1995; Stern, Ray, & Quigley, 2001).

A major problem in reaching a consensus has been the need to give the field direction and identity by distinguishing it from other scientific disciplines while not limiting its potential for growth. Operational definitions are unsatisfactory for they do not provide long-term direction for the field. Definitions of psychophysiology as studies in which psychological factors serve as independent variables and physiological responses serve as dependent variables distinguish it from fields such as psychobiology but have been criticized for being too restrictive (Furedy, 1983). For instance, such definitions exclude studies in which physiological events serve as the independent/blocking variable and human experience or behavior serve as the dependent variable (e.g., the sensorimotor behavior associated with manipulations of the physiology via drugs or operant conditioning, or with endogenous changes in cardiovascular or electroencephalographic activity) as well as studies comparing changes in physiological responses across known groups (e.g., the cardiovascular reactivity of offspring of hypertensive vs. normotensive parents).

Moreover, psychophysiology and psychobiology share goals, assumptions, experimental paradigms, and, in some instances, databases, but differ primarily in terms of the analytic focus. In psychophysiology the emphasis is on integrating data from multiple levels of analysis to illuminate psychological functions and mechanisms rather than physiological structures per se. All of these substantive areas have a great deal to contribute to one another, and ideally this complementarity should not be masked in their definition by the need to distinguish these fields. Indeed, the formulation of structure-function relationships is advanced to the extent that "top down" and "bottom up" information can be integrated. The emergence of areas of research in cognitive neuroscience, psychoneuroendocrinology, and psychoneuroimmunology raise additional questions about the scope of psychophysiology.

Anatomy and physiology encompass the fields of neurology, endocrinology, and immunology due both to their common goals and assumptions, and to the embodiment, in a literal sense, of the nervous, endocrine, and immunologic systems within the organism. Relatedly, psychophysiology is based on the assumptions that human perception, thought, emotion, and action are embodied phenomena; and that measures of physical (e.g., neural, hormonal) processes can therefore shed light on the human mind. The level of analysis in psychophysiology is not on isolated components of the body, but rather on organismic-environmental transactions. That is, psychophysiology represents a top-down approach within the neurosciences that complements the bottom-up approach of psychobiology. Thus, psychophysiology can be defined as the scientific study of social, psychological, and behavioral phenomena as related to and revealed through physiological principles and events in functional organisms. Thus, psychophysiology is not categorically different from behavioral neuroscience, but rather there is currently a greater emphasis in psychophysiology on higher cognitive processes and on relating these higher cognitive processes to the integration of central and peripheral processes.

In the following section, we review some of the major historical developments that have influenced contemporary thinking and research in psychophysiology. As might be expected from the discussion thus far, many of these early developments have stemmed from studies of human anatomy and physiology.

HISTORICAL DEVELOPMENTS

Psychophysiology is still quite young as a scientific field. Studies dating back to the turn of the prior century can be found involving the manipulation of a psychological factor and the measurement of one or more physiological responses (e.g., Berger, 1929; Darrow, 1929; Eng, 1925; Jacobson, 1930; Mosso, 1896; Peterson & Jung, 1907; Sechenov, 1878; Tarchanoff, 1890; Wenger, 1941; Wilder, 1931; see also, Woodworth & Schlosberg, 1954), and such studies would now be considered as falling squarely under the rubric of psychophysiology. Chester Darrow (1964), in the inaugural Presidential Address of the Society for Psychophysiological Research, identified Darwin (1872/1873), Vigoroux (1879), James (1884), and Fere (1888) as among the field's earliest pioneers, yet the mixed responses of the scientific community to this pioneering work affected the field for decades (see Daston, 1978).

The first scientific periodical devoted exclusively to psychophysiological research, the Polygraph Newsletter, was not begun until 1955 and was published until 1963 (Ax, 1964a). There was an organizational meeting in 1959 in Cincinnati, a business meeting in 1960 in Chicago, and the first scientific meeting in 1961 in New York City. The first independent meeting of Society for Psychophysiological Research, however, occurred in Denver in 1962, and the Society was incorporated in 1963 at the Detroit meeting. Based on this history, one might surmise that the Society formed in 1959 and began functioning as a scientific society in 1961. The first edition of the journal, *Psychophysiology*, then subtitled "The Journal of Objective Research in the Physiology of Behavior," was published in July, 1964. When precisely psychophysiology emerged as a discipline, therefore, is difficult to specify, but it is usually identified with the first business meeting of the Society for Psychophysiological Research in 1960 or with the publication of the first issue of the journal, *Psychophysiology*, in 1964 (e.g., Fowles, 1975; Greenfield & Sternbach, 1972; Sternbach, 1966).

Although psychophysiology as a formal discipline has been around just over half a century, interest in interrelationships between psychological and physiological events can be traced as far back as the early Egyptians and Greek philosopher-scientists. The Greek philosopher Heraclitus (c. 600 B.C.) referred to the mind as an overwhelming space whose boundaries could never be fully comprehended (Bloom, Lazerson, & Hofstadter, 1985). Plato (c. 400 B.C.) suggested that rational faculties were located in the head; passions were located in the spinal marrow and, indirectly, the heart; and instincts were located below the diaphragm where they influenced the liver. Plato also believed the psyche and body to be fundamentally different; hence, observations of physiological responses provided no grounds for inference about the operation of psyche (Stern, Ray, & Quigley, 2001). Thus, despite the fact that the peripheral and central nervous system, brain, and viscera were known to exist as anatomical entities by the early Greek scientists-philosophers, human nature was dealt with as a incorporeal entity not amenable to empirical study.

In the second century A.D., Galen (c. 130–200) formulated a theory of psychophysiological function that would dominate thought well into the eighteenth century (Brazier, 1961; Wu, 1984). Hydraulics and mechanics were the technology of the times, and aqueducts and sewer systems were the most notable technological achievements during this period. Bloom et al. (1985, p. 13) suggest: "It is hardly by accident, then, that Galen believed the important parts of the brain to lie not in the brain's substance, but in its fluid-filled cavities" (p. 13). Based on his animal dissections and his observations of the variety of fluids that permeated the body, Galen postulated that humors (fluids) were responsible for all sensation, movement, thoughts, and emotion; and that pathologies – physiological or behavioral – were based on humoral disturbances. The role of bodily organs was to produce or process these humors, and the nerves, although recognized as instrumental in thought and action, were assumed to be part of a hydraulic system through which the humors traveled. Galen's views became so deeply entrenched in Western thought that they went practically unchallenged for almost 1500 years (cf. Kottek 1979).

In the sixteenth century, Jean Fernel (1497–1558) published the first textbook on physiology, *De Naturali Parte Medicinae* (1542). According to Brazier (1959), this book was well received, and Fernel revised and expanded the book across numerous editions. The ninth edition of the book was retitled *Medicina*, and the first section was entitled *Physiologia*. Although Fernel's categorization of empirical observations was strongly influenced by Galen's theory, the book "shows dawning recognition of some of the automatic movements which we now know to be reflexly initiated" (Brazier, 1959, p. 2). This represented a marked departure from traditional views that segregated the control of human action and the affairs of the corporeal world.

Studies of human anatomy during this period in history also began to uncover errors in Galen's descriptions (e.g., Vesalius, 1543/1947), opening the way for questions of his methods and of his theory of physiological functioning and symptomatology. Within a century, two additional events occurred that had a profound impact on the nature of inference in psychophysiology. In 1600, William Gilberd (1544–1603) recognized a difference between electricity and magnetism and, more importantly, argued in his book, *De Magnete, Magneticisque Corporibus, et de Magno magnete tellure*, that empirical observations and experiments should replace "the probable guesses and opinions of the ordinary professors of philosophy."

In addition, the reign of authority as the source of answers to questions about the basis of human experience and behavior was challenged by the work of scholars including Galileo, Bacon, and Newton. Galileo (1564–1642) challenged knowledge by authority in matters of science, by which Galileo meant physical sciences and mathematics. He argued that theologians and philosophers had no right to control scientific investigation or theories, and that observation, experiment, and reason along could establish physical truth (Drake, 1967). Galileo was also aware of limitations of sense data. Concerned with the possibility of illusion and misinterpretation, Galileo believed that mathematics alone offered the kind of certainty that could be completely trusted. Galileo did not extend this reasoning beyond the physical sciences, but scientific investigations of the basis of human experience and behavior benefited from his rejection of authority as a source of knowledge about physical reality, his emphasis on the value of skepticism, and his insistence that more could be learned from results that suggested ignorance (disconfirmation) than from results that fit preconceptions (confirmation).

Francis Bacon (1561–1626) took the scientific method a step further in *Novum Organum* (1620/1855), adding induction to observation and adding verification to inference. Bacon was not a scientist, yet he is regarded as a forerunner of the hypothetico-deductive method (Brazier, 1959; Caws, 1967). Subsequent work on the logic of scientific inference (Popper, 1959/1968) led to the now familiar sequence underlying scientific inference: (1) devise alternative hypotheses; (2) devise a crucial experiment, with alternative possible outcomes, each of which will disfavor if not exclude one or more of the hypotheses; (3) execute the experiment to obtain a clean result; and (4) recycle to refine the possibilities that remain. Such a scheme was accepted quickly in the physical sciences, but traditional philosophical and religious views segregating human existence from worldly events slowed its acceptance in the study of human physiology, experience, and behavior (Brazier, 1977; Harrington, 1987; Mecacci, 1979).

William Harvey's (1578–1657) doctoral dissertation, *De Motu Cordis* (1628/1941), represented not only the first major work to use these principles to guide inferences about physiological functioning, but it also disconfirmed Galen's principle that the motion of the blood in the arterial and venous systems ebbed and flowed independent of one another except for some leakage in the heart. Pumps were an important technological development during the seventeenth century, and Harvey perhaps drew on his observations of pumps in positing that blood circulated continuously through a circular system, pushed along by the pumping actions of the heart, and directed through and out of the heart by the one-way valves in each chamber of the heart. Galen, in contrast, had posited that blood could flow in either direction in the veins. To test these competing hypotheses, he tied a tourniquet above the elbow of his arm just tight enough to prevent blood from returning to the heart through the veins but not so tight as to prevent blood from entering the arm through the arteries. The veins swelled below, but not above the tourniquet, implying that the blood could be entering only through the arteries and exiting only through the veins (Miller, 1978). A variation on Harvey's procedure is used in contemporary psychophysiology to gauge blood flow to vascular beds (Williams, 1984).

During this period, which coincided with a burgeoning world of machines, the human eye was conceived as functioning like an optical instrument. Images were conceived as projected onto the sensory nerves of the retina. Movement was thought to reflect the mechanical actions of passive balloon-like structures (muscles) that were inflated or deflated by the nervous fluids or gaseous spirits that traveled through canals in the nerves. And higher mental functions were still considered by many to fall outside the rubric of the physical or biological sciences (Bloom et al., 1985; Brazier, 1959; Harrington, 1987). The writings of Rene Descartes (1596–1650) reflects the presumed division between the mind and body. The actions of animals were viewed as reflexive and mechanistic in nature, as were most of the actions of humans. But humans alone, Descartes argued, also possess a consciousness of self and of events around them, a consciousness which, like the body, was a thing but, unlike the body, was not a thing governed by material principles or connections. This independent entity called mind, Descartes proposed, resides over volition from the soul's control tower in the pineal gland located at the center of the head:

> The soul or mind squeezed the pineal gland this way and that, nudging the animal fluids in the human brain into the pores or valves, 'and according as they enter or even only as they tend to enter more or less into this or that nerve, they have the power of changing the form of the muscle into which the nerve is inserted, and by this means making the limbs move.' (Jaynes, 1973, p. 172, paraphrasing and quoting from Descartes, 1824, p. 347)

Shortly following Descartes' publication of *Traite de l'Homme* (c. 1633), Steno (1638–1686) noted several discrepancies between Descartes' dualistic and largely mechanistic characterization of human processes and the extant evidence about animal and human physiology. For instance, Steno noted that the pineal gland (the purported bridge between the worlds of the human mind and body) existed in animals as well as humans, that the pineal gland did not have the rich nerve supply implied by Descartes' theory, and that the brain was unnecessary to many animal movements (cf. Jaynes, 1973). Giovanni Borelli (1608–1679) disproved the notion that movement was motivated by the inflation of muscles by a gaseous substance in experiments in which he submerged a struggling animal in water, slit its muscles, and looked for the release of bubbles (Brazier, 1959). These observations were published posthumously in 1680, shortly after the suggestion by Francesco Redi that the shock of the electric ray fish was muscular in origin (Basmajian & De Luca, 1985, Ch. 1; Wu, 1984).

Despite the prevalent belief during this period that the scientific study of animal and human behavior could apply only to those structures they shared in common (Bloom et al., 1985; Harrington, 1987), the foundations laid by the great seventeenth-century scientist-philosophers encouraged students of anatomy and physiology in the subsequent century to discount explanatory appeals to the human soul or mind (Brazier, 1959). Consequently, experimental analyses of physiological events and psychological constructs (e.g., sensation, involuntary and voluntary action) expanded and inspired the application of technological advances to the study of psychophysiological questions. For instance, the microscope was employed (unsuccessfully) in the late seventeenth century to examine the prevalent belief that the nerves were small pipes through which nervous fluid flowed.

According to Brazier (1959, 1977), that electricity might be the transmitter of nervous action was initially seen as unlikely because, drawing upon the metaphor of electricity running down a wire, there was believed to be insufficient insulation around the nerves to prevent a dissipation of the electrical signal. Galvani and Volta's (c. 1800) experiments demonstrated that nerves and muscles were indeed electrically excitable, and research by Du Bois-Reymond (1849) established that nerves and muscles were electrically polarized as well as excitable. Based on reaction times, Helmholtz (c. 1850) correctly inferred that nerves and muscles were not like wires because they propagated electrical impulses too slowly. The work that followed ultimately verified that neural signals and muscular actions were electrical in nature, that these electrical signals were the result of biochemical reactions within specialized cells, and that there was indeed some dissipation of these electrical signals through the body fluids that could be detected noninvasively at the surface of the skin. Specific advances during the nineteenth and twentieth centuries in psychophysiological theory and research are discussed in the remainder of this book. However, the stage had been set by these early investigators for the scientific study of psychophysiological relationships.

PSYCHOPHYSIOLOGICAL RELATIONSHIPS AND PSYCHOPHYSIOLOGICAL INFERENCE

> We praise the 'lifetime of study,' but in dozens of cases, in every field, what was needed was not a lifetime but rather a few short months or weeks of analytical inductive inference . . . We speak piously of taking measurements and making small studies that will 'add another brick to the temple of science.' Most such bricks just lie around the brickyard. (Platt, 1964, p. 351)

The importance of the development of more advanced recording procedures to scientific progress in psychophysiology is clear, as previously unobservable phenomena are rendered observable. Less explicitly studied, but no less important, is the structure of scientific thought about psychophysiological phenomena. For instance, Galen's notions about psychophysiological processes persisted for 1500 years despite the availability for several centuries of procedures for disconfirming his theory in part because the structure of scientific inquiry had not been developed sufficiently.

An important form of psychophysiological inference to evolve from the work of Francis Bacon (1620/1855) and Galileo (Drake, 1967) is the hypothetico-deductive logic outlined above. If the data are consistent with only one of the theoretical hypotheses, then the alternative hypotheses with which the investigator began become less plausible. With conceptual replications to ensure the construct validity, replicability, and generalizability of such a result, a subset of the original hypotheses can be discarded, and the investigator recycles through this sequence. One weakness of this procedure is the myriad sources of variance in psychophysiological investigations and the stochastic nature of physiological events and, consequently, the sometimes poor replicability or generalizability of the results. A second is the intellectual invention and omniscience that is required to specify all relevant alternative hypotheses for the phenomenon of interest. Because neither of these can be overcome with certitude, progress in the short term can be slow and uncertain. Adherence to this sequence provides grounds for strong inference in the long term, however (Platt, 1964).

Physiological responses are often of interest, however, only to the extent that they allow one to index a psychological process, state, or stage. A general analytic framework that has aided the design and interpretation of studies in the area is the subtractive method that has been adapted from studies of mental chronometry. Donders (1868), a Dutch physiologist, proposed that the duration of different stages of mental processing could be determined by subtracting means of simpler tasks that were matched structurally to subsequences of more complex tasks. At the simplest level, experimental design begins with an experimental and a control condition. The experimental condition represents the presence of some factor, and the control condition represents the absence of this factor. The experimental factor might be selected because it is theoretically believed to depend on n information processing stages, and the construction of the control condition is guided to incorporate $n - 1$ information processing stages. This kind of analysis assumes, and depends mathematically on the assumption, that the information processing stages are arranged in strictly serial order with each stage running to completion prior to the initiation of the next.

Nevertheless, the principle underlying the extension of the subtractive design to include physiological (e.g., functional magnetic resonance imaging) measures is twofold: (a) physiological differences between experimental conditions thought to represent n and $n-1$ processing stages supports the theoretical differentiation of these stages, and (b) the nature of the physiological differentiation of experimental conditions (e.g., the physiological signature of a processing stage) may further support a particular psychological characterization of that information processing stage. According to the subtractive method, the systematic application of the procedure of stage deletion (across conditions of an experimental design) makes it possible to deduce the physiological signature of each of the constituent stages underlying some psychological or behavioral response. For instance, if the experimental task ($n+1$ stages) is characterized by greater activation of Broca's area than the control task, this is consistent with both the theoretical conception of the experimental and control tasks differing in one (or more) processing stage(s) and the differential processing stage(s) relating to language production.

If using conventional reaction time measures, the psychological significance of timing differences comes primarily from the putative differences between experimental conditions. With biological measures, however, the psychological significance of specific physiological differences (e.g., activation of Broca's area) comes both from the theoretical differences between experimental conditions *and* from the prior scientific literature on the psychological significance of the observed physiological difference. The convergence of these two sources of information makes social neuroscience methods potentially quite powerful even though they tend to be more complicated and nuanced.

It is important to note a critical difference in the properties of the kinds of measures used for response time experiments and for physiological measurements. If we assume that a process takes a certain period of time because it is composed of a series of steps that each takes a measurable time and wherein each must be completed before the next is begun, the decomposition of the total time into the time for each step seems relatively transparent. Note, however, that the conditions under which this kind of analysis fails are precisely those that hold in imaging experiments (Townsend & Ashby, 1983).

When a particular hypothesized stage of information processing is thought to be responsible for the differential impact of two different conditions on behavior, analyses of concomitant physiological activity can be informative, in one of two ways. If the patterns of physiological activity resulting from the isolation of presumably identical stages are dissimilar, the similarity of the stages is challenged even though there may be similarities between the subsequent behavioral outcomes (cf. Cacioppo & Tassinary, 1990). If, on the other hand, similar patterns of physiological activity result from the isolation of stages that are hypothesized to be identical, convergent evidence is obtained that the same fundamental stage is operative. Note that the greater the extant evidence linking the observed physiological event/profile to a specific psychological operation, the greater the value of the convergent evidence. These data do not provide evidence for a strong inference that the stages are the same (Platt, 1964), but instead such a result raises a hypothesis that can be tested empirically in a subsequent study (Cacioppo & Tassinary, 1990).

There are additional issues that should be considered when using a subtractive framework to investigate elementary stages of psychological processes whether using reaction time or physiological (brain) measures. The subtractive method contains the implicit assumption that a stage can be inserted or deleted without changing the nature of the other constituent stages. But this method has long been criticized for ignoring the possibility that manipulating a factor to insert or delete a processing stage might introduce a completely different processing structure (e.g., Townsend & Ashby, 1983). Using multiple operationalizations to insert or delete a stage may be helpful but this still does not insure strong inference. In addition, to construct the set of comparison tasks using the subtractive method one must already have a clearly articulated hypothesis about the sequence of events that transpires between stimulus and overt response. This assumption renders the subtractive method particularly useful in testing an existing theory about the stages constituting a psychological process and in determining whether a given stage is among the set constituting two separate processes (Cacioppo, Berntson, Lorig, Norris, Rickett, & Nusbaum, 2003). Note, however, that confirmatory evidence can still be questioned by the assertion that the addition or deletion of a particular stage results in an essentially different set of stages or substages, just as is the case with self-report or reaction time measures. If a large corpus of animal and human research links a psychological event to a processing operation, however, the plausibility of the alternative interpretation is greatly diminished.

Whenever a physiological response (or profile) found previously to vary as a function of a psychological processing stage or state is observed, yet another hypothesis is raised – namely, that the same processing stage or state has been detected. A person might be thought to be anxious because they show physiological activation, inattentive because they show diminished activation, happy because they show an attenuated startle response, deceptive because they show activation of the anterior cingulate, and so on. However, one cannot logically conclude that a processing stage or state has definitely been detected simply because a physiological response found previously to vary as a function of a psychological processing stage or state has been observed. (The logical flaw in this form of inference is termed affirmation of the consequent.) We therefore next turn to a general framework for thinking about relationships between psychological concepts and physiological events, and we discuss the rules of evidence for and the limitations to inference in each (see also Cacioppo & Tassinary, 1990; Cacioppo, Tassinary, & Berntson, 2000).

THE PSYCHOLOGICAL AND PHYSIOLOGICAL DOMAINS

A useful way to construe the potential relationships between psychological events and physiological events is to consider these two groups of events as representing independent sets (domains), where a set is defined as a collection of elements who together are considered a whole (Cacioppo & Tassinary, 1990). Psychological events, by which we mean conceptual variables representing functional aspects of embodied processes, are conceived as constituting one set, which we shall call Set Ψ. Physiological (e.g., brain, autonomic, endocrinological) events, by which we mean empirical physical variables, are conceived as constituting another, which we shall call Set Φ. All elements in the set of psychological events are assumed to have some physiological referent – that is, the mind is viewed as having a physical substrate. This framework allows the specification of five general relations that might be said to relate the elements within the domain of psychological events, Ψ, and elements within the domain of physiological events, Φ. These are as follows:

- A one-to-one relation, such that an element in the psychological set is associated with one and only one element in the physiological set, and vice versa.

- A one-to-many relation, meaning that an element in the psychological domain is associated with a subset of elements in the physiological domain.
- A many-to-one relation, meaning that two or more psychological elements are associated with the same physiological element.
- A many-to-many relation, meaning two or more psychological elements are associated with the same (or an overlapping) subset of elements in the physiological domain.
- A null relation, meaning there is no association between an element in the psychological domain and that in the physiological domain.

Of these possible relations, only the first and third allow a formal specification of psychological elements as a function of physiological elements (Cacioppo & Tassinary, 1990). The grounds for theoretical interpretations, therefore, can be strengthened if either (1) a way can be found to specify the relationship between the elements within Ψ and Φ in terms of one-to-one, or at worst, in terms of many-to-one relationships, or (2) hypothetico-deductive logic is employed in the brain imaging studies (Cacioppo, Tassinary, & Berntson, 2000).

Consider that when differences in brain images or physiological events (Φ) are found in contrasts of tasks that are thought to differ only in one or more cognitive functions (Ψ), the data are often interpreted prematurely as showing that Brain Structure (or Event) Φ is associated with Cognitive Function (Ψ). These data are also treated as revealing much the same information that would have been obtained had Brain Structure (or Event) Φ been stimulated or ablated and a consequent change in Cognitive Function Ψ been observed. This form of interpretation reflects the explicit assumption that there is a fundamental localizability of specific cognitive operations, and the implicit assumption that there is an isomorphism between Φ and Ψ (Sarter, Berntson, & Cacioppo, 1996). Interpreting studies of the form P(Φ/Ψ) (i.e., fMRI studies) as equivalent to studies of the form P(Ψ/Φ) is misleading unless one is dealing with 1:1 relationships.[1] Fundamentally, this is a premise that needs to be tested rather than treated as an assumption.

It may be useful to illustrate some of these points using a simple physical metaphor in which the bases of a multiply determined outcome are known. Briefly, let Φ represent the HVAC system, and Ψ the temperature in a house. In the context of psychophysiology, the HVAC system parallels a neural mechanism and the temperature represents the cognitive manifestation of the operation of this mechanism. Although the HVAC system and the temperature are conceptually distinct, the operation of the HVAC system represents both the manipulable cause (see Shadish, Cook, & Campbell, 2002) and a physical basis for the observed temperatures in the house. Thus, $\Psi = f(\Phi)$. A bottom-up approach (i.e., P(Ψ/Φ)) makes clear certain details about the relationship between Ψ and Φ, whereas a top-down approach (i.e., P(Φ/Ψ)) clarifies others. For instance, when the activity of the HVAC system is manipulated (i.e., Φ is stimulated or lesioned), a change in the temperature in the house (Ψ) results. This represents a bottom-up approach to investigating the physical substrates of cognitive phenomena. The fact that manipulating the activity of the HVAC system produces a change in the temperature in the house can be expressed as $P(\Psi/\Phi) > 0$. Note that the P(Ψ/Φ) need not equal 1 for Φ be a physical substrate of Ψ. This is because, in our illustration, there are other physical mechanisms that can affect the temperature in the house (Ψ), such as the outside temperature (Φ′) and the amount of direct sunlight in the house (Φ). That is, there is a lack of complete isomorphism specifiable, at least initially, between the regulated variable (Ψ) and a physical basis (Φ).

In any given context, the temperature in the house may be influenced by any or all of these physical mechanisms. If the outside temperature or the amount of direct sunlight happens to vary when the HVAC system is activated, then the temperature may not covary perfectly with the activation of the HVAC system (i.e., $P(\Psi/\Phi) < 1$) even though the temperature is, at least in part, a function of the operation of the HVAC system (i.e., $P(\Psi/\Phi) > 0$). If the outside temperature and amount of direct sunlight are constant or are perfectly correlated with the activation of the HVAC system, then the temperature in the house and the activity of the HVAC system may covary perfectly (i.e., $P(\Psi/\Phi) = 1$). In the context of psychophysiology, this is analogous to a brain lesion study accounting for some of the variance ($P(\Psi/\Phi) > 0$) or all of the variance ($P(\Psi/\Phi) = 1$) in the cognitive measure in the study. The latter result does not imply the lesioned brain region is a necessary component just as the fact that the temperature in the house covaries perfectly with the activity of the HVAC system does not mean necessarily that there are not other physical mechanisms that may also influence the temperature. Thus, as long as $P(\Psi/\Phi) > 0$, Φ could be considered a predictor (or component) of Ψ; the fact that $P(\Psi/\Phi) = 1$ does not imply that Φ is the only or a necessary cause of Ψ.

The asymmetry between P(Ψ/Φ) and P(Φ/Ψ) and the interpretive problems that may result when simply assuming $P(\Psi/\Phi) = P(\Phi/\Psi)$ are also evident in this metaphor. As outlined above, the former term represents variations in temperature in the house given variations in the activity of the HVAC system, whereas P(Φ/Ψ) represents the activity

[1] Research in which psychological or behavioral factors serve as the independent (or blocking) variables and physiological structures or events serve as the dependent variable can be conceptualized as investigating the P(Φ/Ψ). Research in which physiological structures or events serve as the independent (or blocking) variables and psychological or behavioral factors serve as the dependent variable, in contrast, can be conceptualized as investigating the P(Ψ/Φ). These conditional probabilities are equal only when the relationship between is Ψ and Φ is 1:1 (Cacioppo & Tassinary, 1990). Accordingly, approaches such as stimulation and ablation studies provide complementary rather than redundant information to studies in which physiological (e.g., fMRI) measures serve as dependent measures. This is because stimulation and ablation studies bear on the relationship P(Ψ/Φ), whereas studies in which physiological variables serve as dependent measures provide information about P(Φ/Ψ).

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Excerpt
More information

of the heater given variations in the temperature in the house. Although one would expect to find $P(\Phi/\Psi) > 0$ in some contexts, the fact that the temperature in the house is regulated when the HVAC system is activated does not necessarily imply that changes in the temperature in the house will be associated with variations in the activity of the HVAC system. In the context of local changes in temperature distant from the thermostat of the HVAC system, for example, the observed temperature will fluctuate whereas the HVAC system remains inactive (e.g., outside temperature, Φ'; exposure to direct sunlight, Φ). Thus, the finding that $P(\Phi/\Psi) = 0$ does not mean Φ has no role in Ψ, only that Φ has no role in Ψ in that context. In the context of brain imaging studies, areas that are not found to become active as a function of a cognitive operation may nevertheless be part of a physical substrate for that cognitive operation (just as a HVAC system may remain a part of the physical mechanism responsible for the temperature in a house).

The preceding example illustrates why one would not want to exclude a brain area as potentially relevant to a cognitive operation based on the area not being illuminated in a brain image as a function of the cognitive operation. The converse also holds – that is, a brain area that is illuminated as a function of a cognitive operation may or may not contribute meaningfully to the production of the cognitive operation. Consider an LED on a thermostat (which we will call Φ') that illuminates when the HVAC system (Φ) is operating. In this case, the $P(\Phi/\Psi) = P(\Phi'/\Psi) > 0$. That is, the LED represents a physical element that would show the same covariation with the temperature in the house as would the operation of the HVAC system as long as a top-down approach was used. When the complementary bottom-up approach were used, it would become obvious that disconnecting (lesioning) the HVAC system has effects on the temperature in the house whereas disconnecting (or directly activating) the LED has none.

FOUR CATEGORIES OF PSYCHOPHYSIOLOGICAL RELATIONSHIPS

Relations between elements in the psychological and physiological domains should not be *assumed* to hold across situations or individuals. Indeed, elements in the psychological domain are delimited in the subtractive method in part by holding constant other processes that might differentiate the comparison tasks. Such a procedure is no unique to psychophysiology or to the subtractive method, as most psychological and medical tests can involve constructing specific assessment contexts in order to achieve interpretable results. The interpretation of a blood glucose test, for instance, can rest on the assumption that the individual fasted prior to the onset of the test. Only under this circumstance can the amount of glucose measured in the blood across time be used to index the body's ability to regulate the level of blood sugar. The relationship between the physiological data and theoretical construct is said to have a limited range of validity, because the relationship is clear only in certain well-prescribed assessment contexts. The notion of limited ranges of validity, therefore, raises the possibility that a wide range of complex relationships between psychological and physiological phenomena might be specifiable in simpler, more interpretable forms within specific assessment contexts.

To clarify these issues, it is useful to conceptualize psychophysiological relationships generally in terms of a 2 (One-to-one vs. Many-to-one) $\times$ 2 (Situation Specific vs. Cross Situational) taxonomy. The specific families (i.e., categories) of psychophysiological relationships that can be derived from this taxonomy are depicted in Figure 1.1. The criterial attributes for, and theoretical utility in, establishing each of these categories are specified in the three dimensions illustrated in Figure 1.1; causal attributes of the relationships, and whether the relationships are naturally occurring or artificially induced constitute yet other, orthogonal dimensions and are explicitly excluded here for didactic purposes. For instance, the category in Figure 1.1 labeled "concomitant" refers only to the conditions and implications of covariation and is not intended to discriminate between instances in which the psychological factor is causal in the physiological response, vice versa, or a third variable causes both. In the sections that follow, each type of psychophysiological relationship and the nature of the inferences that each suggests are outlined.

Psychophysiological outcomes. In the idealized case, an *outcome* is defined as a many-to-one, situation-specific (context-dependent) relationship between Ψ and Φ. Establishing that a physiological response (i.e., an element in Φ) varies as a function of a psychological change (i.e., an element in Ψ) means one is dealing at the very least with an outcome relationship between these elements. Note that this if often the first attribute of a psychophysiological relationship that is established in laboratory practice. Whether the physiological response follows changes in the psychological event across situations (i.e., has the property of context independence), or whether the response profile follows only changes in the event (i.e., has the property of isomorphism) is not typically addressed initially. Hence, a given psychophysiological relationship may appear to be an outcome but subsequently be identified as being a marker as the question of isomorphism is examined; a relationship that appears to be an outcome may subsequently be reclassified as being a concomitant once the range of validity is examined; and a relationship that appears to be a marker (or concomitant) may emerge as an invariant upon studying the generalizability (or isomorphism) of the relationship. This progression is not problematic in terms of causing erroneous inferences, however, because, as we shall see, any logical inference based on the assumption one is dealing with an outcome relationship holds for marker, concomitant, or invariant psychophysiological relationships, as well.

Despite the outcome serving as the most elemental psychophysiological relationship, it can nevertheless provide