



MEASURING THE PHYSIOLOGY OF EMOTION AND EMOTION REGULATION—TIMING IS EVERYTHING

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The study of emotion has an intimate relationship to the measurement of physiological activity. The definition of an emotion has been debated for some time in the psychological literature (e.g., Ekman & Davidson, 1994). Ekman (Ekman 1992; Ekman & Davidson, 1994) defined emotion as a psychological state that has a defined and often rapid onset, a defined and usually brief duration, and a set of defined changes in facial muscle activity. Emotions have been described with physiological terms, and theories of emotion incorporate physiological change. For example, in Ekman's definition of emotion, he argues that certain emotions have distinct patterns of autonomic activity and consequently that different emotion states may be the result of autonomic appraisal (often with little conscious awareness). Thus, measurement of physiological activity during the expression and experience of emotion has been the goal of a good deal of psychological research. Finally, there has been a good deal of discussion regarding a definition of emotion regulation. Emotion regulation may best be viewed as the modulation of behaviors that underlie a present emotion state. In this chapter, we discuss one central area for the use of physiological measurement in the study of emotion: the importance of temporal dynamics in measuring physiology and emotion. Prior to that discussion, we present five desiderata that are important to consider when studying psychophysiology in general, and emotion and psychophysiology in particular, from a developmental perspective. For more in-depth discussions of the issues in measurement of emotion, interested readers are referred to important chapters by Davidson (1994b) and our own work (Fox, Schmidt, Henderson, & Marshall, 2006; Schmidt & Fox, 1998a), as well as edited volumes such as that by Schmidt and Segalowitz (2008).

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DESIDERATA FOR DEVELOPMENTAL PSYCHOPHYSIOLOGICAL STUDIES

It Is Critical to Link Behavior to Physiology

It is often appealing to measure physiological responses to a stimulus or experimental manipulation, identify change in physiology, and infer psychological processes as a function of that manipulation. However, we would argue that the physiological data require concordant behavioral observation and measurement so as to accurately interpret physiological effects. It is certainly the case that behavioral response and physiology do not always “correlate.” This may be a result of the fineness of the behavioral assessment, or it may reveal an important dissociation between particular behaviors and their underlying physiology. The optimum situation is one in which both levels of measurement are acquired. Measurement of concurrent behavior is important for multiple reasons, particularly with child populations. Infants and children move, vocalize, or do not attend to stimulus presentation. Movement or vocalization can affect physiology, and physiological measurement during periods of inattention can be misleading. It is best to measure behavior when measuring biology in developmental studies, as this allows one to synchronize the acquisition of behavior and physiology. In doing so, one can later code behavior and extract physiology from those periods of time that reflect a particular emotional response or state. An example of this work can be found in a study by Davidson and Fox (1989) who recorded electroencephalography (EEG) while 10-month-old infants’ behavior was videotaped during both maternal separation and the approach of an unfamiliar adult. Periods in which infants expressed discrete emotions were identified and these time epochs were used to define periods of EEG that were extracted, processed, and analyzed to examine the concordance of physiology and behavior.

Physiological Systems Change With Development

There are obvious changes in the physiology of the peripheral and central nervous systems with development, and these changes *will* affect the interpretation of physiological data. For example, measurement of brain electrical activity via EEG has utilized frequency bands to reflect different cognitive states and states of consciousness. The alpha frequency band, often associated with attention and relaxation, is characterized as falling between 8 and 13 Hz in adults. However, the frequency band for alpha changes as a function of age, beginning around 3–5 Hz in early infancy and moving upward with development (Marshall, Bar-Haim, & Fox, 2002). Similarly, vagal tone, a measure of parasympathetic influence on heart rate akin to respiratory sinus arrhythmia (RSA), is computed as a function of respiratory influences on heart rate. This also changes as a function of age as children’s

respiratory rates and heart rates change with development (Bar-Haim, Marshall, & Fox, 2000; Goto et al., 1997). The morphology of the event-related potential (ERP) also changes with age. In infancy and early childhood, responses to novel or low-frequency events elicit a negative component called the Nc. This deflection changes with age, actually becoming positive and reflecting the more common adultlike P3 component in late childhood (Courchesne, 1978). Finally, experience interacts with development to shape both structure and physiology. This topic is explored later in this monograph in the chapter by Strang, Hanson, and Pollak. Thus, one must be cognizant that the physiological systems being measured are themselves maturing and hence their measurement must take into account developmental status.

Attempt to Determine the Origin of the Signals Being Measured

Modern technology and computers have made it easy to measure the electrocardiogram (ECG) or to record brain electrical activity from participants. Using these methods, one can obtain reliable changes in measures as a function of stimulus presentation or experimental manipulation. What is more difficult is the interpretation of the meaning or underlying source of the signal. For example, heart rate is a multidetermined signal arising from the confluence of both sympathetic and parasympathetic systems, as well as physical movement and thermoregulatory inputs. Researchers have attempted to derive “pure” measures of sympathetic (e.g., preejection phase) or parasympathetic (RSA and vagal tone) activity to more directly interpret links between physiology and behavior. The problem is more complex when dealing with brain electrical activity measures like EEG and ERP. Since electrical activity is being measured at a distance from the source (somewhere in the head), one must identify the source from the output. This problem in electrophysiology, called “the inverse problem,” has led to a number of computational solutions to identify sources of EEG/ERP activity. These solutions are not perfect and necessitate high-density, multilead EEG acquisition. A conservative approach for both EEG and ERP is to refer to activity as scalp derived and nonspecific to any single source in the brain.

Individual Differences Play an Important Role in Understanding Physiology-Behavior Links

As in other areas of psychological research, individual differences have often been viewed as a nuisance, clouding the effects of a particular experimental manipulation. Conversely, psychophysiological studies, and developmental psychophysiology in particular, have long appreciated the importance of both individual variability in response and individual differences in subject

characteristics. Close to 40 years ago, Stephen Porges noted that some infants displayed cardiac deceleration to a visual or auditory stimulus reflecting their attention to the presentation while others did not. Closer inspection of their prestimulus baseline ECG patterns revealed that infants who displayed decelerated responses had more variable heart rates prior to stimulus presentation, while those who did not display deceleration had less variable and more stable heart rates. Porges went on to model these individual differences based on the degree of parasympathetic influence on infant heart rate and the role they played in attention (Porges, 1974; Porges, McCabe, & Yongue, 1982).

Using the difference in EEG power between left and right frontal scalp locations (i.e., EEG asymmetry), Davidson and Fox (1989) found that the pattern of resting frontal asymmetry in 10-month-old infants predicted their affective response to maternal separation. Infants exhibiting right frontal EEG asymmetry were more likely to cry and show distress to separation compared to those with a resting pattern of left frontal EEG asymmetry. These two examples suggest that measuring baseline or resting physiology may contain important information regarding the subject's pattern of behavioral and physiological response to stimulation.

Investigating the Specificity of Discrete Emotions

The argument that emotions have distinct patterns of facial expression that can be measured is based, in part, on Ekman's study of different facial muscles and their actions, which create patterns of facial expression that can be identified across cultures (Ekman, Sorenson, & Friesen, 1969). There have been a number of debates in the field of emotion research about whether this is the case, or whether emotions are less categorical and can be located across dimensions such as arousal and valence. The history of this debate goes back to the suggestion by James (1890) that emotions have different patterns of autonomic activity and, in some models, that this autonomic activity feeds back to the central nervous system for the experience of a particular emotion. Much of this debate has centered on the measurement of autonomic activity using directed facial action tasks (Ekman, Levenson, & Friesen, 1983). Less work has attempted to utilize measures of central nervous system activity such as EEG.

The exception is work by Davidson and colleagues (Davidson, Ekman, Saron, Senulis, & Friesen, 1990; Tomarken, Davidson, & Henriques, 1990), who attempted to elicit discrete emotions in adult subjects using film clips while simultaneously recording EEG. EEG was then extracted during the expression of particular emotions. The results were suggestive of a dichotomy between emotions associated with approach and those associated more with withdrawal. On the other hand, there was no evidence with the EEG for

distinctive patterns for specific discrete emotions. Similarly, Davidson and Fox (1989) examined 10-month-old infant facial expressions in response to maternal separation and approach of an unfamiliar adult while simultaneously recording EEG. Periods of discrete emotion were identified and EEG was extracted during those periods of time. Again, while there was evidence for differences in EEG pattern as a function of motivational state (approach versus withdrawal), there was no evidence for specificity of EEG patterns for discrete emotions.

The Importance of Temporal Dynamics in the Measurement of Emotion—Timing Is Everything

The experience of emotion involves many qualities, including the intensity of the expression, the degree to which the emotion is overtly expressed either facially or vocally, the success (or lack thereof) in communication or signaling, and, lastly, its duration. While each of these qualities is important for understanding the signal value of the emotion (the intent of the person expressing the emotion as well as the success of communication), the duration provides an opportunity to differentiate those emotions that are momentary from those that reflect more enduring mood states. This is particularly important when considering the task of modulating or regulating an emotion or mood. The temporal dynamics of the expression and experience of the emotion, the latency to reach its peak intensity, the duration during which that intensity is maintained, and the time required to return to baseline are all critical components of the regulatory process. Successful regulation of emotion most probably involves mechanisms of attention and cognition that alter the temporal dynamics of emotion experience, and often the lack of success in modulating this temporal picture can lead to disruptive patterns of behavior. Thus, measurement of this dynamic is of critical importance.

Paul Ekman, one of the most important and influential current psychologists involved in the study of emotion, laid out a precise vocabulary and conceptualization of emotion: what it is, what its parameters are, and how to approach its measurement. In a chapter published in 1984, titled “Expression and the Nature of Emotion” (Ekman, Sorenson, & Friesen, 1984), he outlined 10 characteristics of emotion. Among these are the suggestions that there are limits on the duration of an emotion, the timing of an emotion expression reveals information about the experience of that emotion, and specific changes in autonomic and central nervous system activity are related to different emotions. Ekman argued that emotions vary in their onset, offset, and duration and that these parameters inform the psychological experience of the emotion. For example, most emotions are short in duration compared to mood states. Thus, the experience of emotion is short lived compared to enduring

mood states that may not share the same facial, behavioral, or physiological characteristics. Although an emotion can vary in its timing parameters, it is more likely that each emotion possesses central tendencies in onset, offset, and duration. Fear may have a sudden onset and a brief duration, whereas anger may have a longer latency but also longer duration of expression. The temporal dynamics of emotion fit well within a structure for viewing emotions as biological signals, since physiology itself is not static but dynamically changing with the psychological state of the individual. Ekman's approach thus provided a foundation for linking physiological activity to the experience and expression of emotion. Indeed, he postulated that there should be distinct signatures in autonomic activity associated with different emotions. One of the reasons for differentiation of autonomic signals for different emotions involves their adaptive functions; fear requires immediate attention, mobilization of energy, and necessity to withdraw, while anger requires mobilization of energy and behavioral approach. Thus, fear should be accompanied by increased heart rate and low skin temperature, whereas anger would involve increased heart rate but high skin temperature, and happiness would involve low heart rate responses. The ability to empirically identify the presence of emotion using precise methods of behavioral coding opened the door for psychophysicologists to link ongoing physiological activity to the presence of emotion.

Most physiological and biological responses change dynamically over time. One can thus examine this dynamic signal as a function of response to a stimulus, or average its fluctuations over time to derive a mean-level response. The use of heart rate in emotion research is a good example. Heart rate is measured via recording of the ECG. The ECG signal is a complex waveform reflecting electrical activity of the heart muscle as it goes through the process of pumping blood to the body and brain. The different components of this waveform reflect changes in electrical muscle activity, with the most prominent components, known as the QRS complex, reflecting ventricular depolarization. The R wave is usually the largest amplitude wave or spike in the complex. The interval between two R waves in milliseconds is a measure of heart period (the inverse is heart rate, so a 500 ms heart period corresponds to 120 beats per minute). The ECG is easy to measure from and use with infants and young children making it a popular measure with developmental samples. In one study, van IJzendoorn and colleagues presented young children with movie clips selected to elicit different emotions (fear, happiness, and neutral affect) and measured ECG as the children watched the movies (Gilissen, Koolstra, van IJzendoorn, Bakermans-Kranenburg, & van der Veer, 2007). They found increased heart rate during the clips designed to elicit fear compared to clips designed to elicit neutral or positive affect. This is but one example of work that has examined dynamically changing patterns of heart rate during the elicitation of different emotions. Indeed, there is

a good deal of work with this approach that has confirmed the presence of emotion responses in children. Another body of work has attempted to distinguish different emotion regulation responses to certain affective challenges. In one such example, Forbes, Fox, Cohn, Galles, and Kovacs (2006) presented a disappointment paradigm to 4-year-old children and measured heart rate during presentation of the “disappointing” toy as well as behavioral response. Some children who displayed little behavioral change to the presentation of the disappointing toy nevertheless exhibited increased heart rate responses, suggesting these children were able to regulate the expression of overt affect while still displaying an internal physiological response to the event.

Similar to the aforementioned heart rate research, there is also a history of studies examining temporal changes in brain activity during the expression and experience of emotion. In order to monitor dynamic changes in brain activity with a high degree of temporal resolution, researchers utilize computation of an ERP from the ongoing EEG brain electrical activity. Unlike EEG, an ERP is computed in the time domain rather than frequency domain by time-locking brain electrical activity to the presentation of specific stimuli.

A given ERP waveform carries with it several defining characteristics: its polarity, latency, amplitude, scalp distribution, and potential source (Otten & Rugg, 2004), the last of which has become increasingly important given the imperfect relationship between scalp topography and actual brain structure (Key, Dove, & Maguire, 2005). Methods such as cortical source analysis (Scherg & Berg, 1991; Scherg & Picton, 1991) can be used to estimate the locations of current dipoles, a process that can be further improved by combining structural magnetic resonance imaging with ERP to generate individual brain maps as replacements for average brains or Talaraich coordinates (Richards, submitted).

ERP components are generally classified based on their polarity (P for positive, N for negative) and either their order (i.e., N1, P2) or their peak latency after stimulus onset or response (i.e., N170, P300; Key et al., 2005). Shorter latency waveforms have previously been assumed to represent more endogenous, automatic responses to stimuli, with longer latency waveforms representing exogenous components or information processing (Donchin, 1978). In other words, a given ERP component’s latency after stimulus onset may reflect its place in the stream of information processing for that stimulus.

ERP methods have been important in the study of emotion in multiple ways. First, there is a long history of examining the neural bases of face processing and particularly faces of different emotions using ERP. One of the most studied ERP components related to face processing is the N170, a negative deflection that is observed between 156 and 189 ms after visual stimulus presentation of faces in adults and is significantly larger in amplitude in response to human faces compared to other stimuli (Bentin, Allison, Puce,

Perez, & McCarthy, 1996). Rudimentary forms of the N170, the N290, and the P400 have been extensively studied in infants and children as young as one year of age (de Haan & Nelson, 1999; Halit, de Haan, & Johnson, 2003). In addition, its development is continuous and gradual through adolescence. Specifically, Taylor, Batty, and Itier (2004) found that, by midadolescence, children still differ from adults in the pattern of their N170 despite developing a recognizable N170 as early as age 4. The N170 can also be modulated by emotion, such that fearful faces elicit an enhanced ERP compared to neutral, happy, or angry faces in 7-month-olds (Leppanen, Moulson, Vogel-Farley, & Nelson, 2007; Nelson & de Haan, 1996) as well as in adults (Blau, Maurer, Tottenham, & McCandliss, 2007; Leppanen et al., 2007).

Second, there are a number of studies that have examined differences in ERP and information processing between tasks with and without an affective component. For example, Pérez-Edgar and Fox (2003) presented 11-year-olds with both a traditional and emotion Stroop task. The emotion Stroop task involved words that had affective significance (e.g., socially threatening words) and subjects were asked to name the color of these words as well as words reflecting neutral or positive meanings. The authors report differences in ERP components as a function of the affective valence of the word. In another study, 7-year-old children selected for temperamental fearfulness heard words of positive, negative, and socially threatening meaning and had to report whether the speaker was a male or female (Pérez-Edgar & Fox, 2007). Again, ERPs time locked to the word presentation were computed, and differences were found between temperamentally fearful and nonfearful children in the morphology of the ERP components as a function of word meaning.

A third approach to the use of ERP methods in assessing emotion response has been to utilize traditional cognitive tasks and manipulate subject affect during the task. For example, Pérez-Edgar and Fox (2005a) presented children with a traditional Posner spatial cuing task under two different conditions. In one condition, the task was presented as a standard attention-spatial cuing task, while children in the second condition were told that they would be playing for points and were given feedback regarding their performance. In actuality, feedback was random and noncontingent on their actual responses. ERP measures of attention differed as a function of the affective manipulation, with the amplitude of specific components reflecting children's attempts to regulate their attention in the face of emotional demands.

In another series of studies, Lewis and colleagues induced negative emotional states during a go/no-go task while recording high-density EEG (Lewis et al., 2008; Lewis, Lamm, Segalowitz, Stieben, & Zelazo, 2006; Lewis & Stieben, 2004; Stieben et al., 2007). Using a sample of 5- to 16-year-old

children, they found that the amplitudes of both the frontal N2 and P3 ERPs showed effects of negative emotion induction during the middle block of the task (Lewis et al., 2006; Lewis & Stieben, 2004). During this block, a change in the game's point-adjustment algorithm caused the subjects to lose all of their points earned from the previous block, with the effects of negative emotion persisting into the third block despite regaining their points for a prize. Increased N2 amplitudes for no-go versus go trials after emotion induction at all ages were taken to represent an effect of negative emotional states on effortful response inhibition. This task design has also been used to highlight different underlying mechanisms for externalizing and comorbid externalizing-internalizing subtypes of behavior problems in a sample of 8- to 12-year-old boys (Stieben et al., 2007). In the same go/no-go task, the comorbid children showed a significant increase in N2 amplitude in response to emotion induction, while externalizing children displayed consistently lower N2 amplitudes than both comorbid and control children across all blocks. Using the same sample, this task has also been used to identify changes in these mechanisms between pre- and postassessment during a 14-week community-based treatment program for the children and their parents (Lewis et al., 2008). Though children who showed improvement did not display differences in their N2 amplitude, they did show reductions in ventral prefrontal activation during the same time window of the N2 as determined by source modeling software. These results both differentiated them from nonimprovers and brought their activation levels in line with those of nonclinical children. For a more in-depth discussion of EEG/ERP and the emotion-cognition interface, interested readers should refer to the chapter by Bell and Diaz in this monograph.

Yet another approach to studying the temporal dynamics of emotion experience is to measure electromyographic (EMG) activity produced by the eyeblink startle response that is elicited by the sudden onset of an intense stimulus (i.e., startle probe). The potentiated startle response has been associated with amygdala activation (Davis, 2006; Lang, Bradley, & Cuthbert, 1998) and has been shown to be modulated by both emotionally valenced pictures (Cuthbert, Bradley, & Lang, 1996) as well as threat of an aversive stimulus, such as a shock (Grillon & Davis, 1997). Specifically, increased startle magnitude is observed when viewing unpleasant scenes (Lang et al., 1998) or negative facial expressions (Springer, Rosas, McGetrick, & Bowers, 2007), and in the presence of the threat (Grillon & Baas, 2003). In contrast, startle magnitude is attenuated during the presentation of pleasant stimuli (Lang et al., 1998). In addition, startle magnitude has been shown to be modulated by emotion regulation, such that it is decreased when participants are asked to suppress their emotions to unpleasant pictures and increased when asked to enhance their emotions to unpleasant pictures (Jackson, Malmstadt, Larson, & Davidson, 2000; Lee, Shackman, Jackson, & Davidson, 2009). Furthermore,

startle magnitude is greatest during anticipation of viewing affective stimuli compared to either during the stimulus presentation or after the stimulus presentation (Dichter, Tomarken, & Baucom, 2002; Sabatinelli, Bradley, & Lang, 2001).

The startle response has been examined in both infants and children as a measure of emotion. Balaban (1995) found that 5-month-old infants display a potentiated startle response while viewing angry faces and an attenuated startle to happy faces. Similar potentiated startle responses to aversive compared to pleasant pictures have been demonstrated in children (McManis, Bradley, Berg, Cuthbert, & Lang, 2001) and adolescents (Quevedo, Benning, Gunnar, & Dahl, 2009). Several studies have also examined individual differences in startle potentiation among infants (Schmidt & Fox, 1998b), children (Waters, Neumann, Henry, Craske, & Ornitz, 2008), and adolescents (Grillon, Dierker, & Merikangas, 1998; Merikangas, Avenevoli, Dierker, & Grillon, 1999; Reeb-Sutherland et al., 2009). Schmidt and Fox (1998b) found that negative reactive 9-month-old infants showed greater baseline startle and fear-potentiated startle to an approaching stranger than positive reactive infants. In addition, high anxious children have been shown to exhibit an increased startle response to the presentation of neutral and angry faces compared to nonanxious children (Waters et al., 2008). Grillon's research group (Grillon et al., 1998; Merikangas et al., 1999) demonstrated that adolescent girls with a family history for anxiety disorders showed increased startle response during safe cues, while boys showed an increased startle response during threat cues. Similarly, Reeb-Sutherland and colleagues (2009) found that anxious adolescents were high on measures of behavioral inhibition throughout early and middle childhood and showed a potentiated startle response to safety cues compared to nonanxious behaviorally inhibited adolescents and non-inhibited adolescents. Together, these studies suggest that examining the eye-blink startle response may be another useful measure for understanding the processing of emotional information over the course of development.

SUMMARY

In this brief paper, we have presented five principles that are important for utilizing physiological signals when assessing emotion in infants and young children. We have also argued that one of the critical qualities of emotion is its dynamic temporal pattern, and that physiological measures may be uniquely positioned to assess this pattern over time. While researchers often utilize static images to assess subjects' responses, evaluations, or appraisals of emotion, the real-life quality of emotion experience and expression is that of a dynamically changing signal and of a dynamically changing experience over time. Measurement thus requires an approach that can assess the time

course, the information processing flow, and the changes that occur to affect the experience of emotion or success in its communication. Since physiological signals change dynamically, and often will track the temporal changes of emotion, they remain ideally suited for assessing emotion and its regulation over time.