HANDBOOK OF PSYCHOPHYSIOLOGY

SECOND EDITION

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CONTENTS

Part Three. Processes

Part Four. Applications

Part Five. Methodology

Part Six. Appendices

CHAPTER ONE

PSYCHOPHYSIOLOGICAL SCIENCE

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

What is the relationship between the mind and brain? Why is it that in intense fear and anger one's bodily processes feel as if they have a mind of their own? Do feelings and thoughts affect physiological processes and health? Can one learn to control physiological responses and, if so, does the control of these responses or the associated feedback from the responses modulate cognition and emotion? What is the basis of consciousness? How exactly does one person's mood spread to others? Psychophysiology is a field concerned with just such questions. In psychophysiology, the mind is viewed as having a physical substrate. Contrary to unidirectional reductionism, however, the mind is viewed as being more comprehensible if the structural and functional aspects of this physical substrate are considered in conjunction with broader aspects of the functional outputs of that substrate, including verbal, behavioral, and contextual data. As such, psychophysiology is an interdisciplinary field that emphasizes multiple levels of analysis.

It is an exciting time in the field of psychophysiology. Investigations of elementary physiological events in normal thinking, feeling, and interacting individuals are now feasible, and new techniques are providing windows through which 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. Developments in ambulatory recording and computing equipment make it possible to measure peripheral physiological and endocrinological responses in naturalistic as well as laboratory settings. And the emergence of accepted recording standards, signal representation, and multivariate statistical analyses have facilitated study of the interrelationships among autonomic, somatic, brain, endocrinologic, and immunologic processes. 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 psychophysiological inference are important if veridical information is to be extracted from psychophysiological data. These are among the topics covered in depth in this *Handbook*.

Objections have been raised to the notion that the mind can be understood any better by including investigation of its physiological manifestations. For instance, some have suggested that changes in consciousness are sufficient to explain social behavior, and that it is more important to study how people perceive and react to events than to reduce consciousness to physiological events (e.g. Allport 1947; Caldwell 1994). Consciousness has been classified in a variety of ways but is typically thought to include changes in awareness of emotions, needs, motives, cognitions, or expectations (cf. Kipnis 1997). However, concerns about the fragility of theoretical structures based on self-report data have been expressed for more than half a century (Cook & Selltiz 1964; Gutek 1978; Turner & Martin 1984). As Kipnis (1997) noted:

> Unlike the physical and biological sciences, however, these classification systems describe dynamic mental processes that cannot be directly seen, touched, or measured.... Despite the splendor of these visions about how the mind works, these classifications are particularly vulnerable to challenge and replacement. This is because, as I said, there are no empirical procedures used to verify their independent existence. (p. 207)

Others have argued that we do not know, and are not soon to discover, the physical counterparts of psychological processes. Kipnis (1997), for instance, regarded the obstacles to discovering the physical counterparts to these dynamical processes as being overwhelming at present and therefore argued to explain "social behavior in relatively objective

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changes in technology, rather than in subjective changes in mental states" (p. 208).

There are undoubtedly psychological, social, and cultural phenomena whose secrets are not yet amenable to physiological analyses. Yet elementary cognitive and behavioral processes are being illuminated by psychophysiological methods, and more complex cognitive, affective, social, and clinical phenomena are increasingly succumbing to psychophysiological inquiries. Where most psychophysiologists differ from Kipnis (1997), therefore, is not in the importance placed on considering objective environmental factors and contexts, but rather in the value placed on pursuing the physical manifestations of psychological processes and of using biological data to inspire and constrain psychological research and theory.

Consider the range of human experiences that results from exposure to light. The human eye is a sensory receptor organ 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 that can be revealed through the use of specialized equipment to extend the reaches of the human senses. Exposure to ultraviolet light, although imperceptible to the human eye, can alter visual perception by damaging receptors in the eye, or it can influence behavior indirectly by producing sunburn; exposure to infrared light, which is also imperceptible to the human eye, can affect thermal sensations as well as body temperature. Knowledge of the broader organization of the electromagnetic spectrum and its relationship to human vision also makes it possible to design specialized instruments that render ultraviolet and infrared light visible to the human eye. These developments, and our understanding of the effects of electromagnetic energy on various aspects of human behavior, would not be likely if methods were limited to verbal reports and observations limited to the band of visible light. An illustration is the "blindsight" of patients with visual cortical damage, who can accurately respond to light without conscious awareness (Weiskrantz 1986).

Recent studies further indicate that visual perception is not simply a faithful representation of the image cast by a stimulus on the retina; rather, it is a neural image formed by neural mechanisms over the entire visual pathway. When the visual features of an external stimulus produce the experience of a different external stimulus, we call it an illusion. This label does not explain the discrepancy between the external stimulus and the conscious experience of this stimulus, but recent psychophysiological investigations demonstrate how such a discrepancy may occur. Tootell et al. (1995), for instance, used functional magnetic resonance imaging (fMRI) to observe brain activity as individuals watched an expanding grid on a screen and again as individuals viewed the grid when it stopped expanding. When the grid stops expanding, individuals experience an illusion that makes it appear as if the grid is contracting rather than sitting motionless on the screen, an illusion known as the waterfall effect. Tootell et al. (1995) found that activity in the medial temporal (MT) region of the visual system continued during this illusion. These results, combined with animal studies in which stimulation of neurons in the MT region affected visual perception, are consistent with the notion that the pattern of neuronal activity in visual pathways (rather than the external stimulus per se) gives rise to the visual perception of movement.

Studies of the psychophysiology of cold provide another illustration of how consciousness can fit within a broader theoretical context, the nature of which would not be evident by an exclusive focus on verbal reports of feeling states. Physiological processes are temperature-sensitive, and various mechanisms have evolved to maintain core body temperature within the narrow ranges necessary for normal functioning. Most of these mechanisms (e.g., decreased eccrine gland activity to reduce cooling through evaporation, peripheral vasoconstriction to shunt heated blood away from the surface of the skin, shivering to produce additional body heat) are initiated and can operate entirely outside the range of consciousness. If automatic adjustments to raise body temperature prove insufficient, the individual becomes aware of the cold and of the need for willful action to raise body temperature. Mentation can also foster behavioral flexibility and creative adaptation. In this example an individual's actions could take any of a variety of forms, ranging from donning additional clothing to moving to a warmer environment. Thus, consciousness is not a divine endowment that orchestrates the organism's actions from a site on high but instead reflects brain processes that evolved because they confer adaptive advantage to the species. Consciousness may facilitate our ability to establish goals, engage in exploratory behavior, anticipate and predict rewards and punishments, contemplate the likely outcomes of behavioral options, learn vicariously, engage in counterfactual reasoning, and more. But rather than viewing consciousness as the ultimate achievement of the human species that can only be understood unto itself, most psychophysiologists view consciousness as an important but narrow band of influences, instantiated in brain processes and relevant to the governance of human experience and behavior. In this regard, the approach followed by contemporary psychophysiologists is reminiscent of that first adopted by seventeenth-century astronomers:

> 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)

Accordingly, 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, 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.

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.

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, ranging 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.

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 complexity added when moving from physiology to psychophysiology includes both the capacity by symbolic systems of representation (e.g., language and mathematics) to communicate and to reflect upon history and experience as well as the 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 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 areas of physiology and measurement. 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 responses being measured contributes to plausible hypotheses, appropriate operationalizations, laboratory safety, discrimination of signal from artifact, acquisition and analysis of physiological events, legitimate inferences based on the data, and theoretical advancement.

Psychophysiology – like anatomy, physiology, and psychology – 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, 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 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. Environmental psychophysiology elucidates the vagaries of organism–place interdependencies as well as the health consequences of design through unobtrusive physiological measurements. And applied psychophysiology 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 in order 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 (see e.g. Barchas 1976; Cacioppo & Petty 1983; Cacioppo, Petty, & Andersen 1988; Waid 1984). For instance, Meaney and colleagues (1996) provided 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.

Psychophysiology is intimately related to anatomy and physiology, and knowledge of the physiological systems and responses under study contribute to both theoretical and methodological aspects of psychophysiological research. However, as noted by Coles, Gratton, and Gehring (1987), knowledge of the physiological systems, though 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 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 while 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 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. 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, Donchin, & Porges 1986, pp. 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.

There has been little consensus regarding the formal definition of psychophysiology. Some of the early definitions of the field 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 (Ax 1964b; Furedy 1983). 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 humans 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 is still in evidence, this distinction is often blurred by psychophysiologists who modify physiology with drugs or conditioning procedures and by psychobiologists who 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. Ackles, Jennings, & Coles 1985; Hugdahl 1995).

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 they have been criticized as being too restrictive (Coles 1988; 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 versus normotensive parents).

Moreover, psychophysiology and psychobiology – as well as behavioral, cognitive, and social neuroscience – share goals, assumptions, experimental paradigms, and sometimes databases, but they differ primarily in terms of 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.

At present, for instance, there are fundamental limitations in the ability of psychophysiological measures such as brain imaging to accurately reveal functional localization (Barinaga 1997; Sarter, Berntson, & Cacioppo 1996a). Even for functions that are in fact localized to specific neural circuits, these circuits may: be diffusely organized or widely distributed; overlap anatomically or even share common neuronal elements with circuits mediating different functions; or perform different functions (e.g., facilitate or inhibit a given operation) depending on the patterns of input and activation associated with different cognitive states or contexts. These possibilities would clearly complicate efforts to elucidate the cerebral localization of functions. Activation of diffusely organized circuits (or components of circuits), for example, may not yield a sufficiently intense signal to be differentiated from noise or from activity patterns of control tasks. This could lead to a failure to detect a localized function. Alternatively, a focal, detected region within a larger undetected area of activation could lead to an overestimate of the degree of functional localization. Similarly, the existence of functionally distinct but overlapping circuits could lead to an underestimate of the degree of functional localization, as the overlapping area would be activated during multiple cognitive or behavioral contexts.

Perhaps the more problematic possibility is that some central circuits may have differential and overlapping functions depending on the pattern of activation. A helpful example is provided by the research on the functions of "state-setting" systems (Mesulam 1990), particularly the attentional functions mediated via cortical cholinergic and noradrenergic afferents (Sarter et al. 1996b). Research in this area has resulted in fairly specific hypotheses about (i) the attentional processes that depend on the integrity of cortical cholinergic and noradrenergic afferents and (ii) the key role of attentional dysfunctions based on aberrations in activity of these systems in major neuropsychiatric disorders (Robbins & Everitt 1987; Sarter 1994; Sarter & Bruno 1994). Whereas imaging studies have pointed to cortical areas in frontal, temporal, and parietal lobes that may be involved in various types of attention (Cohen et al. 1992; Corbetta et al. 1990, 1991; Grossman et al. 1992; Pardo, Fox, & Raichle 1991; Posner et al. 1988; Posner & Petersen 1990), more "bottom up" approaches aim at the determination of the specific role of acetylcholine in different cortical areas in attentional functions (Metherate & Weinberger 1990).

An understanding of the role of the major afferent projections to cortical areas in attention is facilitated by a convergence of evidence from imaging studies in human patients and from animal studies on the cognitive effects of manipulations of the activity of cortical inputs (Sarter et al. 1996a). Imaging studies may continue to relate sustained attention to prefrontal and superior parietal areas (Pardo et al. 1991), for example, and decreases in the activity in these areas may indeed be associated with the cognitive decline in dementia (Mielke et al. 1994). In isolation, however, the imaging approach is unlikely to reveal the precise functional contribution of individual afferent systems of these areas and, more generally, cannot discriminate different neuronal activity patterns leading to identical signal levels. The point is not to contrast or even prioritize the heuristic power of psychophysiological (top-down) or psychobiological (bottom-up) approaches but rather to illustrate the significance of integrating relevant evidence from psychophysiology and the neurosciences.

The emergence of areas of research in psychoneuroendocrinology (Frankenhauser 1983; Grunberg & Singer 1990; Mason 1972), behavioral neurology (Lindsley 1951; Tranel & Damasio 1985), and psychoneuroimmunology (Ader 1981; Glaser & Kiecolt-Glaser 1994; Henry & Stephens 1977; Jermott & Locke 1984) raises additional questions about the scope of psychophysiology. It is important to note that anatomy and physiology encompass the fields of neurology, endocrinology, and immunology owing to their common goals and assumptions as well as to the embodiment, in a literal sense, of the nervous, endocrine, and immunologic systems within the organism.

Psychophysiology, therefore, is based on the assumptions that human perception, thought, emotion, and action are embodied phenomena, and that physical (e.g. neural and hormonal) responses 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. 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.

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 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 century can be found involving the manipulation of a psychological factor and the measurement of one or more physiological responses (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 (1873), Vigoroux (1879), James (1884), and Fere (1888) as among the field's earliest pioneers. Yet the first scientific periodical devoted exclusively to psychophysiological research, the *Psychophysiology Newsletter,* was not published until 1955 as an outgrowth of the *Polygraph Newsletter* (Ax 1964a). The Society for Psychophysiological Research was formed five years later, and the first issue of the scientific journal *Psychophysiology* was published but a quarter century ago. Precisely when psychophysiology emerged as a discipline is therefore difficult to specify, but it is usually identified with the formation of the Society for Psychophysiological Research in 1960 or with the publication in 1964 of the first issue of *Psychophysiology* (Fowles 1975; Greenfield & Sternbach 1972; Sternbach 1966).

Although psychophysiology as a formal discipline is less than 50 years old, interest in interrelationships between psychological and physiological events can be traced as far back as the early Egyptian 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, & 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 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 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) suggested: "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 1,500 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 (e.g. Vesalius 1543/1947) during this period in history also began to uncover errors in Galen's descriptions, 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, *Magnete*) 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 such scholars as 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 alone 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). 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 clear result; and (4) recycle to refine the remaining possibilities. 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" (1628/1931), represented the first major work to use these principles to guide inferences about physiological functioning, and it also disconfirmed Galen's principle that the motion of the blood in the arterial and venous systems ebbed and flowed independently 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.

During this period, which coincided with a world now burgeoning with 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 ballonlike 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 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, presides 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." (quoted in Jaynes 1973, p. 172)

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. Borelli conducted 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, chap. 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, dissipation 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 1,500 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).

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 previously (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, resulting in the sometimes poor replicability or generalizability of the results. A second weakness is the intellectual invention and omniscience required to specify all relevant alternative hypotheses for the phenomenon of interest. Because neither of these shortcomings can be overcome with certitude, progress in the short term can be slow and uncertain. However, adherence to this sequence provides grounds for strong inference in the long term (Platt 1964).

SUBTRACTIVE METHOD IN PSYCHOPHYSIOLOGY

Physiological responses are often of interest 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 psychophysiological investigations is the "subtractive" method, which has been adapted from studies of mental chronometry (Donders 1868; cf. Cacioppo & Petty 1986; Coles 1989). 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 harbor n information processing stages, and the construction of the control condition is guided to incorporate $n-1$ information processing stages. Differences between these conditions (e.g., on reaction time measures) are thought to reflect the impact (e.g. duration) of the nth information processing stage.

The principle underlying the inclusion of physiological measures in these designs is twofold: (a) physiological differences between experimental conditions thought to represent n and $n-1$ processing stages support 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 "stage deletion" 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) requires 50 msec longer to complete than the control task (n stages), this result is consistent with the theoretical conception of the experimental and control tasks differing in one (or more) processing stage(s) as well as with the differential processing stage(s) requiring approximately 50 msec to perform. Similarly, if the experimental task 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.

When one of these stages is thought to be responsible for the differential impact of two conditions on behavior, analyses of concomitant physiological activity can again be informative in one of two ways. If the patterns of physiological activity resulting from the isolation of presumably identical stages are dissimilar, then the similarity of the stages is challenged even though there may be similarities between the subsequent behavioral outcomes. The greater the evidence from multiple operationalizations that a particular stage is accompanied by a specific physiological profile across the ranges of stimuli employed in the investigations, the more challenging is the dissimilarity in obtained physiological profiles (Cacioppo & Petty 1986).

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. These data do not provide strong evidence that the stages are the same; still, the more peculiar the physiological profile is to a given stage within a particular experimental context, the greater the value of the convergent evidence (Cacioppo & Tassinary 1990).

There are two additional issues that should be considered when using a subtractive framework to investigate elementary stages of psychological processes. First, 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. Using multiple operationalizations to insert or delete a stage may be helpful but, as outlined in what follows, this does not ensure strong logical grounds for inference. If each operational insertion or deletion of a stage has the same effect, then investigators may have greater confidence that these effects are attributable to the conceptual processing stage of interest, or at least that the effects are not an artifact of an unintended confound. Parametric studies of each processing stage can also provide important information about the range over which a stage manifests as a particular physiological profile, thereby improving investigators' ability to generate appropriate comparison conditions. A failure to find the same physiological profile across a wide range of a stimulus believed to invoke a given processing stage does not itself indicate whether a new stage is invoked or whether the old stage manifests differently at various levels of stimulation; however, it does indicate an important limitation when one is interpreting the physiological profile in a subsequent study of this processing stage. As Donchin (1982) suggested, "each hypothesis so tested generates predictions for its own specific range of validity. The observed relations may or may not be universally applicable" (p. 460).

Second, in order 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. 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. Again, the inclusion of several experimental and comparison tasks (i.e., multiple operationalizations) appears to be judicious.

Although there are important limitations on the assumption of simple additive models that make it more useful for studying some types of processes (see e.g. Sanders 1980), the subtractive method can also yield data that are helpful in deriving comprehensive, empirically based models of psychological processes. Again, assume that the comparison is between experimental conditions with different impacts on behavior. If the physiological profile that differentiates these conditions is similar to a distinctive physiological profile that has been found previously to characterize a particular processing stage, the possibility is raised that the same processing stage has been detected in another context. The stronger and more distinctive the link between a physiological profile and a processing stage within the ranges of stimuli used, the stronger is this possibility. Similarly, if the sequence of physiological activity differentiating two conditions can be modeled by concatenating the physiological responses found previously to characterize even more rudimentary processing types or stages, then a model of a set of stages distinguishing these two conditions would be suggested. Again, converging evidence for this empirically derived model could be marshalled from other (e.g., observational or verbal) measures obtained in the experiment and from subsequent experiments.

Whenever a physiological response (or profile) found previously to vary as a function of a psychological processing stage or state is observed, the possibility is raised that the same processing stage or state has been detected. Much of the research in psychophysiology is based on just such reasoning. 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, 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 psychophysiological inference is termed "affirmation of the consequent.") In the next section, we present a general framework for thinking about relationships between psychological concepts and physiological events, and we discuss the rules of evidence

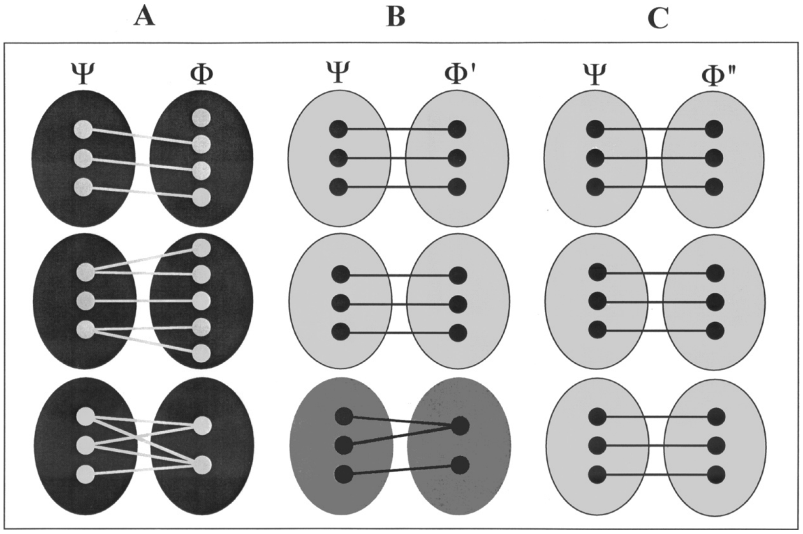

Figure 1. Depiction of logical relations between elements in the psychological (Ψ) and physiological (Φ) domains. Left panel: Links between the psychological elements and individual physiological responses. Middle panel: Links between the psychological elements and the physiological response pattern. Right panel: Links between the psychological elements and the profile of physiological responses across time.

for and the limitations to inference in each (see also Cacioppo & Tassinary 1990).

THE PSYCHOLOGICAL AND PHYSIOLOGICAL DOMAINS

A useful way to construe the potential relationships between psychological and physiological events is to consider these two types of events as representing independent sets (domains), where a *set* is defined as a collection of elements that together are considered a whole. 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.[1] Inspection of Figure 1 (upper left panel) reveals that 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.[2]

Focusing first on the top row of Figure 1, 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 nonpsychological factors have been held constant, their influence on the physiological responses of interest has been identified and removed, or they do not overlap with the physiological event of interest. These objectives are achieved through the application of proper psychophysiological recording techniques. 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 (see Figure 1, top row of panel B).

We can now state five general relations that might be said to map the elements within the domain Ψ of psychological events to elements within the domain Φ of physiological events (see Figure 2); these may be listed 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.

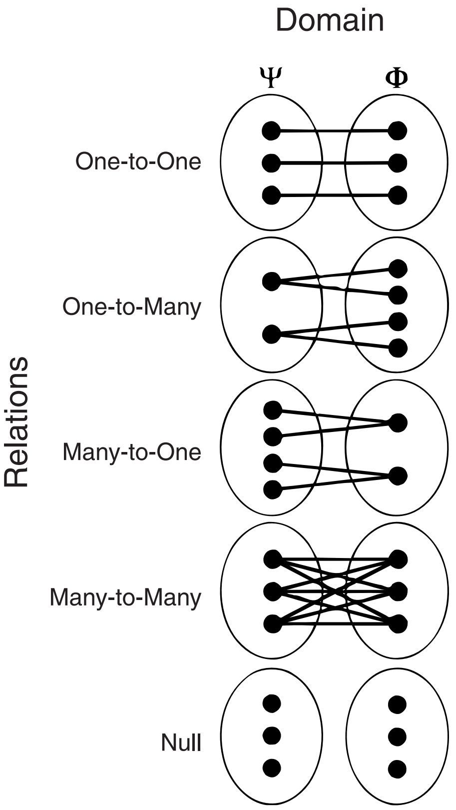

Figure 2. Possible relationships between elements in the psychological (Ψ) and physiological (Φ) domains.

4. A many-to-many relation, meaning that 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.[3]

Of these possible relations, only the first and third allow a formal specification of psychological elements as a function of physiological elements (Coombs, Dawes, & Tversky 1970, pp. 351–71). 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 theoretical interpretations in psychophysiology can therefore be strengthened if 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, many-to-one relationships.

PHYSIOLOGICAL ELEMENTS AS SPATIAL AND TEMPORAL RESPONSE PROFILES

If a one-to-one relation exists then 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 in psychophysiology (Cacioppo & Tassinary 1990; 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.

Another 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. Note that one-to-many relations between sets of psychological and physiological elements can be greatly simplified by reducing them to one-to-one relations as follows. Define a second set Φ' of physiological elements 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 elements in the physiological domain Φ both become one-to-one relations between Ψ and Φ' (see Figure 1, panel B).

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 that two or more psychological elements in Ψ are associated with two or more of the same elements in Φ (see Figure 1, 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 Φ' of physiological elements 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, one-to-one) relations by viewing elements within the physiological domain as representing singular physiological responses and physiological response syndromes.

However, 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. This may still not be a problem, because the set Φ' of physiological elements can be redefined such that the forms of physiological events as they unfold over time are also considered to yield yet another set of physiological elements, Φ'' (Figure 1, panel C; cf. Cacioppo, Marshall-Goodell, & Dorfman 1983). By including both temporal and 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.

ASYMMETRIES IN PSYCHOPHYSIOLOGICAL INFERENCE

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 $P(\Phi \mid \Psi)$, the "probability of Φ given 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 can, in contrast, be conceptualized as investigating the $P(\Psi \mid \Phi)$.

For example, 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 observed. This form of interpretation reflects the explicit assumption that there is a fundamental localizability of specific cognitive operations, as well as the implicit assumption that there is an isomorphism between Φ and Ψ (Sarter et al. 1996a). Causal hypotheses regarding a specific brain structure or process (Φ) underlying a cognitive operation (Ψ)

are of the form $\Psi = f(\Phi)$; they necessarily imply that Φ is always followed by Ψ but do not imply that Ψ is always preceded by Φ.[4] Furthermore, brain events (Φ) may be of interest to the extent that they index a cognitive operation or state, so that the inferences are of the form $\Psi = f(\Phi)$ rather than not-$\Psi = f(\text{not-}\Phi)$. Thus, an aim of psychophysiology can generally be specified by the conditional probability of Ψ, given Φ:

$$P(\Psi \mid \Phi) = 1.$$

The typical structure of the imaging study (and most psychophysiological studies) can be represented by the conditional probability of Φ, given Ψ:

$$P(\Phi \mid \Psi) = x.$$

That is, psychophysiological measures provide information about Φ as a function of Ψ, but the conditional probabilities are equivalent ($P(\Psi \mid \Phi) = P(\Phi \mid \Psi)$) if and only if there is a one-to-one relationship between physiological event Φ and cognitive function(s) or operation(s) Ψ (Cacioppo & Tassinary 1990). Interpreting psychophysiological studies of the form $P(\Phi \mid \Psi)$ as equivalent to psychophysiological studies of the form $P(\Psi \mid \Phi)$ is not misleading if one is dealing with one-to-one relationships. However, this is an assumption that must be tested. Assuming that brain areas become active during specific operations, for instance, reflects a one-to-one relationship and may hinder progress in psychophysiology unless this assumption is tested or its implications for inference recognized. These interpretations should be based on more than mere consistency with the imaging data; ideally, evidence would also be presented demonstrating that the $P(\text{not-}\Psi, \Phi) = 0$ in the assessment context (in which case Φ would be a marker of Ψ) or across contexts (in which case the relationship between Φ and Ψ would be invariant). Strong inferences would then be possible.

Approaches such as stimulation and ablation studies provide complementary rather than redundant information to traditional psychophysiological studies, in which physiological variables serve as dependent measures. This is because stimulation and ablation studies bear on the relationship $P(\Psi \mid \Phi)$, whereas studies in which physiological variables serve as dependent measures provide information about $P(\Phi \mid \Psi)$. Despite the formal parallelism between the expression $P(\Phi \mid \Psi)$ and $P(\Psi \mid \Phi)$, there is a fundamental asymmetry in the heuristic power of studies aimed at the demonstration of $P(\Psi \mid \Phi)$ versus $P(\Phi \mid \Psi)$. The causal role of Φ in process Ψ can be examined by direct experimental manipulation of the physiology. The loss of cognitive function by inactivation of neuronal processes (by mechanical, thermal, or neurochemical means) can serve to establish Φ as causal for function Ψ. Addressing a more complex avenue of research – facilitation of cognitive processes (e.g., attention or memory) by electrical or neurochemical brain activation – can further establish that Φ is a sufficient condition for influencing process Ψ (Sarter et al. 1996a). Whether the observed relationships have import in normal, functioning humans is informed by studies in which Φ as a function of Ψ is examined.

Although both relationships $P(\Psi \mid \Phi)$ and $P(\Phi \mid \Psi)$ can be studied experimentally, the complexity implied in studies aimed at demonstrating $P(\Phi \mid \Psi)$ is based on the fact that experimental alteration of cognitive function Ψ necessarily alters brain activities $\Phi', \Phi, \dots$ (including those, say Φ, that underlie Ψ). Thus, although a psychological context may yield concurrent manifestation in Ψ and Φ', the causal linkage remains in question because an alternate (even undetected) brain event Φ could be causally mediating both Ψ and Φ'. In this case, excluding Φ' as a necessary and/or sufficient condition for the observed Ψ may require a tedious and exhaustive evaluation of the alternative hypothesis not-$\Psi = f(\text{not-}\Phi')$. Note that this conclusion does not challenge the importance and utility of evidence generated by imaging methods, but it does point to fundamental limitations in the strength of the inference deduced from experimental approaches aimed solely at the demonstration of $P(\Phi \mid \Psi)$. The integration of methods and data from bottom-up and top-down approaches provides a means of circumventing some of the thornier interpretive problems of either approach alone, thereby permitting strong inferences in psychophysiology even in areas in which hypothesis-driven research is not yet possible (Sarter et al. 1996a).

AN ILLUSTRATION

As Gould (1985) noted:

> 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. (Essay 9)

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 heater and Ψ the temperature in a house. In the context of psychophysiology, the heater parallels a neural mechanism and the temperature represents the cognitive manifestation of the operation of this mechanism. Although the heater and the temperature are conceptually distinct, the operation of the heater represents a physical basis for the temperature in the house. Thus, $\Psi = f(\Phi)$. A bottom-up approach (i.e. $P(\Psi \mid \Phi)$) makes clear certain details about the relationship between Ψ and Φ, whereas a top-down approach (i.e. $P(\Phi \mid \Psi)$) clarifies others. For instance, when the activity of the heater is manipulated (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. That manipulating the activity of the heater produces a change in the temperature in the house can be expressed as $P(\Psi \mid \Phi) > 0$. Note that the $P(\Psi \mid \Phi)$ need not equal 1 for Φ to 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_1) and the amount of direct sunlight in the house (Φ_2). 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 heater is activated, then the temperature may not covary perfectly with the activation of the heater (i.e., $P(\Psi \mid \Phi) < 1$) even though the temperature is, at least in part, a function of the operation of the heater (i.e., $P(\Psi \mid \Phi) > 0$). If the outside temperature and amount of direct sunlight are constant or are perfectly correlated with the activation of the heater, then the temperature in the house and the activity of the heater may covary perfectly ($P(\Psi \mid \Phi) = 1$). In the context of psychophysiology, this is analogous to a brain lesion study accounting for some of the variance ($P(\Psi \mid \Phi) > 0$) or all of the variance ($P(\Psi \mid \Phi) = 1$) in the cognitive measure used in the study. The latter result does not imply that the lesioned brain region is a necessary component, just as temperature in the house covarying perfectly with heater activation does not mean that no other physical mechanisms could also influence the temperature. Thus, as long as $P(\Psi \mid \Phi) > 0$, Φ can be considered a predictor (or component) of Ψ; that $P(\Psi \mid \Phi) = 1$ does not imply that Φ is the only (or a necessary) cause of Ψ.

Also evident in this metaphor are the asymmetry between $P(\Psi \mid \Phi)$ and $P(\Phi \mid \Psi)$ and the interpretive problems that may result when simply assuming $P(\Psi \mid \Phi) = P(\Phi \mid \Psi)$. As outlined previously, the former term represents variations in temperature in the house given variations in the activity of the heater, whereas $P(\Phi \mid \Psi)$ represents the activity of the heater given variations in the temperature in the house. Although one would expect to find $P(\Phi \mid \Psi) > 0$ in some contexts, the fact that the temperature in the house increases reliably when the heater is activated does not necessarily imply that changes in the temperature in the house will be associated with variations in the activity of the heater. In the winter months, changes in the temperature in the house may be associated with corresponding changes in the activity of the heater. However, in another context (e.g., the summer months), the heater may be uniformly inactive yet housing temperature continues to vary owing to the operation of other physical factors (e.g., outside temperature Φ_1 or exposure Φ_2 to direct sunlight). Thus, the finding that $P(\Phi \mid \Psi) = 0$ means not that Φ has no role in Ψ but 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 heater may remain a part of the physical mechanism 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 solely 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 a light emitting diode (LED) on a thermostat (which we will call Φ') that illuminates when the heater (Φ) is operating. In this case, $P(\Phi \mid \Psi) = P(\Phi' \mid \Psi) > 0$. 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 heater – as long as a top-down approach were used. Were the complementary bottom-up approach to be used, it would become obvious that disconnecting (lesioning) the heater has effects on the temperature in the house whereas disconnecting (or directly activating) the LED has none.

The metaphor also illustrates the "categorical" error: the intuitively appealing notion that the organization of cognitive phenomena maps in a one-to-one fashion into the organization of the underlying neural substrates. The temperature of the house, for instance, does not map into a single "temperature center" in the house; rather, it is determined by several different physical mechanisms. One might argue that the problem is in how Ψ is being defined, that the temperature in the house is not the most useful way of conceptualizing the phenomenon. One solution may be to specify the heater-related contribution to temperature (reconceptualize the function dimension, Ψ as Ψ'), but this is not the only or even the best solution. Suppose, for instance, that the system is designed to maintain the temperature of the house within a narrow range. The problem in such a system may not be in the definition of Ψ but in the full delineation of its physical basis (Φ, Φ_1, Φ_2, and interactions) in order to achieve a closer approximation between functional concepts and models of mechanisms. Although we anticipate that some one-to-one mappings between Φ and Ψ may ultimately be achieved, reaching this ultimate aim requires a recognition of the preliminary state of our knowledge at present and the attendant implications for strong inference. Given the complementary nature of the data from brain imaging and from direct stimulation and lesion studies, progress in psychophysiology should be fostered by an integration rather than a progressive segregation of these approaches and literatures.

Four Categories of Psychophysiological Relationships

As illustrated in the preceding section, relations between elements in the psychological and physiological domains cannot 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 not unique to psychophysiology or to the subtractive method, since many psychological and medical tests 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). Here, 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 1986; Donchin 1982). The notion of limited ranges of validity thus 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.

In order to clarify these issues, it is useful to conceptualize psychophysiological relationships in terms of a 2 (one-to-one vs. many-to-one) by 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 3. The criterial attributes for, and theoretical utility in, establishing each of these categories are specified in the two dimensions illustrated in Figure 3; 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 3 labeled "psychophysiological concomitants" 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.

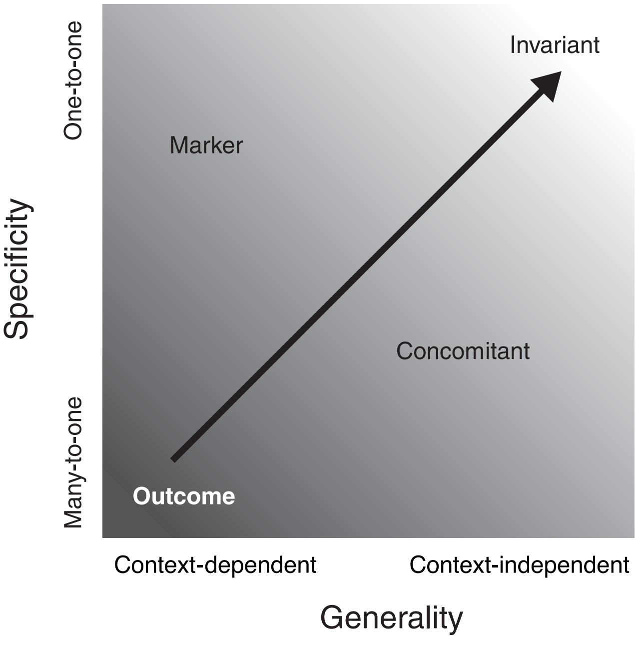

Figure 3. Taxonomy of psychophysiological relationships.

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 that one is dealing at the very least with an outcome relationship between these elements. Note that 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., is context-independent) or whether the response profile follows only changes in the event (i.e., is isomorphic) 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 isomorphy 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 isomorphy) of the relationship. However, this progression is not problematic in terms of causing erroneous inferences; as we shall see, any logical inference based on the assumption that one is dealing with an outcome relationship holds as well for marker, concomitant, or invariant psychophysiological relationships.

Despite serving as the most elemental psychophysiological relationship, the outcome can provide the basis for strong inferences. Specifically, if two psychological models differ in predictions regarding one or more physiological outcomes, then 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.

The identification of a physiological response profile that differentiates the psychological element of interest is sufficient to infer the absence of one or more psychological elements, but it does not provide logical grounds to infer anything about the *presence* of a psychological element. Hence, the identification of psychophysiological outcomes can be valuable in disproving theoretical predictions, but they are problematic as 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 (Prokasy & Raskin 1973). Similarly, EMG (electromyographic) 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 (Stroebel & Glueck 1978). Yet as noted in the previous section, 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 antecedents might have led to the observed physiological response. Procedures such as holding constant any 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 which elements are likely to have caused the observed changes in physiological response, 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 3). Such procedures clearly strengthen the grounds for psychophysiological inference, but they neither assure that all relevant factors have been identified and controlled nor provide a means for quantifying the extent of other influences on psychophysiological responding.

For example, consider 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 $P(\Psi, \Phi) \mid P(\Psi) > P(\Psi, \Phi) \mid P(\Phi)$, it can be seen that $P(\Phi \mid \Psi) > P(\Psi \mid \Phi)$ and hence that research based only on outcome relationships would result in 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 and probabilities may vary across situations. Indeed, comparisons of these probabilities across assessment contexts can provide a means of determining the individual or situational specificity of a psychophysiological relation. Before proceeding to this dimension of the taxonomy outlined in Figure 3, we elaborate further on psychophysiological relations within a specific assessment context when viewed within the framework of conditional probabilities. In particular, as $P(\Psi, \Phi)$ approaches 1 and $P(\text{not-}\Psi, \Phi)$ approaches 0, the element in the physiological domain can be described as being an ideal marker of the element in the psychological domain.

PSYCHOPHYSIOLOGICAL MARKERS

In its idealized form, a psychophysiological *marker* is defined as a one-to-one, situation-specific (context-dependent) relationship between abstract events Ψ and Φ (see Figure 3). The psychophysiological marker relation assumes only that the occurrence of one event (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. It is important to recognize that 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 can vary in their specificity and sensitivity. 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 the psychological construct – and the wider may be the range of validity of the relationship thereby established. 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 terms of sensitivity, a psychophysiological marker may simply signal the occurrence or nonoccurrence of a psychological process or event and possess 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, so that the measure can be used to delineate the onset and offset of the episode of interest, and/or it may vary in amplitude and thus reflect the intensity 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: (1) demonstrating that the presence of the target response reliably predicts the specific construct of interest; (2) demonstrating that the presence of the target response is insensitive to (e.g., uncorrelated with) the presence or absence of other constructs; and (3) specifying 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 condition that its presence is indicative of the presence of this condition. On the other hand, the term "indicant" is more generic and includes invariants, markers, and concomitants, since each allows the prediction of Ψ given Φ. We turn next to a description of concomitants.

PSYCHOPHYSIOLOGICAL CONCOMITANTS

A psychophysiological *concomitant* (or correlate), in its idealized form, is defined as a many-to-one, cross-situational (context-independent) association between abstract events Ψ and Φ (see Figure 3). 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 relationship tends to be more informative given a stronger association between elements in the psychological and physiological domains.

Consider, for instance, the observation that pupillary responses vary as a function of individuals' attitudes toward visually presented stimuli – an observation followed by the conclusion that pupillary response is a "correlate" of people's attitudes (Hess 1965; Metalis & Hess 1982). However, evidence of variation in a target physiological response as a function of a manipulated (or naturally varying) psychological event establishes only 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 if 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 is possible to control the numerous light-reflex–related variables that can confound studies using pictorial stimuli (Goldwater 1972). It is possible, in several of the studies showing a statistical covariation between attitudes and pupillary response, that the mean luminance of individuals' selected fixations varied inversely with their attitudes toward the visual stimulus (Janisee 1977; Janisee & Peavler 1974; 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 if 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, Fowles, and Damasio (1985), for instance, demonstrated that the presentation of familiar faces (e.g., famous politicians, actors) evoked larger skin conductance responses (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. However, to conclude that a psychophysiological concomitant had been established between familiarity and SCRs would mean that the same relationship should hold across situations and stimuli (i.e., the relationship would be context-independent). Yet ample psychophysiological research has demonstrated a psychophysiological outcome opposite to that specified by Tranel et al. (1985) – namely, that novel or unusual stimuli can evoke larger SCRs than familiar stimuli (see e.g. Landis 1930; Lynn 1966; Sternbach 1966). Hence, it is safe to conclude that the relation between stimulus familiarity and skin conductance should not be thought of as a psychophysiological concomitant.[5]

Unfortunately, evidence of faulty reasoning based on the premature assumption of a true psychophysiological correlate (or invariant) is all too easy to find:

> 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 hindrances to scientific advances, it would seem, stem not so much from impenetrable psychophysiological relationships as from a failure to recognize the nature of these relationships and their limitations to induction.

As in the case of a psychophysiological marker, the empirical 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. It is important to emphasize, however, 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. 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 is sometimes 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.

PSYCHOPHYSIOLOGICAL INVARIANTS

The idealized *invariant* relationship refers to an isomorphic (one-to-one), context-independent (cross-situational) association (see Figure 3). 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 arithmetical (algebraic) operations. Moreover, only in the case of invariants does $P(\Psi \mid \Phi) = P(\Phi \mid \Psi)$ 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; as we have argued, such an approach leads to erroneous psychophysiological inferences and vacuous theoretical advances.

It has been suggested occasionally that the psychophysiological enterprise is concerned with invariant relationships. As we have seen, the search to establish one-to-one psychophysiological relationships is important. Moreover, as noted by Stevens (1951):

> 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 analyses does not rest entirely with invariant relationships (Cacioppo & Petty 1985; Donchin 1982). 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 to follow), psychophysiology need not be conceptualized as offering only mappings of context-independent, one-to-one relationships in order to advance our understanding of human processes and behavior.

In summary, 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 (Cacioppo & Petty 1986). 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. These points hold for the neurosciences, as well. 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 is, at least, an outcome. Knowledge that changes in an element in the psychological domain are associated with changes in a physiological response or profile neither assures 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). Nevertheless, both forms of reasoning outlined in this chapter can provide a strong foundation for psychophysiological inferences about behavioral processes.

Conclusion

Psychophysiology is based on the dual assumptions that (i) human perception, thought, emotion, and action are embodied and embedded phenomena and that (ii) the responses of the corporeal brain and body contain information that – in an appropriate experimental design – can shed light on human processes. 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 is therefore, like anatomy and physiology, 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 and a systemic focus. For instance, the social and inferential elements as well as the physical elements of psychophysiology are discussed in the following chapters.

The importance of developing more advanced recording procedures to scientific progress in psychophysiology is clear, as previously unobservable phenomena are rendered tangible. However, advanced recording procedures alone are not sufficient for progress in the field. 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 psychometric approaches can contribute in important ways by generating 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 may be excluded. The study of physiological mechanisms and techniques can sharpen our thinking and reduce the error of our conceptualizations and measurements. Although necessary and important, one should bear in mind that such studies are means rather than ends in psychophysiology. Little is gained, for instance, by simply generating an increasingly lengthy list of correlates between specific psychological variables and additional psychophysiological measures.

A scientific theory is a description of causal interrelations. Psychophysiological correlations are not causal. Thus, in scientific theories, psychophysiological correlations are monstrosities. This does not mean that such correlations have no part in science. They are, in fact, the instruments by which the psychologist may test his or her theories (Gardiner, Metcalf, & Beebe-Center 1937, p. 385).

Thus, in order to further theoretical thinking, this chapter has outlined a taxonomy of psychophysiological relations and suggested a scheme for strong inference based on these relationships. This formulation can help address the following questions:

1. How does one select the appropriate variable(s) for study?
2. How detailed or refined should be the measurement of the selected variables?
3. How can situational and individual variability in psychophysiological relationships be integrated into theoretical thinking about psychophysiological relationships?
4. How can physiological measures be used in a rigorous fashion to index psychological factors?

However, the ultimate value of the proposed way of thinking about psychophysiological relationships rests on its effectiveness in guiding psychophysiological inference through the channels of judgmental fallacies. 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. In our discussions here, the psychological domain is coextensive with the conceptual domain and the physiological domain is coextensive with the empirical domain (Cacioppo & Tassinary 1990).
2. The identity thesis states that there is a physical counterpart to every subjective or psychological event (Smart 1959). Importantly, the identity thesis does not imply that the relationship between physical and subjective events is one-to-one (i.e., invariant). Within the context of psychophysiology, for instance, 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 subjectively appears to be elementary or unique psychological operations (e.g., beliefs, memories, images).

3. Both the many-to-many and the null relation may result in random scatter plots when measuring the natural covariation between elements in the psychological and physiological domains. However, these relations can be distinguished empirically by manipulating the psychological factors and quantifying the change in physiological response (and vice versa). The scatter plot 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.
4. See Cacioppo and Berntson (1992) for a discussion of the distinction between parallel and convergent multiple determinism.
5. Nevertheless, the application of the psychophysiological outcome and assessment context developed by Tranel et al. (1985) in the study of prosopagnosics by Tranel and Damasio (1985) illustrates the scientific value of psychophysiological investigations even when the relationship between elements in the psychological and physiological domains holds only within highly circumscribed assessment contexts.

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