Inferring Psychological Significance From Physiological Signals

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ABSTRACT: A century has passed since the publication of William James's Principles of Psychology, *yet most of the questions James raised about the relation between physiological events and molar psychological or behavioral processes, such as emotion, remain unanswered. The sluggish progress in capitalizing on physiological signals to address general psychological questions is due in part to shortcomings in the quantification of physiological signals in humans and, perhaps more important, to the way in which investigators have been thinking about the relation between physiological signals and psychological operations. In this article, we illustrate these points, and we provide a conceptual framework to foster research and analysis of psychological phenomena based on physiological signals. Psychological operations and physiological responses are defined in terms of configural and temporal properties, and psychophysiological relations are conceptualized in terms of their specificity (e.g., one-to-one versus many-to-one) and their generality (e.g., situation or person specific versus cross-situational and pancultural). This model yields four classes of psychophysiological relations: (a) outcomes, (b) concomitants, (c) markers, and (d) invariants. Finally, the model specifies how to determine whether a psychophysiological relation is an outcome, concomitant, marker, or invariant, and it describes important limitations in inferences of psychological significance based on physiological signals when dealing with each.*

> To begin with, no reader of the last two chapters will be inclined to doubt the fact that objects do excite bodily changes by a preorganized mechanism, or the farther fact that the changes are so indefinitely numerous and subtle that the entire organism may be called a sounding board, which every change of consciousness, however slight, may make reverberate. The various permutations and combinations of which these organic activities are susceptible make it abstractly possible that no shade of emotion, however slight, should be without a bodily reverberation as unique, when taken in its totality, as is the mental mood itself.
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> —James, 1890, p. 450

Over the past several decades, technological advances in bioelectronics, imaging procedures, and laboratory computing have made it possible to record signals noninvasively from the brain and peripheral physiological systems with greater sensitivity and fidelity than ever before (e.g., Coles, Donchin, & Porges, 1986; Druckman & Lacey, 1989). Nevertheless, advances in physiological signal acquisition have not yet had a consistent impact on theory and research in a number of areas in psychology or in the social sciences. We can offer at least three reasons for this state of affairs over which the investigator has control. Of primary concern in this article are limitations of the prevailing models for inferring psychological significance from physiological signals. In addition, however, insufficient technical considerations and elementary signal representation or analysis have contributed. Before addressing models for psychophysiological inference, we briefly discuss these latter points.

Obstacles to Psychophysiological Inference

Technological advances may permit one to venture into frontier areas of research, and breakthrough discoveries can occur even before investigators identify the problems and limitations of new technologies. It is worth emphasizing, therefore, that inadequate technical knowledge can also lead to serious errors of inference. Jonides (1982), for instance, reported the temporal integration of a sequence of two briefly presented visual patterns; this integration could not be explained in terms of receptor physiology, and therefore, it suggested a new and surprising level of cognitive integration. Subsequently, however, Jonides and his colleagues determined that the decay time of the phosphor on the display screen, coupled with their method of presenting the visual patterns, actually resulted in an overlapping of the two stimuli on the screen. Hence, the "temporal integration" occurred on the display screen rather than in the central nervous system (Jonides, Irwin, & Yantis, 1983).

Numerous examples also show that what at first glance appears to be an unreliability in physiological responding is instead the result of evolving measurement procedures. For instance, the electromyogram (EMG) is a continuous record of the intrinsic electrical activity associated with muscle contraction (i.e., muscle action potentials). The relation between behavior and the EMG appeared somewhat unreliable until detailed studies revealed that much of the variability in the electromyogram reflected actual differences in the muscular actions underlying the visible actions (Gans & Gorniak, 1980; Tassinary, Cacioppo, & Geen, 1989). Similarly, the electroencephalogram (EEG) is a continuous record of the intrinsic electrical activity associated with the brain (e.g., excitatory and inhibitory postsynaptic potentials). The

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spontaneous EEG, long thought to represent largely background noise, has recently been described as a chaotic and, therefore, a deterministic and controlled signal (Gleick, 1987). Developments of this kind might be viewed as the normal cost of using complex methods or technologies.

More problematic, the impression can be created that physiological signals bear little consistent relation to psychological or behavioral operations simply because insufficient technical considerations preceded the collection and interpretation of the physiological signals. For example, the relation between affect and electrodermal response—a relation that has been of considerable interest in the social sciences—has appeared quite variable. In an early study, Shock and Coombs (1937) recorded the skin resistance response to pleasant and unpleasant olfactory stimuli. They found that skin resistance response varied as a function of affective intensity and affective valence and that these factors interacted with the sex of the subject in determining the skin resistance response. Subsequent research has replicated the relation between affective intensity and electrodermal response, but the effects attributed to affective valence and gender have been more elusive (e.g., see reviews by McCurdy, 1950; Shapiro & Crider, 1969; Summers, 1970). However, decisions as simple as whether to measure electrodermal activity in terms of resistance (e.g., using constant current technology) or its reciprocal, conductance (e.g., using constant voltage technology), can have dramatic effects. To illustrate this point, Woodworth and Schlosberg (1954, pp. 140–141) reexamined a subset of the data from Lacey and Siegel's (1949) study of the effect of electric shock on the electrodermal response of 92 subjects. When the electrodermal response was expressed in terms of change in skin resistance, one individual (Subject A) appeared to show a response equal to that of another (Subject B). When the electrodermal response was expressed in terms of the change in skin conductance, however, Subject B appeared to show the stronger response to the stimulus by a factor of approximately 26! Thus, conclusions about the physiological effects of the stimulus were completely dependent on the measurement procedure used.

It is important to note that psychophysiological research over the past several decades has shown that measures of skin resistance response are strongly influenced by features irrelevant to the changes in physiological activity that these measures are purportedly gauging. For instance, (a) prestimulus levels of sweat gland activity can influence significantly the size of the electrodermal response to the experimental stimulus when the response is measured in terms of skin resistance rather than skin conductance; (b) measures of the skin resistance response vary in a far less linear fashion with actual changes in underlying physiological activity (e.g., the number of active sweat glands in a region, or their rate of secretion) than do measures of skin conductance response; and (c) measures of skin resistance response are less normally distributed than are measures of skin conductance response (e.g., Lacey & Siegel, 1949; see also Dawson, Schell, & Filion, in press; Venables & Christie, 1980). Given these biometric issues, it is understandable that empirical relations between some experimental treatments and electrodermal activity have appeared unreliable.[1] Unfortunately, despite the fact that this variability might be explained in terms of an unreliability between skin resistance response measures and actual changes in physiological activity, the impression created is that the relation between psychological and physiological events is unreliable. Despite the fact that skin resistance measures have been shown to have poor biometric properties, these measures continue to be used (e.g., Ekman, Levenson, & Friesen, 1983; Elkin & Leippe, 1986).

The appearance of unreliable psychophysiological relations can also stem from imprecision during signal acquisition on the psychological side of the equation. In an important article, Ekman et al. (1983) suggested that reliable autonomic differentiation of emotions had not been observed previously because a variety of emotions in addition to, or instead of, the single target emotion were included in the periods during which autonomic activity was measured. Consistent with this reasoning, Ekman et al. reported autonomic differentiation of emotions when facial expressions of a single emotion (e.g., anger, happiness) were used to demarcate epochs for signal processing.

A second obstacle to inferences about the psychological significance of physiological signals stems from the fact that advances in the comprehensive representation and analysis of complex physiological signals have lagged behind advances in signal acquisition (e.g., Bohrer & Porges, 1982; Cacioppo & Dorfman, 1987; Dern & Walsh, 1963). We have noted that physiological signals usefully can be thought of as a finite time series for purposes of representation and analysis. The amplitude variations across time constitute a waveform or "response" in the time domain; a histogram of these amplitudes within a given period of time constitutes a response in the amplitude domain; the set of cosine curves of varying frequencies into which the amplitude-time function can be decomposed constitutes the response in the frequency domain; and the distribution of the estimates of variance

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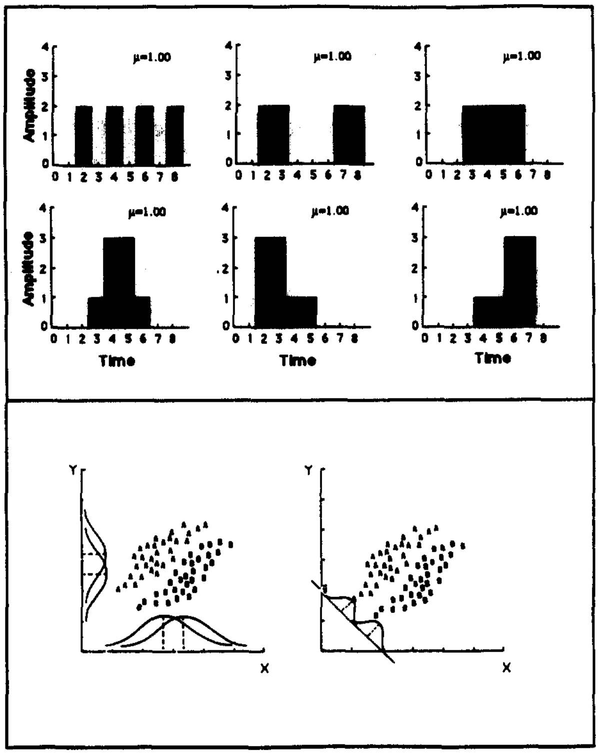
[1] One might question why skin resistance response was ever used in social and psychological research given these considerations. Among the more important reasons are that (a) the instrumentation first developed to record changes in electrodermal activity by exosomatic means used a constant-current technology, which ensured subjects would not be exposed to dangerous current flows but yielded readouts in terms of skin resistance, and (b) most of the relevant theory and research on the physiological mechanisms underlying phasic electrodermal responses that now clearly support the use of skin conductance measures have emerged during the past two decades (cf. Dawson et al., in press).

described by cosine curves of varying frequencies constitutes a response in the power domain (cf. Cacioppo & Dorfman, 1987).

Particular representations make certain information explicit at the expense of other information and hence render some operations or insights easy and others difficult. For instance, information about the size of a signal is clarified by representing a physiological response in the amplitude domain, whereas information about the possible periodicities underlying a signal is made explicit by representing the physiological response in the frequency domain. One important implication is that physiological signals that have been recorded accurately, that bear on psychological or behavioral processes, and that have good biometric properties may nevertheless be rendered mute regarding specific psychological questions due to decisions made during data reduction and analysis. For instance, multistage differential amplification, filtering, and sampling rates from several Hz to several thousand Hz across multiple channels make available detailed information about the form of physiological events in the time, amplitude, frequency, and power domains. Yet little of this information is captured by either traditional psychophysiological measures, the typical physiological measures reported in the social sciences (e.g., peak amplitude, peak latency, and alpha suppression in the EEG), or comprehensive measures of physiological signals within a single (e.g., amplitude) domain (Dorfman & Cacioppo, in press; Glaria & Murray, 1985). To demonstrate these points, we modeled conditions (Cacioppo, Marshall-Goodell, & Dorfman, 1983, Study 1) and created experimental conditions (Study 2) in which muscular tension varied uniquely over time while maintaining similar levels of mean and cumulative muscle tension across conditions (see Figure 1, top panel). We further demonstrated that moment-based waveform analyses in the time and amplitude domains clearly differentiated these conditions, whereas the traditional measures of electromyographic activity (e.g., mean amplitude and total power) did not (see also, Cacioppo & Dorfman, 1987; Cacioppo, Petty, & Morris, 1985). Fridlund and Izard (1983) have also illustrated how distinctive emotions could conceivably evoke distinctive physiological patterns, which would not be evident when using univariate inferential statistics (Figure 1, bottom panel). These studies demonstrate that physiological signals can *appear* mute regarding interesting psychological or behavioral questions because the parameters extracted to represent the signal (e.g., mean amplitude), or the inferential statistical analysis performed on these parameters (e.g., univariate statistics), masks the relevant information.

In sum, technological advances and knowledge contribute to obtaining reliable and valid measures of the physiological events of interest, and comprehensive and systematic methods of signal representation contribute to determining whether there is a relation between psychological operations and physiological events. Neither is sufficient, however, to guide inferences about the psychological significance of physiological signals. For instance, Galen's theory of psychophysiological processes (i.e., body fluids and moods) endured for more than 1,500 years, despite the availability for several centuries of procedures for disconfirming this theory, partly because the structure of scientific inquiry had not been developed sufficiently (Brazier, 1959).

Figure 1
Decisions Regarding Signal Representation and Analysis Can Mask Differences Among Physiological Signals



Note. Top Panel: Six hypothetical integrated electromyographic responses characterized by the same mean amplitude and total electrical energy. Top panel adapted from "Skeletal Muscular Patterning: Topographical Analysis of the Integrated Electromyogram" by J. T. Cacioppo, B. S. Marshall Goodell, and D. D. Dorfman, 1983, *Psychophysiology, 20,* p. 271. Copyright 1983 by the Society for Psychophysiological Research. Bottom panel: Scatterplots of two hypothetical emotions, *A* and *B*, measured using two psychophysiological responses, *X* and *Y*. Left bottom panel: Superposition of marginal distributions of *A* and *B* on *X* and *Y* demonstrates considerable overlap despite clear separability of *A* and *B* in the bivariate space formed by *X* and *Y*. Right bottom panel: Superposition of vector *V* on which the dispersions of *A* and *B* are maximally separated. *V* is a linear combination of *X* and *Y* derived from linear discriminant analysis. Bottom panel is from "Electromyographic Studies of Facial Expressions of Emotions and Patterns of Emotions" (p. 270) by A. J. Fridlund and C. E. Izard. In *Social Psychophysiology: A Sourcebook* edited by J. T. Cacioppo and R. E. Petty, 1983, New York: Guilford Press. Copyright 1983 by Guilford Press. Reprinted by permission.

Although progress has been made, the manner in which many inferences are drawn about the psychological significance of physiological events remains problematic. One stumbling block has been the assumption of psychophysiological isomorphism when, in fact, many physiological responses are multiply determined. Consider again electrodermal activity—one of the most common physiological measures reported in the social and psychological literature (see reviews by Cacioppo & Petty, 1983; Kaplan & Bloom, 1966; G. E. Schwartz & Shapiro, 1973; Shapiro & Crider, 1969). Despite significant advances and improvements in technical aspects of this research, Landis's (1930) observations about the psychological significance of electrodermal activity are as applicable today as they were 60 years ago:

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 or 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. (p. 391)

These observations are not limited to peripheral physiological measures, but apply also to CNS measures of cognitive activity (see Coles, Gratton, & Gehring, 1987; Donchin, 1982). Progress in addressing the questions raised by William James (1890), therefore, is likely to remain slow until advances are made in the inferential models used to link psychological operations and physiological events. We turn to this discussion next.

Psychophysiological Inference

"Experience does not ever err, it is only your judgment that errs in promising itself results which are not caused by your experiments" (Leonardo Da Vinci, c. 1510, cited in Boorstin, 1983, p. 337).

One important form of psychophysiological inference to emerge from the classic work of Francis Bacon (1620/1960) is hypothetico-deductive logic, in which one identifies two or more hypotheses about some phenomenon, devises a set of conditions with alternative possible outcomes that will exclude one or more of the hypotheses, and establishes the conditions and collects the observations while minimizing measurement error (cf. Massaro, 1987; Platt, 1964; Popper, 1959/1968). If the data are consistent with only one of the theoretical hypotheses, then the alternative hypotheses become less plausible. With conceptual replications to ensure the construct validity, replicability, and generalizability of such a result, a subset of the original hypotheses can be discarded, and the investigator recycles through this sequence. One weakness of this procedure is the intellectual invention and omniscience that are required to specify all relevant alternative hypotheses for the phenomenon. Because this difficulty cannot be overcome with certitude, progress in the short term can be slow and uncertain. Adherence to this sequence provides grounds for strong inference in the long term, however.

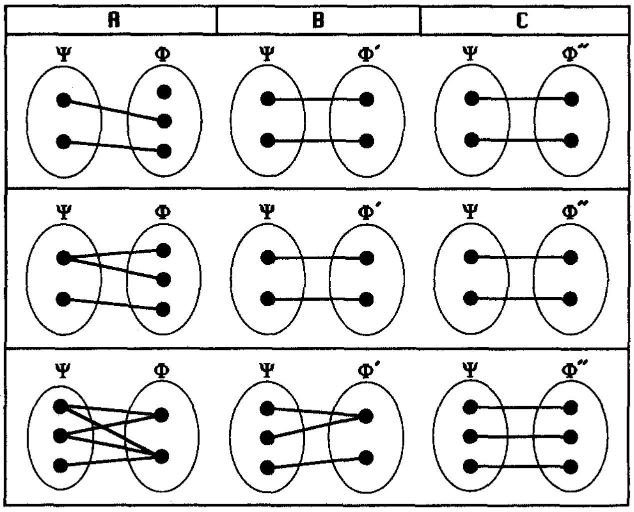
An important issue for cognitive, social, developmental, and clinical scientists is that physiological responses are often of interest to the extent that they may provide an *index* of a psychological process or state; and for neuroscientists psychophysiological techniques are of interest to the extent that they may provide information about the causal role of the physiological event in producing some behavioral phenomenon (e.g., Breckler, 1984; Cooper, 1959; Druckman & Lacey, 1989; Hess, 1965; Madsen, 1985; Wahlke & Madsen, 1982). Therefore, it is noteworthy that the reasoning underlying psychophysiological inferences in many investigations violates the logic of hypothetico-deductive research. A common research strategy is to identify a physiological response that differentiates the presence versus absence of a psychological operation in an effort to assess the instrumental role of the physiological event or to index the presence of the psychological operation for subsequent research. Of course, knowledge that a statement is true (e.g., the presence of a psychological operation is associated with some target physiological event) does not imply that the converse is true. Thus, this research strategy can provide specious grounds for any inference about the causal role of a physiological event and for any inference about the presence or extent of a particular psychological operation based on a physiological event. Although investigators may be aware of the potentially fallacious nature of such conclusions and consider their psychological inferences tentative, relying on such weak designs can retard or undermine the cumulative nature of science (Platt, 1964). Strong inference in psychophysiological research need not be limited to experimental designs based on hypothetico-deductive logic, however. We now turn to alternative conceptualizations.

Elements in the Psychological and Physiological Domains

To begin, let us consider psychological operations or "events" and physiological events as representing two distinct sets (domains) of elements. Psychological events constitute one set (Set Ψ), and physiological events constitute another (Set Φ). Elements within the psychological and physiological sets will be denoted simply by Ψ and Φ, respectively. Inspection of Figure 2 (upper left panel) reveals that all elements in the set of psychological events are assumed to have some physiological referent, reflecting an adherence to the monistic identity thesis.[2]

[2] The identity thesis states that there is a physical counterpart to every subjective or psychological event. Thus, the identity thesis is fundamental to tractable monistic philosophical solutions to the mind-body problem as well as to the scientific discipline of psychophysiology. It is important to note that the identity thesis does not imply that the relation between physical and subjective events is always one-to-one (i.e.,

Figure 2
Depiction of Logical Relations Between Elements in the Psychological (Ψ) and Physiological (Φ) Domains



Note. Panel A: Links between the psychological elements and individual physiological responses. Panel B: Links between the psychological elements and the physiological response pattern. Panel C: Links between the psychological elements and the profile of physiological responses across time.

There are, however, physiological elements that are not associated with elements in the psychological set. The existence of these psychologically irrelevant physiological events (e.g., random physiological fluctuations or local homeostatic adjustments) is important for purposes of artifact prevention or elimination. However, such physiological elements can be ignored if nonpsychologic factors are constant, their influence on the physiological responses of interest is identified and removed, or these elements do not overlap with the physiological event(s) of interest. These objectives, as well as the reliable and valid specification of elements in Φ, are advanced through the application of proper psychophysiological recording and analysis strategies (e.g., see Cacioppo & Tassinary, in press; Coles et al., 1986). The important point here is that reaching these objectives simplifies the task of specifying psychophysiological relations by eliminating physiological events that have no direct relevance to the target psychological events (e.g., see Figure 2, top row of Panel B).

We can now state five general relations that may exist between elements within the domain of psychological events, Set Ψ, and elements within the domain of physiological events, Set Φ—the next step in our effort to specify Ψ = f(Φ).

Physiological Elements as Spatial and Temporal Response Profiles

First, a *one-to-one* relation can exist, such that an element in Set Ψ is associated with one and only one element in Set Φ, and vice versa. Such relations provide strong grounds for inference but are not common at present in the psychophysiological literature (cf. Cacioppo, Petty, & Tassinary, 1989; Coles, 1989; Donchin, 1982). The functional opposite of the one-to-one relation is the *null relation,* in which the element in the physiological domain is unrelated to, and hence harbors no information about, the element in the psychological domain. The establishment of a null relation allows one to drop the physiological event from Set Φ in subsequent inquiries of the target psychological element.

A third form of relation is *one-to-many,* meaning that an element in Set Ψ is associated with two or more elements in Set Φ (see Figure 2, middle row of Panel A).[3] One-to-many relations can be simplified by reducing them to one-to-one relations in the following fashion: Define a second set of physiological elements, Φ′, such that any subset of physiological elements associated reliably with the psychological element is replaced by a single element in Φ′, which now represents a physiological syndrome or response pattern. Thus, one-to-many relations between elements in the two domains become one-to-one relations between Ψ and Φ′ (see Figure 2, Panel B).

The remaining relations are *many-to-one,* when two or more psychological elements are associated with the same physiological element, and *many-to-many,* when two or more psychological elements are associated with the

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 relation between a psychological event and a physiological response is constant across time, situations, or individuals; (d) every physiological response has specific psychological significance or meaning; or (e) the organization and representation of psychological phenomena at a physiological level will mirror what appears subjectively to be elementary or unique psychological operations (e.g., beliefs, memories, or images). Psychophysiological inferences based on analogy can, therefore, involve the commission of the logical error of affirming the consequent.

Readers might also note that a psychological element may represent any psychological construct (e.g., psychological operation, stage, process, or state) that forms part of the investigator's theoretical set, whereas a physiological element represents one or more physiological measures (e.g., tonic levels, phasic responses, or syndrome of responses) that form part of the investigator's observational set. In the most general sense, therefore, we are concerned here with inferring theoretical significance from empirical observations.

[3] Coombs, Dawes, and Tversky (1970, pp. 351–371) provided a general overview of one-to-one, many-to-one, one-to-many, and many-to-many relations among sets of elements. It should be noted, however, that what Coombs et al. labeled "one-to-many" and "many-to-one" relations we refer here to as "many-to-one" and "one-to-many," respectively. This change in nomenclature was made so that the labels symbolize "psychophysiological" mappings (e.g., one-to-many means here that one element in Set Ψ covaries with many elements in Set Φ). The goal, however, is to specify elements in Set Ψ *as a function of elements* in Set Φ. Hence, in the present nomenclature, only one-to-one and one-to-many relations allow a formal specification of a psychological element as a function of physiological signals.

same (or an overlapping subset of) elements in Set Φ (see Figure 2, lower row of Panel-A).[4] Neither of these relations allows a formal specification of psychological elements as a function of physiological signals because each element in Set Φ maps into multiple elements in Set Ψ. This is important because, as noted earlier, the research in which one is trying to infer psychological significance from physiological signals typically involves, or is based on prior research involving, the manipulation of or blocking on elements in the psychological domain and the measurement of elements in the physiological domain. Establishing that variations in a psychological element are associated with changes in one or more physiological responses does *not* allow strong inferences about the psychological significance of these physiological responses if variations in other elements in the psychological domain also are associated with these physiological response(s)—that is, if the psychophysiological relation is many-to-one or many-to-many. The grounds for psychophysiological inference can be strengthened, therefore, if the correspondence between the target elements within Sets Ψ and Φ can be specified in terms of a one-to-one relation.

The many-to-one and many-to-many relations can also be simplified by redefining what constitutes an element in the psychological or physiological domain. To illustrate, any subset of elements in Set Φ associated with one or more psychological elements may be represented in Set Φ' by a single element representing a profile of physiological responses. In so doing, some many-to-many relations between elements in Sets Ψ and Φ can be expressed as one-to-one relations simply by viewing elements within the physiological domain as including physiological response profiles.

Such a reconceptualization may not be sufficient to cast all of the psychophysiological relations of interest in terms of one-to-one. However, the set of physiological elements, Φ', can be redefined again such that information about the *form* of physiological responses as they unfold over time is also considered, yielding yet another set of physiological elements, Set Φ'' (see Figure 2, Panel-C). By including configural and temporal information regarding the physiological events in the definition of the elements in Set Φ'', many complex psychophysiological relations can be expressed as one-to-one relations—as we illustrate in the next section.

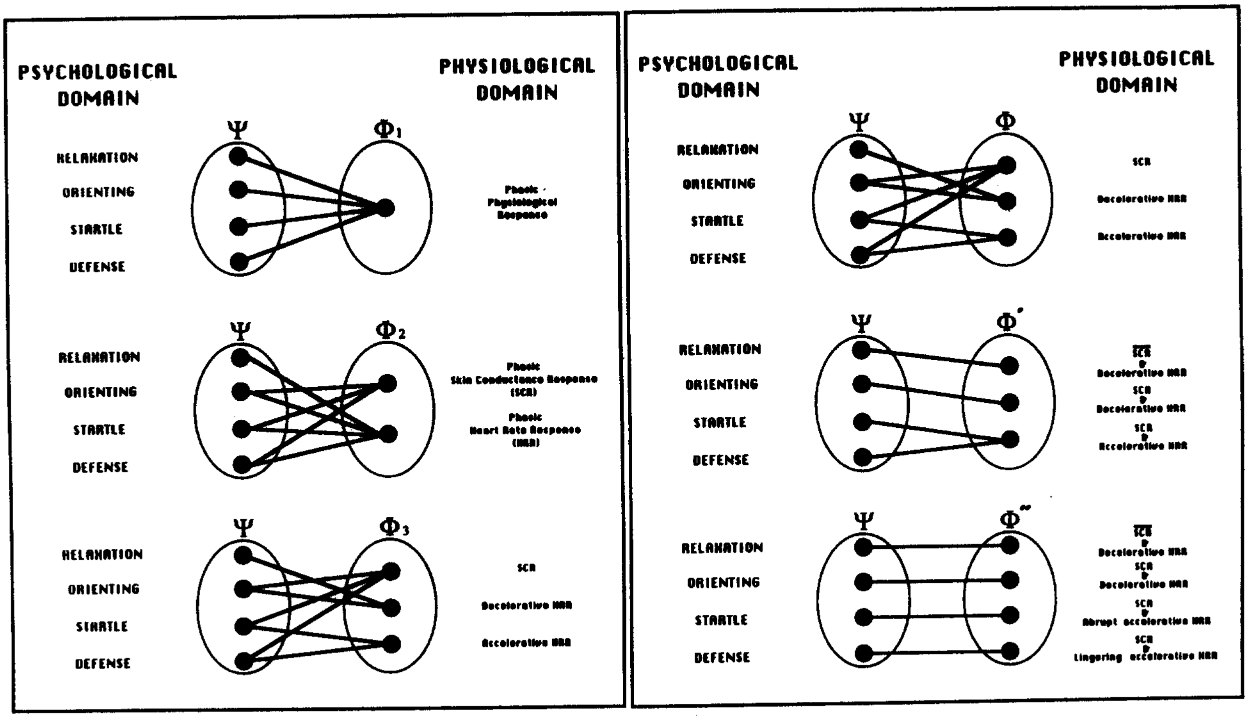
Before proceeding, we might note briefly analogous methods of reconceptualizing the elements in the psychological domain. Personality processes, cultural differences, and individual differences that modulate the relations between events Ψ and Φ'' can lead to a redefinition of the psychological domain such that these interacting factors become "elements" in Ψ'. In addition, psychological events, like physiological signals, unfold over time, and the temporal attributes of psychological events could also be used to redefine Ψ' to obtain Ψ''. We address a variation on these possibilities in the next major section, although for the sake of brevity we focus primarily on reconceptualizing elements in the physiological domain to achieve a one-to-one psychophysiological relation. Differing response thresholds, measurement error, and stochastic properties of physiological responding are also ignored here for didactic purposes. Their inclusion does not change the present framework, but rather results in the fuzzy Sets Ψ_ϵ and Φ_ϵ, in which elements (e.g., physiological response profiles) are defined in terms of thresholds or in stochastic terms, respectively. Parametric manipulations, internal replications, and conceptual replications are useful in practice when addressing the elements in and relations between Sets Ψ_ϵ and Φ_ϵ.

An illustration. Consider the relations among the relaxation, orienting, defense, and startle response as elements within the psychological domain, and changes in skin conductance (SCR) and an accelerated or decelerated heart rate (HR) as elements within the physiological domain (see Figure 3). For illustrative purposes, we have simplified the elements to include only these four constructs within Set Ψ and to include only two response measures within Set Φ. Even with these simplifications, there are clear obstacles to strong inference. Whether one defines elements in the physiological domain as any physiological change (Φ_1 in the top-left panel), the absolute value of phasic changes in skin conductance and heart rate (Φ_2 in the middle-left panel), or as phasic, directional changes in skin conductance and heart rate (Φ_3 in the bottom-left panel), the relationship is many-to-many, and no psychological event can be specified formally as a function of physiological elements. Notice that even in the most sophisticated of these representations (Φ_3), two of the elements in Set Ψ are associated with increased HR, the remaining two are associated with decreased HR, and three of these four elements are associated with SCRs. Because each element in Set Φ maps into multiple elements in Set Ψ, psychological elements cannot be specified as a function of physiological events. For example, although manipulations that evoke the orienting response are associated reliably with a SCR (Lynn, 1966), it can be seen in Figure 3 that this physiological response does not provide strong grounds for inferring the magnitude or even the presence of an orienting response.

These seemingly perplexing data can also be used to illustrate how the grounds for inferring psychological significance from physiological events can be strengthened considerably if the configural and temporal patterns of physiological responses are considered. As a starting point, let Set Φ represent the phasic physiological responses associated with the relaxation, orienting, defense, and startle responses (Figure 3, top right panel). The set of physiological elements, Set Φ, is redefined such that any subset of physiological elements reliably associated with at least

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

Figure 3
Depiction of Relations Between the Psychological Constructs of Relaxation, Orienting, Startle, and Defense and the Physiological Measures of Heart Rate (HR) and Skin Conductance Response (SCR)



Note. Top left panel: Links between the psychological elements and a change in physiological activity. Middle left panel: Links between the psychological elements and absolute change in heart rate and skin conductance. Bottom left and top right panels: Links between the psychological elements and individual physiological responses. Middle right panel: Links between the psychological elements and the physiological response pattern. Bottom right panel: Links between the psychological elements and the profile of physiological response across time.

one psychological element is replaced by a single, unique element in Set Φ′. This reconceptualization results in a one-to-one relation between the relaxation response and physiological events and between the orienting response and physiological events, and in a many-to-one relation between the concepts of startle and defense reactions and physiological events (see Figure 3, middle right panel). Two of the four psychological events can now be specified as a function of physiological events, although the grounds for inference remain weak even in this simplified example when increased HR and SCR are observed.

Next, Set Φ′ is redefined to allow consideration of the form of the physiological responses as they unfold across time, the result being Set Φ″. Both defense and startle are reliably associated with increased HR and SCR (Figure 3, middle right panel), but the HR acceleration peaks and returns to normal within approximately two seconds in the case of startle and does not begin to rise for several seconds and peaks much later following the stimulus in the case of the defense response (Lynn, 1966; Turpin, 1986). With this additional refinement, strong inferences about each of these psychological elements can now be drawn from the observed physiological events (see Figure 3, bottom right panel).

Four General Classes of Psychophysiological Relationships: Further Implications for Inferring Psychological Significance From Physiological Signals

Were we to go through the whole list of emotions which have been named by men, and study their organic manifestations, . . . [we should] find that our descriptions had no absolute truth; that they only applied to the average man; that every one of us, almost, has some personal idiosyncrasy of expression, laughing or sobbing differently from his neighbor, or reddening or growing pale where others do not. (James, 1890, pp. 447–448)

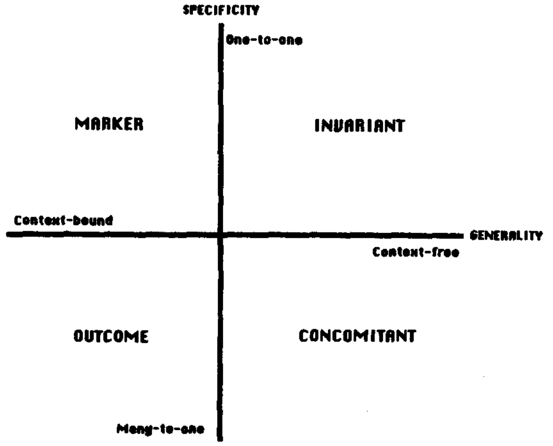
William James anticipated that relations between elements in the psychological and physiological domains cannot be assumed to hold across situations and individuals. This state of affairs is not unique to psychophysiology, however, as a variety of psychological and medical assessment procedures involve constructing specific assessment contexts in order to achieve interpretable results. The interpretation of a blood glucose test, for instance, rests on the assumption that the individual fasted prior to the test. Only under this circumstance can the amount of glucose measured in the blood across time be used to index the body's ability to regulate the level of blood sugar. The relation between the physiological data and theoretical construct is said to have a *limited range* of validity because the relation holds only for certain persons or situations (Cacioppo & Petty, 1986; Donchin, 1982). Turning this complexity to advantage, we find that a number of normally complex (e.g., many-to-many) relations between psychological and physiological phenomena might be specifiable in simpler, more interpretable forms within restricted assessment contexts.

Briefly, in addition to considering the configural and temporal form of the elements in Sets Φ and Ψ, one usefully can think of psychophysiological relations in terms of their *specificity* (e.g., one-to-one vs. many-to-one) and *generality* (e.g., situation or person specific vs. cross situational or pancultural). The cells depicted in Figure 4 represent the four quadrants within this two-dimensional space. The causal relations between the psychological and physiological elements, and whether the relations are naturally occurring or artificially induced, constitute yet other, orthogonal dimensions. The category in Figure 4 labeled "concomitants," for example, refers only to the conditions and implications of covariation and is not intended to discriminate among instances in which the psychological operation causes the physiological event (or vice versa), reciprocal influences exist, or a third variable is responsible for their covariation. In the sections that follow, we consider each class of psychophysiological relationship depicted in Figure 4 and the nature of the inferences each enables.

Outcomes

In the idealized case, an outcome is defined as a many-to-one, individual or situation-specific relation between Ψ and Φ (or, equivalently, Φ′ or Φ″). Establishing that a physiological event varies as a function of a psychological operation suggests that the psychophysiological relation is an outcome. This is typically the first kind of relation to be established in psychophysiological studies, and in psychological studies using physiological measures, because it is seldom possible to address initially whether: (a) the physiological event covaries with changes in the psychological event across situations and individuals (i.e., has the *property of generality*); (b) the physiological response covaries only with changes in this psychological event (i.e., has the *property of specificity*); and (c) the property of generality or specificity can be achieved by redefining either the physiological elements (i.e., Φ′ or Φ″) or the psychological elements (i.e., Ψ′ or Ψ″).[5] Hence, a given psychophysiological relation may be classified initially as an outcome but subsequently be reclassified as: (a) a marker once the property of specificity is established, at least within a limited assessment context; (b) a concomitant once the property of generality is demonstrated; or (c) an invariant once both the properties of generality and specificity have been established.

Figure 4
Major Dimensions and Classes of Psychophysiological Relations



This does not cause erroneous inferences. Any strong inference predicated on an outcome relation holds for marker, concomitant, or invariant psychophysiological relations, as well, because inferences based on hypothetico-deductive logic: (a) are the only form considered strong when dealing with an outcome relation (or when just an outcome relation has been documented thus far), and (b) are guided by the absence rather than the presence of empirical evidence for a hypothesis. That is, when two theoretical models differ in their predictions regarding one or more physiological responses, empirical support fails to emerge for at least one of these competing hypotheses. The logic of the experimental design, therefore, allows theoretical inferences to be drawn based on physiological signals—in particular, on the absence of predicted physiological signals. Of course, no single operationalization of psychological constructs is convincing. If multiple operationalizations of the theoretical constructs result in the same physiological responses, however, then investigators are justified in rejecting the theoretical model(s) yielding empirically unsupported predictions. Strong inferences about the psychological significance of physiological events, therefore, *are necessarily* guided by hypothetico-deductive logic when dealing with a many-to-one psychophysiological relation (i.e., outcomes, concomitants), and *can* be guided by hypothetico-deductive logic when dealing with one-to-one psychophysiological relations (see Figure 4).[6]

[5] The points made in the remainder of this article hold whether referring either to the physiological domains of Φ, Φ′, or Φ″, or to the psychological domains of Ψ, Ψ′, or Ψ″. Hence, to simplify the presentation, Set Φ is used to represent physiological domain Φ, Φ′, or Φ″; and Set Ψ is used to denote psychological domain Ψ, Ψ′, or Ψ″.

[6] Although "strong inferences" are limited to interpretations of physiological data based on hypothetico-deductive logic when dealing with an outcome relationship, considerable model building can proceed using adaptations of the subtractive and additive factors methodologies from cognitive psychology. For details about these latter frameworks, their adaptation from chronometric to physiological measures, and their application to the study of social processes, readers should consult Cacioppo and Petty (1986).

As we have noted, when a physiological event differentiates the presence versus absence of a particular psychological element, one may infer the *absence* of this psychological element given the nonoccurrence of the physiological event, but one cannot infer anything about the *presence* of the psychological element given the occurrence of the physiological event. Thus, the identification of psychophysiological outcomes can be valuable in disproving theoretical predictions, but it is insufficient when the goal is to achieve an index of an element in the psychological domain. This caveat is often noted in discussions of the scientific method and perhaps equally often is violated in scientific practice (Platt, 1964). Skin conductance, for instance, has been a major dependent measure in psychological research because emotional arousal is thought to lead to increased skin conductance (e.g., see Prokasy & Raskin, 1973). Similarly, EMG activity over the forehead region has been a target measure in relaxation biofeedback because tension has been found to increase EMG activity over this region (e.g., see Stroebel & Glueck, 1978). Simply knowing that manipulating a particular psychological element such as emotional arousal leads to a particular physiological response such as electrodermal activation does not logically enable inferences about the former based on observations of the latter because other elements or events (e.g., attention, mentation, or movement) might also produce the observed physiological event. There are several ways to reduce many-to-one relations to one-to-one relations (i.e., going from psychophysiological outcomes to psychophysiological markers or invariants; see Figure 4), such as holding constant any variations in irrelevant psychological elements; measuring all psychological elements that covary with the target physiological event (whether or not they are of interest) to determine to which the observed changes in physiological response are likely to be attributable; and excluding observations of the target physiological event that are believed to covary with irrelevant psychological elements prior to interpreting the physiological data. Such procedures clearly can strengthen the grounds for psychophysiological inference, but they do not ensure that all relevant factors have been identified or controlled, nor do they provide a means of quantifying the extent to which extraneous influences are affecting the target physiological event. Moreover, the argument of parsimony, if applied after an initial demonstration that a physiological event covaries with changes in the psychological event of interest (i.e., establishing an outcome relation), can lead investigators to inadequately research, and therefore woefully underestimate, other factors and elements in Set Ψ that also might covary with the target physiological event.

These issues are crystallized if one thinks about psychophysiological relations in terms of conditional probabilities. To illustrate, let Ψ represent the specific element of interest in the psychological domain (e.g., feelings) and Φ represent the physiological profile (e.g., facial EMG activity) of interest. From probability theory, it is clear that the probability of Φ given $\Psi[P(\Phi/\Psi)]$ can differ dramatically from the probability of Ψ given $\Phi[P(\Psi/\Phi)]$. An outcome relation is fundamentally an empirical statement that the $P(\Phi/\Psi)$ is significantly different from zero. A physiological *index* of a psychological event, on the other hand, can be conceptualized as a statement about $P(\Psi/\Phi)$, where

$$P(\Psi/\Phi) = P(\Psi, \Phi)/P(\Phi) \quad (1),$$

or, equivalently,

$$P(\Psi/\Phi) = P(\Psi, \Phi)/[P(\Psi, \Phi) + P(\bar{\Psi}, \Phi)] \quad (2).$$

Note that although it may not be possible to specify all relevant factors in the psychological domain that might affect or covary with the target element in the physiological domain, it *is* possible to determine (a) the extent to which changes in the physiological element covary with changes in the psychological element of interest, and (b) the probability that changes in the physiological element occur in the *absence* of changes in the psychological element of interest. As can be seen in Equations 1 and 2, the utility of Φ as an index of Ψ is weakened by (a) an unreliable covariation between Ψ and Φ, or (b) the frequent occurrence of Φ in the absence of Ψ. Therefore, two important goals of basic research designed to refine representations of Φ (e.g., through improved signal acquisition or understanding of the underlying biological mechanism) are to (a) improve the reliability of the covariation between Ψ and Φ, and (b) reduce the likelihood of observing Φ in the absence of Ψ, while leaving generally intact the observation of Φ in the presence of Ψ. For this reason, basic research on physiological signals and on the underlying biological mechanisms can be of considerable importance for scientists interested only in molar social, cognitive, or behavioral phenomena.

It is also possible for the absence of a response in the physiological domain to serve as a marker of an element in the psychological domain. For example, it might be the case that the absence of habituation to orienting stimuli is a predictor for individuals at risk for schizophrenia, or that the disappearance of an orienting response marks the transition from wakefulness to sleep in selected contexts. Such cases can be conceptualized within the present formulation in either of two ways. First, an element in Set Φ could be defined such that the *absence* of an evoked physiological response is denoted by Φ and the *presence* of the evoked physiological response is denoted by $\bar{\Phi}$. In this case, Equations 1 and 2, and their subsequent derivations would apply unaltered. Alternatively, Equations 1 and 2 could be rewritten such that:

$$P(\Psi/\bar{\Phi}) = P(\Psi, \bar{\Phi})/P(\bar{\Phi}) \quad (3),$$

or, equivalently,

$$P(\Psi/\bar{\Phi}) = P(\Psi, \bar{\Phi})/[P(\Psi, \bar{\Phi}) + P(\bar{\Psi}, \bar{\Phi})] \quad (4).$$

In this case, the absence of a physiological response in Equations 3 and 4 would be the functional equivalent to the presence of a physiological response in Equations 1 and 2.

Markers

In its idealized form, a psychophysiological marker is defined as a one-to-one relation between abstract events Ψ and Φ, which has a limited range of validity. The marker relation assumes only that the occurrence of one predicts the occurrence of the other within a given context or for a given category of individuals. Such a relation 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. In addition, 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. 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 within a given assessment context. The terms *index* and *indicant,* on the other hand, are more generic and refer to any physiological element that provides a mapping into a single element in the psychological domain. Hence, invariants and markers constitute indexes, although with differing ranges of validity.

For instance, previous research (e.g., Cacioppo, Petty, Losch, & Kim, 1986) has demonstrated that mild negative emotional imagery and unpleasant sensory stimuli lead to greater electromyographic activity over the brow muscle region than mild positive imagery and stimuli. Such research does not address whether facial electromyographic activity is a sensitive and specific marker of emotion, however, despite its occasional use in the literature to "index" emotion. In a recent study to address this issue, Cacioppo, Martzke, Petty, and Tassinary (1988) recorded facial electromyographic activity while individuals were interviewed about themselves. Afterward, these individuals were asked to describe what they had been thinking and feeling during specific segments of the interview characterized by distinctive forms of electromyographic responses over the brow region in the context of ongoing but stable levels of activity elsewhere in the face. Results indicated that ballistic EMG bursts over the brow region were the most predictive of the valence of subjects' feelings during the interview. These results suggest that well-defined forms of facial electromyographic responses may serve as markers of emotion when the person's primary task is to ruminate about how he or she feels and is unaware that facial actions are being monitored.

Psychophysiological markers, like all indexes, can vary in their particulars and sensitivity. The more detailed the form of the physiological response and/or the pattern of associated physiological responses (i.e., Φ), the greater may be the likelihood of achieving a one-to-one relation between Φ and Ψ, and the wider may be the range of validity of the relation thereby achieved. This is because, as noted earlier, the utility of Φ to index Ψ is generally strengthened by defining the physiological element so as to minimize its occurrence in the absence of the psychological element of interest while also leaving intact the strong covariation between Ψ and Φ.

In terms of sensitivity, a physiological event may simply signal, once threshold is exceeded, the occurrence or nonoccurrence of a psychological event. Alternatively, the physiological event may be related in a prescribed assessment context to the psychological event by some well-defined temporal function, such that the measure can be used to delineate the onset and offset of the episode, or it may vary in amplitude such that it emulates the intensity of the psychological event.

In sum, markers represent a fundamental relation 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 that the relation between a physiological and a psychological event qualifies as a marker are to (a) demonstrate that the presence of the physiological element reliably predicts the psychological element, (b) demonstrate that the physiological element is insensitive to (e.g., uncorrelated with) variations in other psychological elements or factors in the assessment context, and (c) specify the boundary conditions for the validity of the two preceding conditions.

Concomitants

A psychophysiological concomitant, in its idealized form, is defined as a many-to-one association between abstract events Ψ and Φ that generalizes across both situations and individuals.

To illustrate, Hess (1965) observed that pupillary responses were larger to pleasant than to unpleasant visual stimuli. This initial finding was interpreted as indicating that pupillary response is a "correlate" or "bidirectional index" of people's attitudes (e.g., Feldman, 1985; Hess, 1965; Metalis & Hess, 1982). This inference was premature, however, because evidence of variation in a target physiological response as a function of a manipulated (or naturally varying) psychological event establishes only an outcome relation; such a relation is necessary but not sufficient for the establishment of a psychophysiological concomitant, or "correlate," for several reasons.

First, the manipulation of the same psychological element in another context may alter or eliminate the covariation between the psychological and physiological elements because the latter is evoked either by a stimulus that had been fortuitously or intentionally correlated with the psychological element in the initial measurement context, or by a noncriterial attribute of the psychological element that does not generalize across situations. For instance, the hypothesis that pupil size is a correlate of attitudes has not been supported in studies using nonpictorial (e.g., auditory, tactile) stimuli, in which it has been 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 subjects' idiosyncratically selected fixations varied inversely with their attitudes toward the visual stimulus (Janisee, 1977).

Second, the manipulation of the same psychological element in another situation may alter or eliminate the covariation between the psychological and physiological elements because changes in the physiological event are 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. For instance, variations in mental load have a small, concomitant effect on pupillary diameter, which can be observed when luminance and eye fixation are carefully controlled (Beatty, 1982). However, little consistent relation between pupillary diameter and variations in processing load would be expected in less constrained testing situations, such as during a class, because of the presence of other uncontrolled factors (e.g., light reflexes) that also have powerful effects on the pupillary response (cf. Beatty, 1986).

Finally, when estimating the strength of the covariation between a psychological and physiological element, it is important *not* to rely simply on the extent to which manipulated or planned variations of Ψ are associated with corresponding changes in Φ. Measurement of the physiological response each time the psychological element is manipulated (or varies naturally) can lead to an *overestimate* of the strength of the relation and hence to erroneous inferences about the psychological element based on the physiological response. As can be seen in Equations 1 and 2, this overestimation occurs to the extent that changes in the physiological response not synchronized to variations in the psychological element go unnoticed and, therefore, are not taken into consideration when estimating the psychophysiological covariation. Thus, base-rate information about the occurrence of the physiological event across situations and individuals must also be considered (see Equation 2). This can be done in practice by quantifying the natural covariation between elements in the psychological and physiological domains and by examining the replicability of the observed covariation across situations and individuals.

Invariants

The idealized invariant relation refers to a general, isomorphic (one-to-one) association. Only in the case of an invariant relation does $P(\Psi/\Phi) = P(\Phi/\Psi)$ and $P(\bar{\Psi}, \Phi) = P(\Psi, \bar{\Phi}) = 0$. To say that there is an invariant relation, therefore, implies that (a) a particular element in Φ is present if and only if a specific element in Ψ is present, and (b) the element in Ψ is present if and only if the corresponding element in Φ is present. As Stevens (1951) noted,

> The scientist is usually looking for invariance whether he knows it or not. Whenever he discovers a functional relation between two variables his next question follows naturally: under what conditions does it hold? 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)

Although an invariant relation provides a strong basis for inferring psychological significance from physiological signals, such relations usually have been assumed rather than formally established. This may be problematic because any dissociation between a physiological measure and a psychological construct invalidates what might have been assumed to be an invariant psychophysiological relationship (cf. Donchin, 1982; M. Schwartz & Pritchard, 1982). The orienting and the defense response, for example, are associated with similar increases in electrodermal activity but have differing effects on general physiological mobilization (cf. Graham & Clifton, 1966; Lynn, 1966). Inferences about changes in "arousal" based only on changes in electrodermal activity can be questioned, therefore, especially when no attention has been given to other possible determinants of electrodermal responding that might be operating. Hence, assuming rather than establishing that a relation is invariant can lead to erroneous inferences and misleading theoretical "advances" should this assumption prove incorrect (e.g., see Landis, 1930). This practice can also create the *illusion* that psychophysiological relations are inherently unreliable and that there is nothing psychologically significant to be inferred from physiological signals. One advantage of the present formulation is that a framework is provided regarding (a) how to determine whether a psychophysiological relation is an outcome, concomitant, marker, or invariant, and (b) what can be inferred about psychological significance from physiological signals whether the extant data indicate one is dealing with an outcome, marker, concomitant, or invariant relation.

The implicit assumption or requirement that to be of interest, physiological events must map across situations and individuals in a one-to-one manner onto psychological operations can result in the rejection of reliable, valid, and sensitive measures and blunt scientific advance. Indeed, revered self-report measures of attitudes, such as the Thurstone and Likert scales, and chronometric measures of mental processes would all need to be abandoned if they were held to the requirement of invariance. Although it is important to demonstrate rather than simply to assume invariance to avoid fallacious reasoning based on physiological data, physiological signals can provide a good deal of information about psychological significance whether or not invariance exists.

Conclusion

The development and application of physiological recording procedures can contribute to progress in studies of molar social and psychological phenomena, as previously contested predictions are resolved, previously unobservable phenomena are rendered observable, and previously accepted conclusions are called into question. Less explicitly studied, but no less important, are the models for psychophysiological relations. We have suggested that progress toward answering questions about complex or molar psychological phenomena based on physiological signals can be escalated if greater attention is given to the task of inferring psychological significance from physiological signals. Should, for instance, reliable somatovisceral differentiation of emotions be demonstrated, as James (1890) theorized and Ax (1953) and Ekman et al. (1983) indicated, then important preliminary data for pursuing peripheral determinants of emotion would be achieved. This is because research in which emotions are varied while physiological activity is measured can be seen as addressing $P(\Phi/\Psi)$. As we have outlined, additional research addressing $P(\Psi/\Phi)$ is needed if psychophysiological profiles are to be used to index emotions.

Furthermore, due to the causal nature of James's theory, the following conditions are also implied, at least idiographically: (a) An operator (e.g., somatovisceral afferentiation) exists which generates a feeling, which responds to physiological changes, and which is organized so that the connection between the physiological responses and the feeling can be analyzed in terms of a mechanistic sequence; (b) occurrences of the physiological changes invariably begin before occurrences of the feeling; and (c) the physiological changes are always followed by the feeling (i.e., $P(\Psi/\Phi) = 1.0$), although at least in the general case when establishing causal influence, the feeling may occur in the absence of these physiological changes (i.e., $P(\Phi/\Psi) \leq 1.0$).

New conceptual models and research designs for inferring psychological significance from physiological signals may contribute, at least in a small way, to progress toward answering important questions about the relation between complex psychological processes and physiological events, and to a more consistent and productive use of physiological signals in studies of psychological phenomena in the social and psychological sciences.

In sum, an early definition of psychophysiology was the study of the effects of psychological variables on physiological responses. Consistent with this focus, much of the research has involved the manipulation of (or blocking on) psychological variables while recording physiological responses. Drawing on this research, psychophysiological assessments have often been implemented for the purpose of testing causal hypotheses regarding the role of physiological events or for the purpose of gauging the presence or extent of a particular psychological event or process. However, except in instances in which the psychophysiological relation is invariant or in which two (or more) theories make competing predictions about the physiological response, knowledge of the effects of variations in psychological/behavioral variables on a physiological response does not provide sufficient information for a strong inference about the psychological variable given the physiological response. We view the obstacles to scientific advance and to a cumulative knowledge-base as stemming not so much from impenetrable psychophysiological relations, but rather from the varieties of psychophysiological relations and the limitations to induction inherent in each. The proposed framework may provide a means for expanding the domain of strong inferences about psychological operations based on physiological events.

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