SECTION A: CONCEPTUAL FOUNDATIONS

1 *Psychophysiology and psychophysiological inference*

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> Nothing could be more obvious than that the earth is stable and unmoving, and that we are the center of the universe. Modern Western science takes its beginning from the denial of this commonsense axiom...Common sense, the foundation of everyday life, could no longer serve for the governance of the world. When "scientific" knowledge, the sophisticated product of complicated instruments and subtle calculations, provided unimpeachable truths, things were no longer as they seemed.
>
> (Boorstin, 1983, p. 294)

1.1 INTRODUCTION

Psychophysiology concerns the study of cognitive, emotional, and behavioral phenomena as related to and revealed through physiological principles and events. As a discipline, psychophysiology not only addresses fundamental questions regarding human processes (e.g., mind–body relationships, organismic–environmental transactions, psychosomatic disorders), but also provides a conceptual perspective and a methodological armamentarium that cuts across aspects of the biological, behavioral, and social sciences.

Two cardinal postulates underlying the discipline are that physiological processes, subjective experience, and overt actions all harbor information about human nature and each of these domains also contains irrelevant data, artifacts, and misinformation. Consequently, knowledge regarding physiological mechanisms, biometric and psychometric properties, and experimental design is important in extracting veridical information about human nature. Consistent with this perspective, verbal reports as the standard of validity are challenged, reductionism as being the idealized endpoint in studies of human nature is rejected, and overt behavior as the optimally sensitive or discriminable measure of underlying processes is questioned.

Consider, for instance, the human eye – a sensory receptor that is sensitive to only a narrow band of the electromagnetic spectrum. One *could* refer to this limited band of electromagnetic energy as the "psychological" domain since electromagnetic phenomena falling within this band have clear and obvious effects on human experience. However, the visible light band is but a small part of a broader, coherent spectrum of electromagnetic energy that can also influence human experience and behavior and can be revealed through the use of specialized equipment to extend the reaches of the human senses. Reference to the portion of the electromagnetic spectrum to which our eyes respond as "visible" rather than "psychological," therefore, more accurately denotes the existence of a broader electromagnetic spectrum and the interaction between this stimulus and a particular information detection and processing mechanism. Note, too, that the existence and broader organization of the electromagnetic spectrum and its various effects on the behavior of humans and animals would not be comprehensible if observations were limited to the band of visible light.

Similarly, psychophysiologists often utilize specialized equipment to study the spectrum of physiological events that allow functional descriptions and, in some instances, influence the operation of systems underlying human experience and behavior. To illustrate, consider the following sampler of psychophysiological research.

A neonate too young to comprehend or control purposeful behavior nevertheless exhibits heart rate responses when new or significant stimuli are presented; variations in this procedure reveal the attentional processes of neonates can be tracked using tracings produced by an electrocardiogram (Graham & Jackson, 1970).

A young individual sleeping quietly with eyes closed periodically shows extended sequences of rapid eye movements, as assessed by electrooculography; awakening the individual during this period usually reveals the person was dreaming (Foulkes, 1962).

A student sits quietly as auditory tones are presented through headphones; averaging of the electroencephalographic recordings time-locked to these tones reveals a larger brain potential is evoked approximately 300 ms following unexpected tones, in contrast to those expected (Squires, Wickens, Squires, & Donchin, 1976).

A college student, during a moment of self-disclosure, reflects briefly on an unpleasant experience; minute muscle action potentials, detectable using electromyography, mark this emotional event despite the person neither speaking about nor showing visible signs of the unpleasant thought or feeling (Cacioppo, Martzke, Petty, & Tassinary, 1988).

A suspect in a criminal case is questioned about evidence found at the scene of the crime; although the suspect denies knowing anything about the crime, physiological reactions are repeatedly more pronounced when information associated with the crime is presented than when equally provocative information not associated with the crime is presented (Lykken, 1981).

Married couples engage in a conflict conversational interaction while general autonomic activity is monitored; the higher the autonomic responses observed in this conflict interaction, the lower the marital satisfaction three years later (Levenson & Gottman, 1985).

An elderly individual who has bilateral occipitotemporal brain damage no longer seems to recognize her spouse or other familiar people; yet electrodermal activity is heightened when their pictures are presented (Tranel & Damasio, 1985).

An underlying theme in each of these studies is that the stimuli, thoughts, emotions, and experiences that are apparent to or can be articulated by the individual may represent but a narrow band of influences relevant to the governance of human experience and behavior. It should not be surprising, then, that 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, therefore, are to define the area of research and theory referred to as psychophysiology, review briefly 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. Additional information about the history, foundations, principles, techniques, and theories of psychophysiology is provided in the subsequent chapters of this book.

1.2 THE CONCEPTUALIZATION OF PSYCHOPHYSIOLOGY

> The body is the medium of experience and the instrument of action. Through its actions we shape and organise 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 whose collective aim is to elucidate 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. Fields of study within this discipline include surface anatomy (the study of the form and markings of the surface of the body), gross anatomy (the study of structures that can be examined without a microscope), systemic anatomy (the study of specific systems of the body such as the nervous or cardiovascular systems), and developmental anatomy (the study of structural development from the fertilized egg to the adult form) (Solomon & Phillips, 1987).

Physiology concerns the study of bodily function or how the parts of the body work. What constitutes a body part in physiology varies with the level of bodily organization going from the chemical (e.g., actin, myosin) to cellular (e.g., muscle fiber) to tissue (e.g., striated muscle) to organ (e.g., biceps) to body system (e.g., muscular system) to the human organism (Figure 1.1). Thus, the anatomy and physiology of the body are intricately interrelated.

Fundamental to the conceptualization of psychophysiology are the assumptions that (1) human perception, thought, emotion, and action are embodied phenomena and (2) the responses of this corporeal body can help reveal the mechanisms underlying human nature. Psychophysiology, therefore, is also intimately related to anatomy and physiology but is concerned with what might be termed supraphysiological or psychological phenomena – the experience and behavior of organisms in the physical and social environment – rather than with the structure or function of body parts per se (see Figure 1.1). Among the complexities added when moving from physiology to psychophysiology are the capacity by symbolic systems of representation (e.g., language, mathematics) to communicate and to reflect upon history and experience and the social and cultural influences on physiological response and behavior. Both of these contribute to plasticity, adaptability, and variability in behavior (Cacioppo, 1982; Gale & Edwards, 1983). And although psychology and psychophysiology share the goal of explaining human experience and behavior, physiological constructs and processes are an integral component of theoretical thinking in psychophysiology.

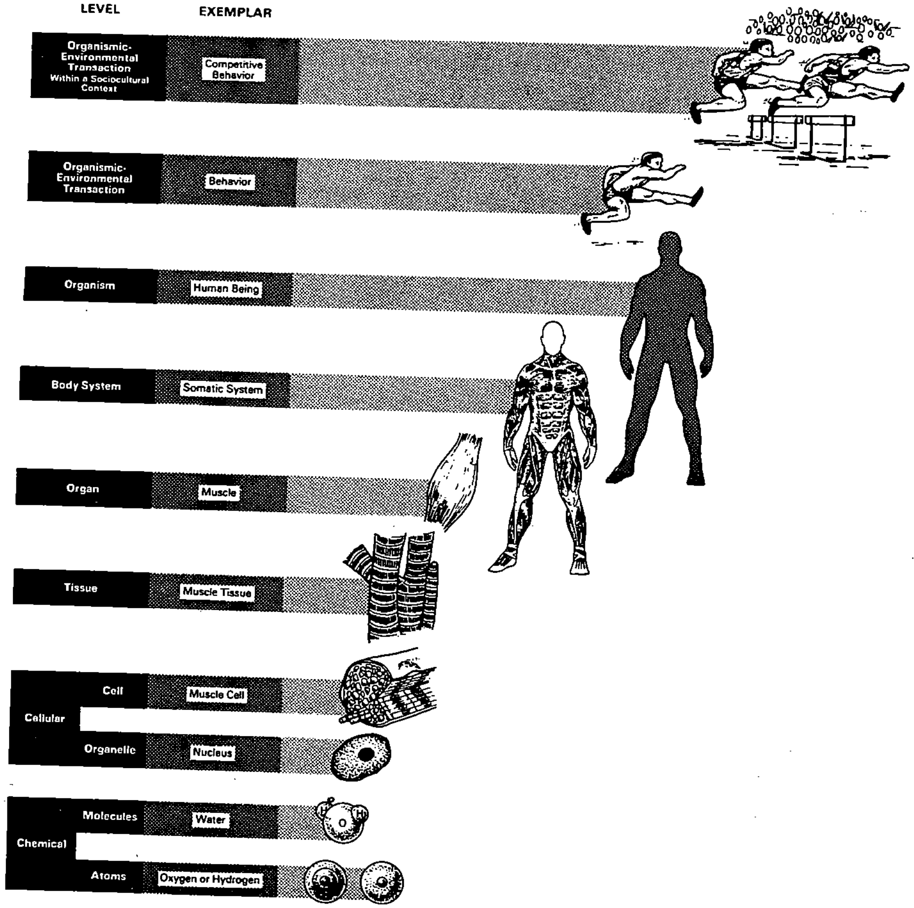

Figure 1.1. Levels of structural organization underlying human behavior.

1.2.1 *Psychophysiology as a scientific field of study*

Psychophysiology is still quite young as a scientific discipline although the concept of such a discipline dates back at least 150 years (Adams, 1839). Studies conducted around the turn of the 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; see also, Troland, 1929–1932; Woodworth, 1938/1947), 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 Féré (1888/1976) as among the Field's earliest pioneers. Yet the first scientific periodical devoted exclusively to psychophysiological research, *Psychophysiology Newsletter*, was not begun until 1955 as an outgrowth of *Polygraph Newsletter* (Ax, 1964a). The Society for

Psychophysiological Research was formed 5 years later, and the first issue of the scientific journal *Psychophysiology* was published but a quarter century ago. When precisely psychophysiology emerged as a discipline, therefore, is difficult to specify, but it is usually identified with the formation of the Society for Psychophysiological Research in 1960 or with the publication of the first issue of *Psychophysiology* in 1964 (Fowles, 1975; Greenfield & Sternbach, 1972; Sternbach, 1966). Scientific organizations for psychophysiological research have since been established around the world, including Great Britain, Japan, Australia, and West Germany.

The formation of this international society and journal brought together scientists from diverse fields including physiology, neurology, electrical engineering, experimental psychology, clinical psychology, neurophysiology, psychiatry, and social and developmental psychology (e.g., Cacioppo & Petty, 1981; Kaplan & Bloom, 1960; Porges & Coles, 1976). The diverse goals and interests of these individuals, the technical obstacles confronting the early investigators, and the importance of understanding the physiological systems underlying their observations 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 both for theoretical and pedagogical reasons. Physiological systems provide the foundation for information processing and behavior and are often the target of systematic observation. Hence, an understanding of the physiological system(s) under study and the biological principles underlying the responses being measured is important not only for the discrimination of signal from artifact, the safety of the individuals involved, and the acquisition and analysis of digital arrays and descriptive parameters that are reliable and valid representations of the physiological events of interest, but also for the stimulation of plausible hypotheses, the development of appropriate operationalizations, the guidance of inferences based on physiological data, and consequently, the advancement of theory regarding human nature.

Like anatomy, physiology, and psychology, however, psychophysiology is a broad science organized in terms of a *thematic* as well as a *systemic* focus. 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 through physiological measures, including the reciprocal relationship between physiological and social systems. *Developmental psychophysiology* deals with developmental changes in psychophysiological relationships as well as the study of psychological development and aging through noninvasive physiological measurements. *Clinical psychophysiology* concerns the study of disorders in the organismic–environmental transactions and ranges from the assessment of disorders to interventions and treatments of the disorders. And *applied psychophysiology* deals with the implementation of psychophysiological principles in practice, such as operant training ("biofeedback"), desensitization, relaxation, and lie-detection procedures.

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 (see Figure 1.1). Others, such as social psychophysiology, have no 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 to anatomy and physiology as well as to psychophysiology (e.g., see Barchas, 1976; Cacioppo & Petty, 1983, Cacioppo, Petty, & Andersen, 1988; Waid, 1984). In sum, 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 nature.

1.2.2 *Physiological and psychological perspective*

We have suggested that psychophysiology is intimately related to anatomy and physiology, and further that knowledge of the physiological systems and responses under study contributes to both theoretical and methodological aspects of psychophysiological research (see also, Coles, Donchin, & Porges, 1986; Parts II and III of this volume). Physiological or technical expertise alone, however, is no substitute for a well-conceived experimental design. As Coles, Gratton, and Gehring (1987) noted, knowledge of the physiological systems, although contributory, is logically neither necessary nor sufficient to ascribe psychological meaning to physiological responses. The ascription of psychological meaning to physiological responses ultimately resides in the quality of the experimental design and the psychometric properties of the measures (see Strube, chapter 2). 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 (see Coles, Gratton, & Fabiani, chapter 13).

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 perspectives 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 (e.g., see reveiw by Cacioppo, Petty, & Tassinary, 1989). 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, p. ix–x)

Thus, the joint consideration of physiological and functional perspectives reduces errors of operationalization, measurement, and inference, and, hence, enriches theory and research on human processes and behavior.

1.2.3 *Definitions of psychophysiology*

Thus far, we have discussed the major assumptions, levels of analysis, and goals of psychophysiology, and we have traced briefly the history of the field as a scientific

discipline. Specifying a formal definition of psychophysiology is more difficult. Some of the initial definitions of psychophysiology were in operational terms such as research in which the polygraph was used, research published by workers in the field, and research on physiological responses to behavioral manipulations (cf. Furedy, 1983). Other early definitions were designed explicitly to differentiate psychophysiology from the older and more established field of physiological psychology by designating what was unique at that time about psychophysiological inquiries, such as the use of humans in contrast to animals as subjects, 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). Illustrative definitions offered over the past several decades follow:

> Psychophysiology...is our name for the science which starts with the facts learned by introspection, and seeks their determinants in the physical structures and processes of biological organisms. Its problem is solely that of determining the formal laws, or mathematical functions which hold between curious respective aspects of consciousness and of living matter. (Troland, 1929, p. 144)

> Psychophysiology is the science which concerns the physiological activities which underlie or relate to psychic events. (Darrow, 1964, p. 4)

> Psychophysiology is best defined by its goals and methods as they are described in the reports published by its research workers....The general goal of psychophysiology is to describe the mechanisms which *translate* between psychological and physiological systems of the organism....The progressive theme of psychophysiological method has been to extend measurement to more covert behavior with decreasing interference with the organism. (Ax, 1964b, p. 8)

> Any research in which the dependent variable (the subject's response) is a physiological measure and the independent variable (the factor manipulated by the experimenter) a behavioral one. (Stern, 1964, p. 90)

> Psychophysiology is the study of the interrelationships between the physiological and psychological aspects of behavior. It typically employs human subjects, whose physiological responses are usually recorded on a polygraph while stimuli are presented which are designed to influence mental, emotional, or motor behavior; and the investigator need not be a psychologist. (Sternbach, 1966, p. 3)

> The field of psychophysiology is concerned with the measurement of physiological responses as they relate to behavior. (Andreassi, 1980, p. 3)

> Psychophysiology is the study of psychological processes in the intact organism as a whole by means of unobtrusively measured physiological processes. (Furedy, 1983, p. 13)

> Psychophysiology is the study of mental or emotional processes as revealed through involuntary physiological reactions that can be monitored in an intact subject. (Lykken, 1984, p. 175)

> Psychophysiology as a scientific discipline is concerned with the theoretical and empirical relationships among bodily processes and psychological factors. (Ackles, Jennings, & Coles, 1985, p. ix)

> In general terms, psychophysiology is the scientific study of the relationship between mental and behavioral activities and bodily events. (Surwillo, 1986, p. 3)

> Psychophysiology...is characterized by an emphasis on human behavior as a complex system in which physiological responses, subjective experiences and overt behavior interact in

complex ways such that to separate out any one of these aspects from the others is to severely limit the theoretical or practical value of any explanatory models that are developed. (Christie & Gale, 1987, p. 8)

As is apparent, there is disagreement regarding the definition of psychophysiology. 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 distinghish it from fields such as physiological psychology but have been criticized for being too restrictive (Furedy, 1983; cf. Coles, 1988). For instance, such definitions exclude noninvasive studies of higher order mental processes in which physiological events serve as the independent/blocking variable and human experience or behavior serves as the dependent variable (e.g., the sensorimotor behavior associated with operantly conditioned or endogenous changes in cardiovascular or electroencephalographic activity), and studies comparing changes in physiological responses across known groups (e.g., the cardiovascular reactivity of offspring of hypertensive vs. normotensive parents). Moreover, psychophysiology and physiological psychology/psychobiology share goals, assumptions, experimental paradigms, and in some instances, databases but differ primarily in terms of the level of analysis (e.g., organismic–environmental vs. organ–cellular level) and, consequently, the experimental strategy *typically* employed (e.g., noninvasive–reversible vs. invasive–irreversible experimental procedures). These fields clearly 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 (e.g., see Johnson & Anderson, chapter 8).

The emergence of areas of research in psychoneuroendocrinology (e.g., Baum, Grunberg, & Singer, 1982; Frankenhauser, 1983; Mason, 1972), behavioral neurology (e.g., Lindsley, 1951; Tranel & Damasio, 1985; Tranel, Fowles, & Damasio, 1985; see Matsumoto, Walker, Walker, & Hughes, chapter 3), and psychoneuroimmunology (e.g., Ader, 1981; Henry & Stephens, 1977; Jemmott & Locke, 1984; Kiecolt-Glaser et al., 1984; see Kennedy, Glaser, & Kiecolt-Glaser, chapter 6) raises additional questions about how to define the discipline of psychophysiology. Importantly, 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 immunological systems within the organism. Given the parallels among anatomy, physiology, and psychophysiology outlined in the preceding, however, psychophysiology should be defined in terms that accommodate its early focus on the actions of the nervous system as well as more recent psychological and behavioral studies involving neural, endocrinological, and immunological systems and the interactions among these systems.

To summarize, psychophysiology is based on the assumptions that human perception, thought, emotion, and action are embodied phenomena and that the physical responses of the corporeal body, in an appropriate experimental design, can shed light on human nature. The level of analysis in psychophysiology is not on isolated components of the body, but rather on organismic–environmental transactions, with reference to both physical and sociocultural environments. Psychophysiology can therefore be defined as the scientific study of social, psychological, and behavioral phenomena as related to and revealed through physiological principles and events. In this way, a hierarchy is formed in which anatomy is concerned with bodily structure, physiology with bodily functions, and psychophysiology with organismic–environmental transactions (see Figure 1.1).

In the following section, we review some of the major historical developments that have contributed to contemporary thought 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.

1.3 HISTORICAL DEVELOPMENT

We often think, naively, that missing data are the primary impediments to intellectual progress – just find the right facts and all problems will dissipate. But barriers are often deeper and more abstract in thought. We must have access to the right metaphor, not only the requisite information. Revolutionary thinkers are not, primarily, gatherers of facts, but weavers of new intellectual structures. (Gould, 1985, Essay 9)

Although psychophysiology as a formal discipline is only about 30 years old, awareness of and 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 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 physiologial responses provided no grounds for inference about the operation of psyche (Stern, Ray, & Davis, 1980). 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 scientist-philosophers, human nature was dealt with as a noncorporate entity unamenable to empirical study. The classification of observations instead tended to be along qualitative lines without measurement, empirical assessment, or validation.

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, 1959, 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." 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.

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 (1540 or 1544–1603) recognized a difference between electricity and magnetism and, more importantly, argued in his book, *Magnete*, that empirical observations and experiments should replace "the probable guesses and opinions of the ordinary professors of philosophy." Francis Bacon (1561–1626) took the scientific method a step further in *Novum Organum* (1620/1889), adding induction to observation and adding verification to inference. Brazier (1959) summarized the importance of this work as follows:

> Scientists before him were content with performing an experiment in order to make an observation; from this observation a series of propositions would follow, each being derived from its predecessor, not by experiment but by logic. Bacon's contribution to scientific method was to urge, in addition, the rigorous application of a special kind of inductive reasoning proceeding from the accumulation of a number of particular facts to the demonstration of their interrelation and hence to a general conclusion. (p. 3)

Francis Bacon's formulation and subsequent work on the logic of scientific inference (cf. Platt, 1964; 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) *De Motu Cordis* (1628/1941), not only represented 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, Harvey 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 (see Johnson & Anderson, chapter 8; Papillo & Shapiro, chapter 14).

During this period, which coincided with a burgeoning world of machines, the human eye was conceived as functioning like an optical instrument whose image was projected onto the sensory nerves of the retina; movement was thought to reflect the mechanical actions of passive balloonlike structures (muscles) 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 René Descartes (1596–1650) reflect 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 that, 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 values, "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)

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 nature 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 for 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 & DeLuca, 1985; 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, and by 1849 Du Bois-Reymond provided evidence using the galvanometer of electrical charges from human muscles as a result of volitional muscle contraction.

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. Luigi Galvani's (1737–1798) experiments on the effects of electricity on muscle contraction and the work that followed (see Cacioppo, Tassinary, & Fridlund, chapter 11) 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.[1]

1.4 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 (Brazier, 1959).

One important form of psychophysiological inference to emerge from the work of Francis Bacon (1620/1889) involves the identification of two or more hypotheses about some phenomenon, devising a set of conditions with alternative possible outcomes that will exclude one or more of the hypotheses, and establishing the conditions and collecting the observations while minimizing measurement error (cf. Platt, 1964; Popper, 1959/1968). 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 recyles 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 (cf. O'Connor, 1985). 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).

Importantly, physiological responses are often of interest only to the extent that they allow one to index a psychological process or state. This is an important endeavor, but the sequence underlying psychophysiological inferences often violates the logic of hypothetico-deductive research because inferences about events in the psychological domain are not based so much on the exclusion of alternative hypotheses as on reasoning by analogy. In a typical example, a physiological response is identified that is affected by variations in the psychological process of interest. This physiological response is subsequently monitored, perhaps in yet a different assessment context, in an effort to determine the likely presence or extent of the psychological process of interest (see review by Cacioppo & Petty, 1986). In an illustrative study, subjects were exposed to moderately or highly counterattitudinal assertions while electrodermal activity was monitored (Cooper, 1959). Results revealed greater changes in electrodermal activity following exposure to the highly counterattitudinal assertions. Based on prior research showing that emotionally arousing stimuli are associated with increased electrodermal activity, the higher electrodermal responding to highly rather than moderately counterattitudinal assertions was interpreted as meaning that more extreme attitudes were imbued with greater emotion. That is, electrodermal activity appeared *as if* an emotionally arousing stimulus had been presented. The problem with this form of psychophysiological inference is that knowledge that a statement is true (e.g., the manipulation of a psychological factor leads to a change in some target physiological response) does *not* imply that the converse is true. For instance, the prior research showing that factors other than emotional arousal can influence electrodermal activity (e.g., novelty stimulus significance; see Dawson, Schell, & Filion, chapter 10) was not considered. The logical flaw in this form of psychophysiological inference is termed the affirmation of the consequent (Runes, 1961; cf. Cacioppo, Petty, & Losch, 1986).

This need not be the case, however. In this section, we present 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, 1989).

1.4.1 *A simple taxonomy of psychophysiological relationships*

1.4.1.1 *Elements in the psychological and elements in the 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. Psychological events are conceived as constituting one set, which we shall call set Ψ, and physiological events are conceived as constituting another, which we shall call set Φ (Troland, 1929, p. 144–145).[2] Inspection of Figure 1.2 (upper left panel) reveals that all elements in the set of

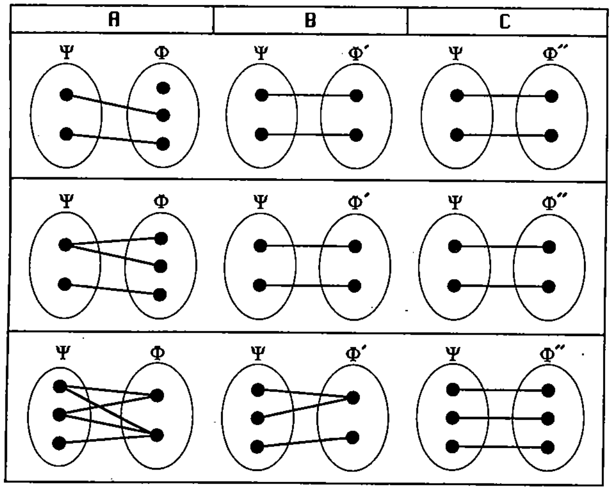

Figure 1.2. Depiction of logical relations between elements in the psychological (Ψ) and physiological (Φ) domains. *Panel A:* Links between psychological elements and individual physiological responses. *Panel B:* Links between psychological elements and physiological response patterns. *Panel C:* Links between psychological elements and profile of physiological responses across time.

psychological events are assumed to have some physiological referent, reflecting our adherence to the monistic identity thesis (i.e., the first assumption underlying psychophysiology).[3]

Focusing first on the top row of Figure 1.2, the existence of psychologically irrelevant physiological events (e.g., random physiological fluctuations; increased electrodermal activity due to minor variations in body temperature) is of importance in psychophysiology for purposes of artifact prevention or elimination. However, such elements within the physiological domain can be ignored if nonpsychologic factors have been held constant, their influence on the physiological responses of interest has been identified and removed, or it does not overlap with the physiological event of interest. These objectives are achieved through the application of proper psychophysiological recording techniques (which are discussed in detail in part III of this book). The important point here is that the achievement of these objectives simplifies the task of specifying psychophysiological relationships, in the ideal case, by eliminating physiological events that have no direct relevance to psychological events (e.g., see Figure 1.2, top row of panel B).

We can now state 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 (see Figure 1.3). These are as follows:

1 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.
2 A one-to-many relation, meaning that an element in the psychological domain is associated with a subset of elements in the physiological domain.
3 A many-to-one relation, meaning that two or more psychological elements are associated with the same physiological element.

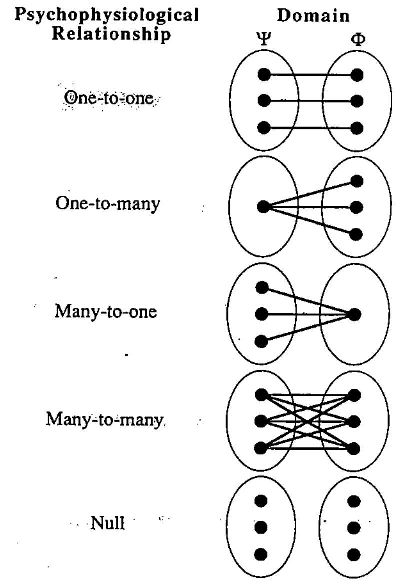

Figure 1.3. Possible relationships between elements in the psychological domain (Ψ) and elements in the physiological domain (Φ).

4 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.
5 A null relation, meaning there is no association between an element in the psychological domain and that in the physiological domain.[4]

Of these possible relations, only the first and second allow a formal specification of psychological elements as a function of physiological elements (cf. Coombs, Dawes, & Tversky, 1970, pp. 351–371). This is important because, as we have noted, psychophysiological research typically involves the manipulation of (or blocking on) elements in the psychological domain and the measurement of elements in the physiological domain. The grounds for inductive reasoning in psychophysiology, therefore, can be strengthened if a way can be found to specify the relationship between the elements within Ψ and Φ in terms of a one-to-one relationship. Although somewhat involved, this is often possible.

1.4.1.2 *Physiological elements as spatial and temporal response profiles*

First, a one-to-one relation can exist, such that an element in the psychological set is associated with one and only one element in the physiological set. Such relationships provide strong grounds for inference but are not common cross-situationally at present in psychophysiology (e.g., see Coles et al., 1987; Donchin, 1982). The functional opposite of the one-to-one relation is the null relation, which means that the element in the physiological domain is unrelated to and, hence, harbors no information about the element in the psychological domain.

A third form of relation between elements in the psychological and physiological domains is the one-to-many, meaning that an element in the psychological domain is associated with a subset of elements in the physiological domain. Importantly, one-to-many relations between sets of psychological and physiological elements can be simplified greatly, reducing them to one-to-one relations, in the following fashion: Define a second set of physiological elements, Φ', such that any subset of physiological elements associated with the psychological element is replaced by a single element in Φ', which now represents a physiological syndrome or response pattern. Thus, one-to-one and one-to-many relations between elements in the psychological domain, Ψ, and the elements in the physiological domain, Φ, both become one-to-one relations between Ψ and Φ' (see Figure 1.2, middle row).

The remaining relations that can exist between elements in these domains are the many-to-one, meaning that two or more psychological elements are associated with the same physiological element; and the many-to-many, meaning two or more psychological elements in Ψ are associated with two or more of the same elements in Φ (see Figure 1.2, lower row of panel A). These relations can also be simplified with a few changes in how one conceptualizes an element in the physiological domain.

As before, a new set of physiological elements, Φ', is defined such that any subset of physiological elements associated with one or more psychological elements is replaced by a new element representing a profile of physiological responses. Thus, the elements in Φ' again represent a specific pattern or syndrome of physiological events, and many-to-many relations between elements in Ψ and Φ can be reduced to many-to-one (or, in some cases, to one-to-one) relations by viewing elements within the physiological domain as representing singular physiological responses and physiological response syndromes.

Such a reconceptualization may not be sufficient to cast *all* of the psychophysiological relations of interest in terms of one-to-one or many-to-one relations, however. This may still not be a problem because the set of physiological elements Φ' can be redefined again such that the *forms of physiological events as they unfold over time* are also considered to yield yet another set of physiological elements, Φ'' (see Figure 1.2, panel C; cf. Cacioppo, Marshall-Goodell, & Dorfman 1983). By including temporal (as well as spatial) information regarding the physiological events in the definition of the elements in Φ'', many complex psychophysiological relationships can be reduced to one-to-one or many-to-one relations (cf. Davis, 1957).[5]

1.4.1.3 *An illustration*

Consider the relationship between the orienting, defense, and startle responses as elements within the psychological domain, and changes in skin conductance response (SCR) and heart rate response (HRR) as elements within the physiological domain (see Stern & Sison, chapter 7, for a discussion of the constructs of orienting, defense, and startle). For illustrative purposes, we have simplified the elements within Ψ to include only the constructs of orienting, defense, and startle, and we have simplified the elements with Φ to include only SCR and HRR (Figure 1.4, upper panel). Even with these simplifications, the illustration clearly reveals the obstacles to strong psychophysiological inference. All three elements within Ψ are associated with changes in skin conductance and heart rate. Thus, if elements in the physiological domain are defined as changes from basal levels of activity, then the relationship is many-to-many, and physiological events cannot be specified as a

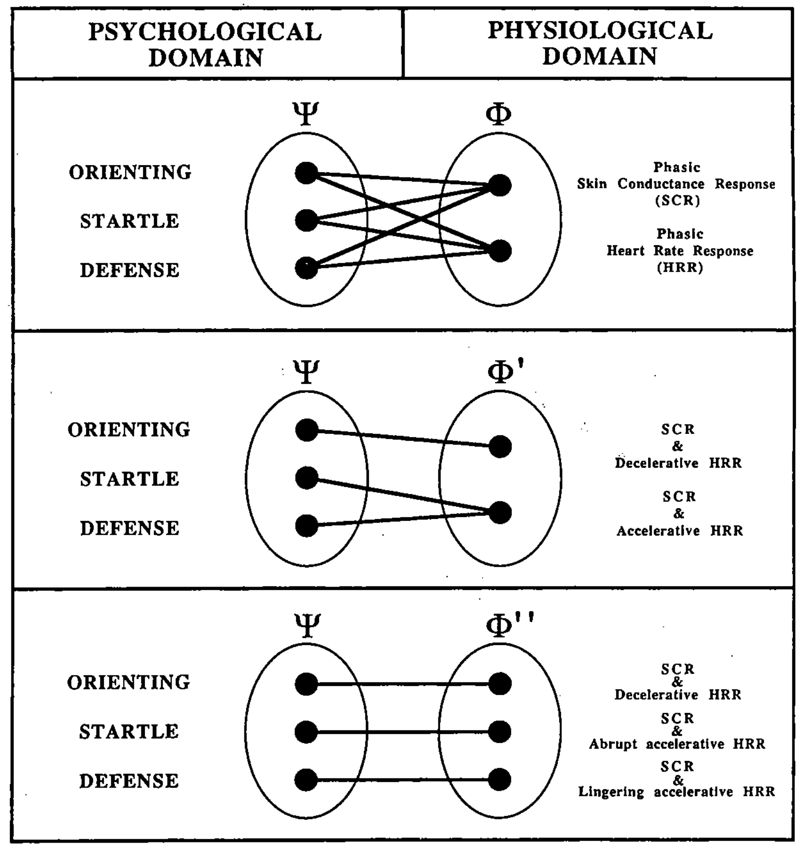

Figure 1.4. Depiction of logical relations between psychological constructs of orienting, startle, and defense and physiological measures of heart rate (HR) and skin conductance response (SCR). *Top panel:* Links between psychological elements and individual physiological responses. *Middle panel:* Links between psychological elements and physiological response pattern. *Bottom panel:* Links between psychological elements and profile of physiological responses across time.

function of psychological process (cf. Coombs et al., 1970). Accordingly, events in the physiological domain provide no basis for strong inferences about events in the psychological domain. For instance, although manipulations that are known to affect the intensity of the orienting reaction have differentiable effects on SCRs, it can be seen in Figure 1.4 that the SCR alone does not provide strong grounds for inferring an orienting response in this assessment context.

As noted, the grounds for psychophysiological inference are strengthened considerably if the spatial and temporal pattern of physiological events are considered. First, the set of physiological elements Φ is redefined such that any subset of physiological elements reliably associated with one (or more) psychological elements is replaced by a single, unique, element in Φ'. This reconceptualization of the elements constituting the physiological domain results in a one-to-one relation between the orienting reaction and physiological events; and a many-to-one relation between the concepts of startle and defense reactions and physiological events (see Figure 1.4, middle panel). The physiological events in this context can now be specified as a function of psychological elements, although the grounds for inference remain weak even in this simplified example when both increased HRR and SCR are observed.

Next, the set of physiological elements, Φ', are again redefined such that the form of the physiological responses as they unfold across time is considered. Returning to the example in Figure 1.4, both defense and startle are reliably associated with increased HRR and SCR (middle panel), but the HRR acceleration peaks and returns to normal within approximately 2 seconds in the case of startle but does not begin to rise for several seconds and peaks much later following the stimulus in the case of the defense response (Turpin, 1986). With this additional refinement in the conceptualization of psychophysiological relationships, strong inferences about which of these three psychological processes is operative can now be drawn from the associated physiological events (see Figure 1.4, bottom panel).

1.4.2 *Four categories of psychophysiological relationships*

Another complication in specifying psychophysiological relationships arises because relations between elements in the psychological and physiological domains cannot be assumed to hold across situations and individuals. This is simple to see in Figure 1.4. The elements in the psychological domain were delimited in part by holding constant other factors, such as wakefulness, general somatic activity, and the prestimulus level of physiological activity. Such a procedure is not unique to psychophysiology, as both 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 (Guyton, 1971). 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 (Cacioppo & Petty, 1985; Donchin, 1982). 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 (cf. Cacioppo et al., 1989).

To clarify these issues, it is useful to conceptualize psychophysiological relationships generally in terms of their *specificity* (one-to-one vs. many-to-one) and *generality* (context-bound vs. context-free) with the cells depicted in Figure 1.5 representing the four quadrants within this dimensional space. Causal attributes of these 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 quadrant in Figure 1.5 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 category of psychophysiological relationship and the nature of the inferences that each suggests are outlined.

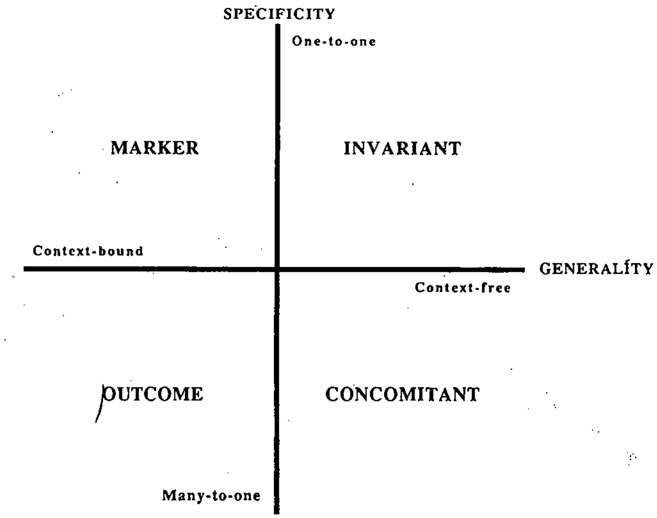

Figure 1.5. Dimensions and families of psychophysiological relationships.

1.4.2.1 *Outcomes*

In the idealized case, an outcome is defined as a many-to-one, situation-specific (context-bound) relationship between Ψ and Φ'' (see Figures 1.3 and 1.5). 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. This is 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 generality) or whether the response profile follows only changes in the event (i.e., has the property of specificity) is typically not possible to address initially. Hence, a given psychophysiological relationship may appear to be an outcome but subsequently be identified as being a marker as the question of specificity 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 specificity of the relationship. This progression is not problematic in terms of causing erroneous inferences, however, because any logical inference based on the assumption one is dealing with an outcome relationship holds for marker, concomitant, or invariant psychophysiological relationships as well.

This is because although the outcome is the most elemental psychophysiological relation, it can nevertheless provide the basis for strong inferences. Specifically, when two psychological models differ in predictions regarding one or more physiological outcomes, the logic of the experimental design allows theoretical inferences to be drawn based on psychophysiological outcomes alone. That is, a psychophysiological outcome enables systematic inferences to be drawn about psychological constructs and relationships based on hypothetico-deductive logic. Of course, no single operationalization of the constructs in a crucial experiment is likely to convince the adherents of both theories. If multiple operationalizations of the theoretical constructs result in the same physiological outcome, however, then strong theoretical inferences can be justified (Cacioppo & Petty, 1986).

Although the identification of a physiological response profile that is an outcome of the psychological element of interest is sufficient to infer the *absence* of this psychological element, it does not provide logical grounds to infer anything about the *presence* of the psychological element. Hence, the identification of psychophysiological outcomes can be valuable in disproving theoretical predictions, but this is insufficient when one aspires to physiological *indices* of elements in the psychological domain. This caveat is often noted in discussions of the scientific method and is perhaps equally often violated in scientific practice (Platt, 1964). Skin conductance, for instance, has been a major dependent measure in psychological research because emotional arousal is thought to lead to increased skin conductance (e.g., see Prokasy & Raskin, 1973). Similarly, electromyographic (EMG) activity over the forehead region has been a frequent target measure in relaxation biofeedback because tension has been found to increase EMG activity over this region (e.g., see Stroebel & Glueck, 1978). As noted in the previous section, however, simply knowing that manipulating a particular element in the psychological domain leads to a particular response in the physiological domain does not logically enable one to infer anything about the former based on observations of the latter because one does not know what other elements or events might bear an outcome relationship to the observed physiological response. Procedures such as holding constant and variations in the elements in the psychological domain that are not of interest, measuring these elements in addition to those of immediate theoretical interest to determine to which the observed changes in physiological response are likely to be attributable, and excluding those physiological responses believed to covary with these irrelevant elements all represent attempts to reduce many-to-one relationships to one-to-one relationships (i.e., going from psychophysiological outcomes to psychophysiological markers; see Figure 1.5). Such procedures clearly strengthen the grounds for psychophysiological inference, but they do not assure that all relevant factors have been identified or controlled, nor do they provide a means of quantifying the extent of other influences on psychophysiological responding.

These limitations can be further diminished by conceptualizing psychophysiological relationships in terms of conditional and joint probabilities (Cacioppo et al., 1988; Cacioppo & Tassinary, 1989). To illustrate, let Ψ represent the specific element of interest in the psychological domain (e.g., an emotional report) and Φ'' represent the physiological profile (e.g., facial EMG activity) of interest. It is clear from probability theory that $P(\Phi''/\Psi)$ could differ dramatically from $P(\Psi/\Phi'')$; perhaps less obvious is that this asymmetry is the root of many of the problems in psychophysiological inference outlined in the preceding. An outcome relation establishes $P(\Phi''/\Psi)$ (or, at least, that such a probability is nonzero); physiological indices of psychological events (i.e., markers, invariants), on the other hand, can be conceptualized rigorously as a statement about $P(\Psi/\Phi'')$, where

$$P(\Psi/\Phi'') = P(\Psi, \Phi'')/P(\Phi'') \tag{1}$$

or, equivalently,

$$P(\Psi/\Phi'') = P(\Psi, \Phi'')/[P(\Psi, \Phi'') + P(\text{Not}-\Psi, \Phi'')] \tag{2}$$

Although it is not possible to specify all relevant factors that might affect the element in the physiological domain one wishes to use to index an element in the psychological domain, it *is* possible to determine (both) the extent to which changes in the physiological element covary with changes in the psychological element of interest and the probability that changes in the physiological response occur in the absence of changes in the psychological construct of interest. As can be seen in equations 1 and 2, the utility of Φ'' to serve as an index of Ψ is weakened by the occurrence of Φ'' in the absence of Ψ. Conversely, the refinement of measures of Φ'' (e.g., through greater spatial and temporal resolution or through technological advances) is of scientific value to the extent that by doing so one reduces the likelihood of its observation in the absence of the psychological element of interest while leaving its observation in the presence of the psychological element of interest generally intact.

Consider, for example, what can be expected if the probability of a physiological element $\{P(\Phi'')\}$ is greater than the probability of the psychological element of interest $\{P(\Psi)\}$. Since this implies that $P(\Psi, \Phi'')/P(\Psi) > P(\Psi, \Phi'')/P(\Phi'')$, it can be seen from equation 1 that $P(\Phi''/\Psi) > P(\Psi/\Phi'')$ and, consequently, that research based only on outcome relationships leads to an overestimation of the presence of the psychological element.

We should emphasize that these probabilities are simply a way of thinking more rigorously about psychophysiological relations; one still needs to be cognizant that these relationships (e.g., probabilities) may vary across situations (e.g., assessment contexts). Indeed, comparisons of these probabilities across assessment contexts can provide a means of determining the generality of a psychophysiological relation. Before proceeding to this dimension of the two-dimensional space depicted in Figure 1.5, however, we elaborate further on psychophysiological relations within a specific assessment context when viewed within the framework of conditional and joint probabilities. In particular, as $P(\Psi, \Phi'')$ approaches 1.0 and $P(\text{Not}-\Psi, \Phi'')$ approaches 0.0 within a specific assessment context, the element in the physiological domain can be described as being an ideal marker of the element in the psychological domain.

1.4.2.2 Markers

In its idealized form, a psychophysiological marker is defined as a one-to-one, situation-specific (i.e., context-bound) relationship between abstract events Ψ and Φ'' (see Figures 1.3 and 1.5). The psychophysiological marker relation implies that the occurrence of one (usually a physiological response, parameter of a response, or profile of responses) predicts the occurrence of the other (usually a psychological event) within a given context. Thus, markers are characterized by limited ranges of validity. Such a relationship may reflect a natural connection between psychological and physiological elements in a particular measurement situation or it may reflect an artificially induced (e.g., classically conditioned) association between these elements (e.g., see Cacioppo & Sandman, 1981; Petty & Cacioppo, 1983; Tursky & Jamner, 1983). Importantly, minimal violations of isomorphism between Ψ and Φ'' within a given assessment context can nevertheless yield a useful (although imperfect) marker when viewed in terms of conditional probabilities.

Markers, like concomitants and invariants, can vary in their specificity. The more distinctive the form of the physiological response and/or the pattern of associated physiological responses, the greater is the likelihood of achieving a one-to-one relationship between the physiological events and psychological construct and the wider may be the range of validity of the relationship thereby achieved. This is because the utility of an element in Φ'' to index an element in Ψ is generally strengthened by defining the physiological element so as to minimize its occurrence in the absence of the element in the psychological domain.

In addition, a psychophysiological marker may simply signal the occurrence or nonoccurrence of a psychological process or event, possessing no information about the temporal or amplitude properties of the event in a specific assessment context. At the other extreme, a psychophysiological marker may be related in a prescribed assessment context to the psychological event by some well-defined temporal function such that the measure can be used to delineate the onset and offset of the episode of interest and/or it may vary in amplitude such that it emulates the intesnity of the psychological event.

In sum, markers represent a fundamental relationship between elements in the psychological and physiological domains that enables an inference to be drawn about the nature of the former given measurement of the latter. The major requirements in establishing a response as a marker are to (1) demonstrate that the presence of the target response reliably predicts the specific construct of interest, (2) demonstrate that the presence of the target response is insensitive to (e.g., uncorrelated with) the presence or absence of other constructs, and (3) specify the boundary conditions for the validity for the relationship. The term *tracer* can be viewed as synonymous with marker, for each refers to a measure so strictly associated with a particular organismic–environmental conditon that its presence is indicative of the presence of this condition. We turn next to a description of concomitants.

1.4.2.3 *Concomitants*

A psychophysiological concomitant (or correlate), in its idealized form, is defined as a many-to-one, cross-situational (context-free) association between abstract events Ψ and Φ'' (see Figures 1.3 and 1.5). That is, the search for psychophysiological concomitants assumes there is a cross-situational covariation between specific elements in the psychological and physiological domains. The assumption of a psychophysiological concomitant is less restrictive than the assumption of invariance in that one-to-one correspondence is not required, although the stronger the association between the elements in the psychological and physiological domains, the more informative tends to be the relationship.

Consider, for instance, the observation that pupillary responses vary as a function of individuals' attitudes toward visually presented stimuli, an observation that was followed by the conclusion that pupillary response is a *correlate* or *bidirectional index* of people's attitudes (Barlow, 1969; Hess, 1965; Metalis & Hess, 1982). However, evidence of variation in a target physiological response as a function of a manipulated psychological event establishes an outcome relation, which is necessary but insufficient for the establishment of a psychophysiological concomitant or correlate.

First, the manipulation of the same psychological element (e.g., attitudes) in another context (e.g., using auditory rather than visual stimuli) may alter or eliminate the covariation between the psychological and physiological elements because the latter is evoked either by a stimulus that had been fortuitously or intentionally correlated with the psychological element in the initial measurement context or by a noncriterial attribute of the psychological element that does not generalize across situations. For instance, the attitude–pupil size hypothesis has not been supported using nonpictorial (e.g., auditory, tactile) stimuli, where it has been possible to control the numerous light-reflex-related variables that can confound studies using pictorial stimuli (Goldwater, 1972). It is conceivable, therefore, that in several of the studies showing a statistical covariation between attitudes and pupillary response, the main luminance of subjects' selected fixations varied inversely with their attitudes toward the visual stimulus (see Janisee, 1977; Janisee & Peavler, 1974; Stern & Dunham, chapter 15; Woodmansee, 1970).

Second, the manipulation of the same psychological element in another situation may alter or eliminate the covariation between the psychological and physiological elements because the latter is evoked not only by variations in the psychological element but also by variations in one or more additional factors that are introduced in (or are a fundamental constituent of) the new measurement context. Tranel et al. (1985), for instance, recently demonstrated that the presentation of familiar faces (e.g., famous politicians, actors) evoked larger SCRs than did the presentation of unfamiliar faces. This finding and the procedure and set of stimuli employed were subsequently used in a study of patients with prosopagnosia (an inability to recognize visually the faces of persons previously known) to demonstrate that the patients can discriminate autonomically between the familiar and unfamiliar faces despite the absence of any awareness of this knowledge. Thus, the first study established a psychophysiological relationship in a specific measurement context, and the second study capitalized on this relationship. To conclude that a psychophysiological concomitant had been established between familiarity and SCRs, however, would mean that the same relationship would hold across situations and stimuli (i.e., relationship would be context independent). Yet ample psychophysiological research has demonstrated the opposite psychophysiological outcome specified by Tranel et al. (1985); that is, novel or unusual (i.e., unfamiliar) stimuli evoke larger SCRs than familiar stimuli (e.g., see Landis, 1930; Lynn, 1966; Sternbach 1966). Hence, the relation between stimulus familiarity and skin conductance does not constitute a psychophysiological concomitant.[6]

Unfortunately, evidence of faulty reasoning based on the premature assumption that one is dealing with a true psychophysiological concomitant (or invariant) is all too easy to find. Over half a century ago, Landis commented in his review of the psychological factors associated with electrodermal changes that:

> I find in going through the literature that the psychogalvanic reflex has been elicited by the following varieties of stimuli ... sensations and perceptions of any sense modality (sight, sounds, taste, etc.), associations (words, thoughts, etc.), mental work or effort, attentive movements or attitudes, imagination and ideas, tickling, painful or nocive stimuli, variations in respiratory movements or rate, suggestion and hypnosis, emotional behavior (fighting, crying, etc.), relating dreams, college examinations, and so forth .... Forty investigators hold that it is specific to, or a measure of, emotion of the affective qualities; ten others state that it is not necessarily of an emotional or affective nature; twelve men hold that it is somehow to be identified with conation, volition, or attention, while five hold very definitely that it is nonvoluntary; twenty-one authorities state that it goes with one or another of the mental processes; eight state that it is the concomitant of all sensation and

perception; five have called it an indicator of conflict and suppression; while four others have used it as an index of character, personality, or temperament. (Landis, 1930, p. 391)

The hinderances to scientific advances, it would seem, stem not only from obscure psychophysiological relationships, but also from difficulties in recognizing order and limitations to induction in complex psychophysiological relationships.

As in the case of a psychophysiological marker, the establishment of a psychophysiological concomitant logically allows an investigator to make a probability statement about the absence or presence (if not the timing and magnitude) of a particular element in the psychological domain when the target physiological element is observed. However, the strength of the inference in this case will be theoretically limited by the actual number and nature of elements in the psychological domain. In addition, it is important to emphasize that the estimate of the strength of the covariation used in such inferences should not come solely from evidence that manipulated or planned variations of an element in Ψ are associated with corresponding changes in an element in Φ''. Measurements of the physiological response each time the psychological element is manipulated (or changes) can lead to an overestimate of the strength of this relationship and, hence, to erroneous inferences about the psychological element based on the physiological response. As can be seen in equations 1 and 2, this overestimation occurs to the extent that there are changes in the physiological response not attributable to variations in the psychological element of interest. Hence, except when one is dealing with an invariant relationship, establishing that the manipulation of a psychological element leads cross-situationally to a particular physiological response or profile of responses is not logically sufficient to infer that the physiological event will be a strong predictor of the psychological element of interest; base rate information about the occurrence of the physiological event across situations must also be considered. This can be done in practice by quantifying the natural covariation between elements in the psychological and physiological domains and by examining the replicability of the observed covariation across situations.

1.4.2.4 *Invariants*

The idealized invariant relationship refers to a one-to-one (isomorphic), context-free (cross-situational) association (see Figures 1.3 and 1.5). To say that there is an invariant relationship, therefore, implies that (1) a particular element in Φ'' is present if and only if a specific element in Ψ is present; (2) the specific element in Ψ is present if and only if the corresponding element in Φ'' is present, and (3) the relation between Ψ and Φ'' preserves all relevant arithmetic (algebraic) operations. Moreover, only in the case of invariants does $P(\Psi/\Phi'') = P(\Phi''/\Psi)$, and $P(\text{Not} - \Psi, \Phi'') = P(\text{Not} - \Phi'', \Psi) = 0$. This means that the logical error of affirmation of the consequent is not a problem in psychophysiological inferences based on an invariant relation. Hence, the establishment of an invariant relationship between a pair of elements from the psychological and the physiological domains provides a strong basis for psychophysiological inference. Unfortunately, invariant relationships are often assumed rather than formally established, and as we have seen, such an approach leads to erroneous psychophysiological inferences and misleading theoretical "advances."

It has been suggested occasionally that the psychophysiological enterprise is, by its

very nature, concerned with invariant relationships (e.g., see review by Cacioppo, Petty, & Tassinary, 1989). The search to establish one-to-one psychophysiological relationships is clearly important. As S. S. Stevens (1951) noted:

The scientist is usually looking for invariance whether he knows it or not. Whenever he discovers a functional relation between two variables his next question follows naturally: under what conditions does it hold? In other words, under what transformation is the relation invariant? The quest for invariant relations is essentially the aspiration toward generality, and in psychology, as in physics, the principles that have wide application are those we prize. (p. 20)

It should be emphasized, however, that evidence for invariance should be gathered rather than assumed and that the utility of psychophysiological analysis does not rest entirely with invariant relationships. Without this recognition, the establishment of *any* dissociation between the physiological measure and psychological element of interest invalidates not only the purported psychophysiological relationship but also the utility of a psychophysiological analysis. However, as outlined in the preceding sections of this chapter and in the chapters that follow, psychophysiology need not be conceptualized as offering only mappings of context-free, one-to-one relationships to advance our understanding of human nature.

To summarize, the minimum assumption underlying the psychophysiological enterprise is that psychological and behavioral processes unfold as organismic–environmental transactions and, hence, have physiological manifestations, ramifications, or reflections. Although invariant psychophysiological relationships offer the greatest generality, physiological concomitants, markers, and outcomes also can provide important and sometimes otherwise unattainable information about elements in the psychological domain. In laboratory practice, the initial step is often to establish that variations in a psychological element are associated with a physiological change, thereby establishing that the psychophysiological relationship are, at least, an outcome. Knowledge that changes in an element in the psychological domain is associated with changes in a physiological response/profile assures neither that the response will serve as a marker for the psychological state (since the converse of a statement does not follow logically from the statement) nor that the response is a concomitant or invariant of the psychological state (since the response may occur in only certain situations or individuals or may occur for a large number of reasons besides changes in the particular psychological state). Nonetheless, both hypothetico-deductive reasoning and Bayesian analyses can provide a strong foundation for psychophysiological inferences about human nature.

1.5 CONCLUSION

Psychophysiology is based on the assumptions that human perception, thought, emotion, and action are embodied phenomena and that bodily responses contain information that in an appropriate experimental design can shed light on human nature. The level of analysis in psychophysiology is not on isolated components of the body but rather on organismic–environmental transactions, with reference to both physical and sociocultural environments. Psychophysiology, therefore like anatomy and physiology, is a branch of science organized around bodily systems whose collective aim is to elucidate the structure and function of the parts of and interrelated systems in the human body in transactions with the environment. Like psychology, however, psychophysiology is concerned with a broader level of inquiry than anatomy and physiology and can be organized in terms of both a thematic as well as a systemic focus. For instance, the social and inferential elements as well as the physical elements of psychophysiology are discussed in the chapters that follow.

The development of more advanced recording procedures is important to scientific progress, as previously contested predictions are resolved, previously unobservable phenomena are rendered tangible, and previously accepted conclusions are called into question. However, advanced recording procedures are not sufficient. The theoretical specification of a psychophysiological relationship necessarily involves reaching into the unknown and, hence, requires intellectual invention and systematic efforts to minimize bias and error. Psychological theorizing based on known physiological and anatomical facts, exploratory research and pilot testing, and classic biometric and psychometric approaches can each contribute in important ways by their generation of testable hypotheses about a psychophysiological relationship. It should be equally clear, however, that the scientific effectiveness of psychophysiological analyses does not derive logically from physiologizing or from the measurement of organismic rather than (or in addition to) verbal or chronometric responses. Its great value stems from the stimulation of interesting hypotheses and from the fact that when an experiment agrees with a prediction about orchestrated actions of the organism, a great many alternative hypotheses are usually excluded. There is little to be gained, for instance, by simply generating an increasingly lengthy list of "correlates" between psychological and physiological variables. To further theoretical thinking, therefore, we have outlined a taxonomy of psychophysiological relations, and we have suggested a scheme for strong inference based on these relationships. Among the questions this formulation can help to address are (a) how does one select the appropriate variable(s) for study, (b) how detailed or refined should be the measurement of the selected variables, (c) how can situational and individual variability in psychophysiological relationships be integrated into theoretical thinking about psychophysiological relationships, and (d) how can physiological measures be used in a rigorous fashion to index psychological factors. The ultimate value of the proposed way of thinking about psychophysiological relationships rests on its effectiveness in guiding psychophysiological inference, for as Leonardo Da Vinci (c. 1510) noted:

> Experience does not ever err, it is only your judgment that errs in promising itself results which are not caused by your experiments.

NOTES

1 For additional detail, readers may also wish to consult the interesting historical accounts by Brazier (1959, 1977), Wu (1984), Jaynes (1973), Mecacci (1979), and Fulton (1926, ch. 1).

2 To simplify the illustration of how physiological responses can be used as a basis for strong inferences about elements in psychological domain, the physiological domain is co-extensive with the empirical domain and the psychological domain co-extensive with the theoretical domain in our discussions here. It should be emphasized, however, that which of these is the conceptual domain and which is the empirical may vary across psychophysiological inquiries. The relationships and formulas outlined in the text are based on the assumption that physiological measures are serving as indices of psychological elements. If the situation were reversed, then so, too, would be the relationships and formulas.

3 Briefly, the identity thesis states that there is a physical counterpart to every subjective or psychological event of (cf. Smart, 1959). Thus, the identity thesis is fundamental to tractable monistic philosophical solutions to the mind-body problem as well as to the scientific discipline of psychophysiology. Importantly, the identity thesis does *not* imply that the relationship between physical and subjective events is one-to-one (i.e., invariant). For example, with the context of psychophysiology, the identity thesis does not necessarily imply that the physiological representation will be one-to-one in that (a) there will be one and only one physiological mechanism able to produce a given psychological phenomenon; (b) a given psychological event will be associated with, or reducible to, a single isolated physiological response rather than a syndrome or pattern of responses; (c) a given relationship between a psychological event and a physiological response is constant across time, situations, or individuals; (d) every physiological response has specific psychological significance or meaning; or (e) the organization and representation of psychological phenomena at a physiological level will mirror what appears subjectively to be elementary or unique psychological operations (e.g., beliefs, memories, images). Given invariance cannot be assumed, psychophysiological inferences based on analogy can involve the commission of affirming the consequent (Cacioppo & Tassinary, 1989).

4 Both the many-to-many and the null relation may result in random scatterplots when measuring the natural covariation between elements in the psychological and physiological domains. These relations can be distinguished empirically, however, by manipulating the psychological factors and quantifying the change in physiological response (and vice versa). The scatterplot between this psychological factor and physiological response should remain random in the case of a null relation between them, but not if they are part of a many-to-many relation.

5 For the sake of brevity, the focus here is on reconceptualizing elements in the physiological domain to achieve a one-to-one psychophysiological relation. One can also consider analogous ways of reconceptualizing the elements in the psychological domain. In addition, measurement error and stochastic properties of physiological responding have been ignored for didactic purposes. Their inclusion does not change the framework outlined in the text but rather results in the fuzzy sets Ψ_F and Φ_F", where elements (e.g., physiological response profiles) are defined in stochastic terms.

6 Nevertheless, the application of the psychophysiological outcome and assessment context developed by Tranel, Fowles, and Damasio (1985) in the study of prosopagnosics by Tranel and Damasio (1985) illustrates the scientific value of psychophysiological inquiries even when the relationship between elements in the psychological and physiological domains hold only within highly circumscribed assessment contexts.

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