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IT'S ABOUT TIME

Event-Related Brain Potentials and the Temporal Parameters of Mental Events

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> Time as a dimension of every mental or behavioral process lends itself to measurement . . . [but] a technical difficulty at once suggests itself. "The speed of thought," we say; but as soon as we set about measuring the time occupied by a thought we find that the beginning and end of any measurable time must be external events. We may be able in the future to use "brain waves" as indicators of the beginning and end of a mental process.
>
> (Woodworth, 1938, p. 298)

The timing of mental events is among the most important and enduring constructs in psychology (see Jensen, 2006). Particularly in social-personality (see Chaiken & Trope, 1999) and cognitive psychology (e.g., Jacoby, 1991), numerous theories posit "dual processes" for understanding thought and action in which a central organizing principle is the idea that some mental processes unfold rapidly and spontaneously, whereas others rely on a slower, more deliberative form of processing. This dichotomy is nicely underscored by the title of Daniel Kahneman's (2011) book, *Thinking, Fast and Slow*. This dichotomy also can be understood is in terms of the influence of rapidly occurring processes on slower developing events. For example, impressions of people formed in milliseconds can contribute to thoughts, decisions, and behaviors that affect interpersonal interactions over minutes, days, or years (e.g., Ambady & Rosenthal, 1992).

For centuries, scientists and philosophers believed that thought happened instantaneously, too quickly to be measured (see Glynn, 2010). But in 1850, Hermann von Helmholtz hit upon a method for measuring the speed of thought. Using a device called a galvanometer, von Helmholtz measured the time required for an electrical impulse applied to a sciatic nerve to cause movement in a calf muscle, inferring that this method emulates the electrical impulses that naturally travel along nerve fibers. Using this procedure, von Helmholtz discovered that neural transmission speed was not instantaneously fast but in fact was relatively sluggish—around 30 meters per second in humans. This discovery, coupled with subsequent extensions to the central nervous system (see Hodgkin, 1964), led to the revolutionary idea that the speed of thought could be quantified, setting the stage for virtually all of experimental psychology.

Despite the enduring attractiveness of this idea, the measures typically used in cognitive and social-personality psychology provide limited information regarding the timing and function of mental events. Most behavioral responses (e.g., accuracy or response time [RT]) represent a single, discrete outcome of the operations of numerous processes with overlapping (and often unknown) temporal parameters operating at different levels (e.g., perceptual, cognitive, motor), some of which may not be of interest to the researcher (see Bartholow, 2010). RTs measured in different experimental conditions generally are assumed to vary because of the content, duration, or temporal sequencing of mental events across conditions (see Donders, 1969; Posner, 1978). To the extent that separating these influences is of theoretical interest, using RTs alone is likely to be insufficient.

In contrast, event-related potentials (ERPs) are uniquely suited to characterizing the temporal properties of specific mental processes. The electroencephalogram (EEG), from which ERPs are derived, can be measured with a temporal resolution of less than a millisecond (up to 2,500 samples per second [Hz]), faster than the native temporal resolution of neural activity (Reed, Vernon, & Johnson, 2004). This allows researchers to assess reflecting mental operations that unfold over tens or hundreds of milliseconds (see Amodio, Bartholow, & Ito, 2014). When combined with methodological and theoretical rigor, ERPs allow researchers a way of more directly accessing otherwise unobservable neurocognitive processes that support psychological constructs. The utility of ERPs for characterizing the temporal architecture of the information-processing system (i.e., *mental chronometry;* Posner, 1978) was convincingly demonstrated by Coles and colleagues (1985), who showed that RT in a cognitive control task varied according to three distinct and largely independent processes (response priming, stimulus evaluation, and response competition) that partially overlap in time during stimulus processing. These data challenged the long-held assumption that processing proceeds in serial stages (see Sternberg, 1969), and supported the alternative idea that processes conjointly accumulate information contributing to behavioral responses. Perhaps more importantly, such findings represent a realization of Woodworth's (1938) long-anticipated vision of a better means for timing mental events.

When applied to understanding social-personality processes, ERPs are especially helpful as covert measures of processes that occur too rapidly for assessment via self-report or other behavioral methods (i.e., implicit processes). Additionally, ERPs have considerable promise as markers of individual differences whose variability can signify temperament or other person-level processes (e.g., Bress, Meyer, & Proudfit, 2015). Despite these advantages, the potential of the temporal specificity of ERPs to advance social-personality theory remains largely untapped. In this chapter, we describe the utility and reliability of several widely studied ERPs within social-personality psychology. Our approach acknowledges that social-personality psychologists are interested in both mental processes and behavior, and thus we emphasize that this technique may be used to complement behavioral measures, not replace them. Note that space limitations preclude a comprehensive review of ERPs and their application to social-personality psychology; additional information can be found in other sources (e.g., Amodio & Bartholow, 2011; Amodio et al., 2014; Von Gunten, Bartholow, & Volpert, 2016).

What Are ERPs?

In simplest terms, ERPs are electrical signals produced by the firing of (mainly cortical) neurons. An ERP waveform (see Figure 5.1) represents a defined segment of ongoing brain electrical activity (i.e., electroencephalogram; EEG) that

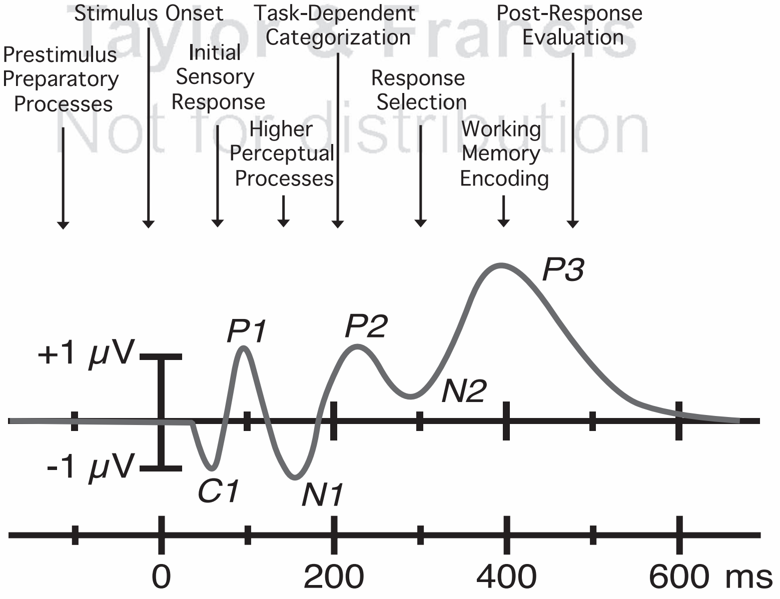


FIGURE 5.1 A Schematic Representation of an ERP Waveform Elicited by a Visual Stimulus

Note: The x-axis represents time and the y-axis represents amplitude in microvolts. The positive and negative deflections represent typical ERP components named for their polarity ("P" for positive, "N" for negative) and ordinal position in the waveform. Here, positive amplitudes are plotted upward, although ERP waveforms are often plotted with negative values upward according to electrophysiological convention. Image used with permission, © 2016 S. J. Luck.

is time-locked to a discrete event, commonly a stimulus presentation or a participant's behavioral response. Tiny electrical signals produced by post-synaptic potentials in activated neurons propagate through the brain to the surface of the scalp, where they are detectable by electrodes. The sequences of positive and negative voltage fluctuations observed in the EEG signal reflect opposing ends of an electrical dipole (akin to a common battery) created by the summation of these potentials generated in millions of activated neurons that are synchronously active and spatially aligned perpendicular to the scalp (see Allison, Wood, & McCarthy, 1986; Luck, 2014).

Researchers generally are interested in the magnitude and/or timing of specific fluctuations, often referred to as *components*, occurring at particular intervals in the ERP that theory and prior research have associated with psychological processes of interest. As with any measure of an unobservable entity, linking physiological events to psychological processes requires inferences. In ERP research generic inferences assume: (a) that ERP components represent the activity of one or more information-processing operations; (b) that variations in the size (i.e., amplitude) of these components reflect the degree of engagement of those operations; and (c) that variations in the timing (i.e., latency) of the components reflect differences in the temporal parameters of those operations, such as their initiation and duration (see Donchin, Karis, Bashore, Coles, & Gratton, 1986).[1]

How Are ERPs Measured?

Recording ERPs requires that stimuli be discrete events presented within a task in which the timing of stimulus onset and offset (and, when appropriate, behavioral responses) can be precisely controlled. Participants in ERP experiments typically sit upright before a video display, often with fingers placed on keys of a response device. While they complete the task EEG is recorded from an array of electrodes placed on the scalp, arranged according to standard placement guidelines (see American Encephalographic Society, 1994).

The most common approach to ERP measurement relies on a signal averaging approach in which stimulus- or response-locked epochs of EEG activity from numerous trials of the same type are averaged. Through this averaging process, EEG activity elicited by events of interest (i.e., signal) increases, whereas activity unrelated to the event (i.e., noise) will vary randomly across epochs and tend to average to zero. These averaged epochs are aligned with reference to a pre-event baseline period—usually 100–200 ms—so that EEG amplitude at the time of event onset will be zero. Trials containing large EEG artifacts (e.g., from muscle movement) are discarded. There are numerous options for quantifying ERP signals (see Gratton & Fabiani, 2017), but the most common involve measuring the average amplitude within a researcher-defined segment of the ERP waveform (generally a component of interest) and/or the post-event latency at which component amplitude peaks. (For a more extensive consideration of the neurophysiological origins, measurement processes and inferential considerations important for ERPs, see Luck, 2014).

Psychometric Properties of ERPs

Validity

A measure's validity indexes the extent to which it assesses the construct it is intended to assess. With respect to ERPs, validity refers to the psychological significance of a given component or voltage deflection. Given that the ERP waveform represents the summation of a number of different underlying components (see Luck, 2014), each theoretically reflecting a different neurocognitive process or processes, psychophysiologists must devise various approaches to disentangle the contributions of these processes and their psychological significance. The simplest approach is to experimentally manipulate the engagement of a process and then measure its effects. For example, studies showing that rare stimuli elicit larger amplitude in some component (e.g., the P3) than frequent stimuli provide evidence that the component may index novelty detection (e.g., Friedman, Cycowicz, & Gaeta, 2001). Further manipulations can then determine whether the component responds to novelty per se, or if novel stimuli represent some more general property (e.g., motivational significance; see Nieuwenhuis, Aston-Jones, & Cohen, 2005) responsible for the component's variation.

Sometimes, a known-groups validity approach (Cronbach & Meehl, 1955) is used. If two groups differ along a psychological trait or construct and a particular physiological response is thought to be linked to that construct, then a group difference should be evident in that physiological response. Consider the reward positivity (RewP), an ERP component elicited in response to performance feedback (e.g., winning money during a gambling task) that has been linked to reward sensitivity (Proudfit, 2015). Using a known-groups validity approach, Foti and colleagues (2014) found reduced RewP responses to rewarding feedback among individuals with major depressive disorder who exhibited blunted positive affective reactivity. This finding increases the RewP's validity as a measure of reactivity to reward.

Reliability

Reliability refers to the overall consistency of a measure and represents the upper limit of that measure's validity (e.g., Nunnally & Bernstein, 1994). Two types of reliability are of interest for ERPs: internal and retest reliability. Conceptually, *internal reliability* measures the extent to which responses elicited by trials of the same type are interchangeable within a given task. This is typically assessed in ERPs using split-half reliability (cf., Thigpen, Kappenman, & Keil, 2017), where waveforms recorded on odd and even trials for each subject are separately averaged. The measurement of interest (e.g., component amplitude or latency) is then computed for each waveform within each subject and their degree of association is tested using the Pearson product-moment correlation (*r*) and/or the intraclass correlation coefficient (ICC; Shrout & Fleiss, 1979).

While the majority of ERP studies examine effects of within-subjects manipulations, interest in individual differences in the psychological processes indexed by ERP components is increasing. Investigation of the suitability of ERP components as measures of trait constructs requires the additional consideration of *test-retest reliability*, the degree to which an ERP measure is stable over time. This idea is closely tied to recent interest in the use of ERPs (and other neurophysiological measures) as "neuromarkers" for various clinical phenotypes (e.g., Kwako, Momenan, Litten, Koob, & Goldman, 2016; Olvet & Hajcak, 2008; Williams et al., 2005), but the same logic applies to using such measures as markers for personality or trait dimensions (e.g., Pailing & Segalowitz, 2004). (For more extensive discussions of psychometric principles applied to psychophysiology, see Clayson & Miller, 2017; Strube & Newman, 2017; Thigpen et al., 2017).

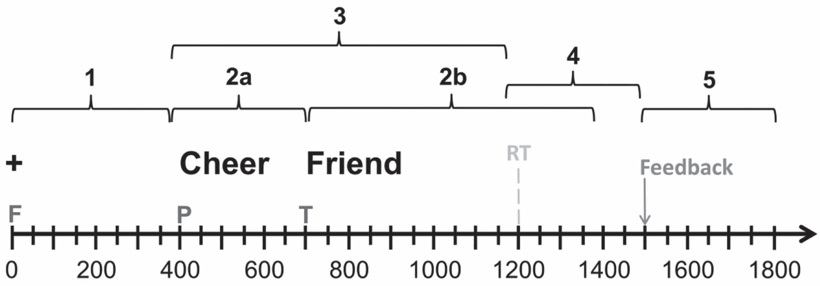
Applying ERPs to Information Processing

As computer memory and hard-drive space has become less expensive, it has become commonplace for ERP researchers to record EEG continuously throughout experimental tasks. A major advantage of this approach (over recording only during stimulus- or response-defined epochs) is that it permits a researcher to track information processing across multiple events within a given trial and/or examine changes in resting EEG between trials. For example, in addition to the cognitive operations elicited by a stimulus itself, it could be of theoretical interest to understand pre-stimulus, anticipatory processes (e.g., Ruge, Jamadar, Zimmermann, & Karayanidis, 2013), response preparation (e.g., Smolders & Miller, 2012), and post-response processes (e.g., Chang, Chen, Li, & Li, 2014), and, in some paradigms, processes elicited by performance feedback (e.g., Proudfit, 2015). In essence, and in contrast to the relatively impoverished information provided by RT, ERPs make it possible to track the mental processes contributing to behavioral responses from pre-perceptual anticipation through perception and response, and beyond. This point is illustrated in Figure 5.2, which lists five types of processes for which ERPs can be used to elucidate mental events that could be of interest in a given experimental trial. The following sections consider each of these processes in turn.

Anticipatory Processes

Contingent Negative Variation (CNV)

In some paradigms, researchers want to determine whether learning has occurred or expectations concerning an upcoming stimulus have been developed. Research



1. **Anticipatory processes:** attention; arousal
2. **Stimulus processing:** configural encoding; evaluative categorization
3. **Response preparation:** expectations and/or partial stimulus evaluation inform response activation
4. **Response processing:** performance monitoring/evaluation; salience of errors
5. **Feedback processing:** sensitivity to reward vs. nonreward

FIGURE 5.2 Mental Events During Affective Priming Plausibly Elucidated by ERPs

Note: Timing of a trial from a hypothetical affective priming task in which a fixation cross (F) signals trial onset and is followed after 400 ms by a prime word (P), which is followed after 300 ms by a target word (T). Participants must classify the target (positive or negative) as quickly as possible by making a right- or left-hand button press. Reaction time (RT; 500 ms on this trial) and accuracy are recorded, and feedback indicating whether the response was accurate and fast enough is provided 300 ms later. Recording EEG provides a temporally precise way to measure each of five processes, indicated by brackets delineating their occurrence, during each trial.

has shown that preparing a movement or waiting for the onset of a stimulus is accompanied by a slowly developing negative voltage in the EEG (see Brunia, van Boxtel, & Böcker, 2012). This negativity reflects one of several processes depending on the context in which it is elicited. For example, the CNV has been characterized as reflecting the successful transition from evaluating the potential for reward (on the basis of a cue) to motivated approach behavior during reward anticipation (Novak & Foti, 2015). RT is reduced as CNV amplitude increases (see Haagh & Brunia, 1985), indicating some functional significance of CNV-related brain activity for task performance. Reviews of CNV results across numerous paradigms have led to the conclusion that the CNV reflects a combination of motor preparation and anticipatory attention (Brunia et al., 2012). Attempts to separate these two influences led to the discovery of the slow negativity described next.

Stimulus-Preceding Negativity (SPN)

In some cases imperative stimuli may not require a behavioral response, but if timing of events within a task is predictable an anticipatory negative voltage leading up to stimulus onset—the SPN—can still be observed. Initially, the SPN was introduced as a way to describe differences between the CNV and a potential strictly reflecting movement preparation (the so-called *Bereitschaftspotential*; Kornhuber & Deecke, 1965). van Boxtel and Böcker (2004) described three types of stimuli likely to be preceded by this SPN: (a) performance feedback; (b) instructions for an upcoming task; and (c) affective stimuli. At the most basic level, in tasks that require no behavioral response measuring the SPN is useful as a way of determining whether or not participants are paying attention. This is especially useful if the stimuli themselves are affective, as such stimuli tend to elicit greater anticipatory attention (see Donkers, Nieuwenhuis, & van Boxtel, 2005). Thus, the SPN is sensitive to experimental manipulations but also can distinguish preexisting groups on relevant dimensions. For example, Fleming and Bartholow (2017) recruited groups of participants representing high and low risk for alcohol-related problems and measured their EEG while they completed a conditioned learning task. As predicted, the SPN preceding delivery of a predicted alcohol odor (but not a predicted nonalcohol odor) was larger in the high-risk group.

Stimulus Processing

Most commonly, researchers are interested in the neurocognitive processes elicited by stimuli representing constructs of theoretical interest. The components described next have been well utilized for this purpose.

N170

Most social interactions begin with face perception, and much of our social communication—conveying moods, emotions, and reactions—is accomplished through facial expressions. Early psychophysiological studies of face processing suggested that regions of the inferior temporal lobe appear specialized for the processing of human faces (Kanwisher, McDermott, & Chun, 1997). The N170 component is a negative deflection observed over the occipital-temporal region ~170 ms following the onset of a face (Bentin, Allison, Puce, Perez, & McCarthy, 1996) and is known to arise from activity in this area (e.g., Corrigan et al., 2009). Extensive experimentation has shown that the N170 represents the configural encoding of faces (Rossion & Jacques, 2011) and therefore can index the degree to which an object is spontaneously categorized as a human face. Although very few published studies to date have documented the reliability of the N170, current evidence suggests excellent internal reliability (*r*s = .77–.97, ICCs = .77–.90; Cassidy et al., 2012) based on split-half reliability analyses within tasks.[2] N170 also appears to remain stable over a one-month period (*r*s = .82–.85, ICCs = .75–.95; Cassidy et al., 2012; Huffmeijer, Bakermans-Kranenburg, Alink, & van Ijzendoor, 2014).

There has been intense debate over whether social and motivational factors can have a top-down influence on perceptual experience, including face perception (see Firestone & Scholl, 2016). Classic models hold that the configural encoding of faces is a purely stimulus-driven, bottom-up process, occurring too early to be influenced by top-down factors (Bruce & Young, 1986). However, studies have shown that self-reported judgment of faces is affected by top-down variables, such as context (e.g., Freeman, Penner, Saperstein, Scheutz, & Ambady, 2011). Behavioral and hemodynamic neuroimaging measures of face processing are limited in their ability to resolve this issue, but the very early emergence of the N170 makes it a good candidate to weigh-in on this debate. Several recent studies have shown that face encoding, as indicated by the N170, may be moderated by a host of top-down social-motivational factors, including minimal group distinctions (Figure 5.3; Ratner & Amodio, 2013), feelings of power (Schmid & Amodio, 2017), and experimental task demands (Senholzi & Ito, 2013). Such data present the strongest case to date for top-down effects on initial face encoding (for review, see Kawakami, Amodio, & Hugenberg, 2017).

Little research has documented individual differences in the N170. Amodio and colleagues have reported that both implicit prejudice (Ofan, Rubin, & Amodio, 2011) and dispositional social anxiety (Ofan, Rubin, & Amodio, 2014) covary with the degree to which the N170 differentiates White from Black faces, but much more data is needed before strong claims can be made regarding the usefulness of the N170 as an index of individual differences.

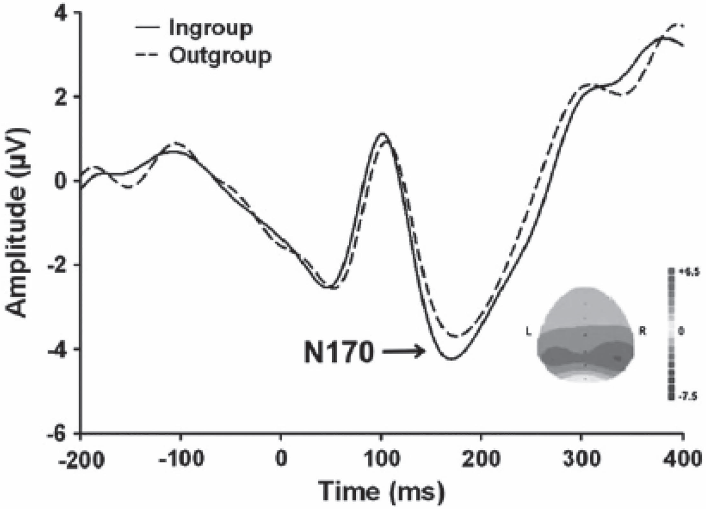


FIGURE 5.3 N170 Amplitude as an Index for Face Encoding

Note: N170 amplitude elicited by faces during a classic minimal groups experiment is larger (more negative) for arbitrarily assigned ingroup than outgroup members. Time = 0 on the x-axis represents face presentation onset. Reprinted with permission from Ratner and Amodio (2013).

P3

First described in the mid-1960s (e.g., Chapman & Bragdon, 1964), the P3 (or P300, or P3b[3]) is perhaps the most widely studied ERP component in the literature. The P3 is a positive-going deflection maximal at midline parietal scalp locations, which peaks 300–800 ms after the onset of a task-relevant stimulus (see Figure 5.1) (for review, see Nieuwenhuis et al., 2005; Polich, 2007). Because P3 amplitude is enhanced for novel or infrequent stimuli (e.g., Friedman et al., 2001), an early, dominant theory linked P3 amplitude to working memory updating (Donchin, 1981; Donchin & Coles, 1988). That is, when the category of a stimulus differs from that represented by previously attended stimuli, the currently activated mental representation requires updating; this process has been linked to enhanced P3. Of particular interest for social psychologists, this logic also applies when stimulus categories differ only on subjectively determined qualities. In an early demonstration of this property, Cacioppo, Crites, Berntson, and Coles (1993) found enhanced P3s to targets participants had previously indicated they liked (e.g., carrots), compared to targets they did not like (e.g., Brussels sprouts), revealing the utility of the P3 as a tool to understand internally held attitudes and evaluations. Current theory links the P3 with the incentive value (Begleiter, Porjesz, Chou, & Aunon, 1983) or motivational significance (Nieuwenhuis et al., 2005) of an eliciting stimulus. Numerous studies have found that affective or arousing stimuli elicit larger P3 amplitude compared to neutral stimuli (reviewed in Olofsson, Nordin, Sequeira, & Polich, 2008), supporting this general idea.[4] This theory explains the P3's sensitivity to novelty as a reflection of rare stimuli's motivational significance.

Perhaps of greater interest in the current context, the latency at which the P3 peaks has been shown to reflect the speed or ease with which stimulus evaluation occurs. Considerable research shows that P3 latency increases as stimulus evaluation becomes more difficult (e.g., Kutas, McCarthy, & Donchin, 1977; see also Coles et al., 1995). Critically, P3 latency is largely independent of overt response activation. In a convincing demonstration of this property, McCarthy and Donchin (1981) independently manipulated stimulus discriminability and stimulus-response compatibility in a choice RT task. They found that although reaction time was affected by both discriminability and stimulus-response compatibility, P3 latency was affected only by stimulus discriminability. Thus, not only can P3 latency augment RT and provide insight into pre-response stimulus categorization (see Dien, Spencer, & Donchin, 2004), this measure also can provide such information in paradigms requiring no behavioral response.

P3 amplitude has acceptable internal reliability (*r*s = .54–.93, ICCs = .50–.53; Cassidy et al., 2012; Fabiani, Gratton, Karis, & Donchin, 1987; Hämmerer, Li, Völkle, Müller, & Lindenberger, 2013; Kinoshita, Inoue, Maeda, Nakamura, & Morita, 1996; Polich, 1986; Walhovd & Fjell, 2002). In adolescents, Segalowitz and Barnes (1993) found somewhat lower internal reliability (r = .48) when based on 40 target trials (though this might not be enough trials for a stable estimate).

While most P3 work has examined effects of experimental manipulations, P3 also has been shown to correlate with individual differences. For example, based on the idea that the P3 is larger when evaluative categorization of a target differs from a preceding context (Cacioppo et al., 1993), Ito and colleagues (2004) measured P3 while White participants completed a task in which faces (White and Black) were shown infrequently amid strings of positive or negative images. Ito et al. found that greater explicit anti-Black attitudes were associated with larger P3s for Black (vs. White) targets when the affective context was positive (i.e., Black faces are more evaluatively divergent from positive images than are White faces); the opposite pattern emerged when the affective context was negative.

Regarding the suitability of the P3 as a trait measure, P3 amplitude has acceptably stable retest reliability in a variety of tasks (rs = .53–.85, ICCs = .54–.92) among participants from across the lifespan, including children (Hämmerer et al., 2013), adolescents (Williams et al., 2005), young and middle-aged adults (Fabiani et al., 1987), and elderly adults (Walhovd & Fjell, 2002). However, this appears not to hold in some contexts, including P3 elicited by olfactory stimuli (Thesen & Murphy, 2002), P3s measured during highly complex cognitive tasks (Schall, Catts, Karayanidis, & Ward, 1999), and P3s elicited by targets presented at highly predictable intervals (Sandman & Patterson, 2000). This evidence suggests that stimuli with the greatest motivational significance (i.e., those that are infrequent and unpredictable) elicit P3s that are the most stable over time.

Response Preparation

Lateralized Readiness Potential (LRP)

When participants use one hand to make a behavioral response, a negative potential can be observed from electrodes placed over the motor cortex (central scalp, a few centimeters from midline) contralateral to the responding hand. The source of this *LRP* has been localized to primary motor cortex (Eimer, 1998; Miller & Hackley, 1992), and its onset begins before the response is emitted. Moreover, if participants have information concerning which response (left or right) will be required for an upcoming stimulus, the LRP can be observed even before stimulus onset (e.g., Kutas & Donchin, 1980). These properties suggest that LRP onset reflects the time at which response preparation is initiated in the brain (see Smulders & Miller, 2012). Thus, when combined with simultaneous measures of stimulus evaluation that can be dissociated from response-related processes, such as P3 latency, the LRP can provide millisecond-level resolution of the neural basis of stimulus-response associations.

These properties of the LRP make it very useful for understanding two phenomena that are of particular interest to experimental social psychologists. First, the emergence of the LRP can establish the point at which response preparation can begin. In this way, the LRP has been used to demonstrate that partial response activation can occur before analysis of a stimulus is complete (see Coles, Gratton, & Donchin, 1988; Miller & Hackley, 1992), contrary to discrete-stage models of processing (e.g., Sanders, 1980; Sternberg, 1969), which hold that contingent stages operate in strict temporal succession, such that each process must finish before the next can begin. The LRP also has been applied to understand the mental operations responsible for affective priming effects. For example, Bartholow, Riordan, Saults, and Lust (2009) recorded EEG while participants performed an evaluative priming task (Fazio et al., 1986) and found evidence that responses were activated by prime words, prior to target word onset (see also Eder, Leuthold, Rothermund, & Schweinberger, 2012). Moreover, the probability of congruent trials strongly affected response activation as indicated by the LRP: when targets were highly likely to be prime-congruent, preparation of a congruent response was evident prior to target onset; when targets were highly likely to be prime-incongruent, preparation of an incongruent response was evident in the LRP during the prime-to-target interval (see Figure 5.4). These findings helped to establish that response preparation and response conflict (when the prepared response conflicts with the one required by a target) are critical components of the well-known affective congruency effect in evaluative priming (also see Klinger, Burton, & Pitts, 2000).

Response Processing

Error-Related Negativity (ERN)

Cognitive control, or the ability to focus attention on relevant information while ignoring the influence of distraction (see Braver, 2012), is important to many aspects of social behavior (e.g., see Amodio, 2011; Bartholow, 2010). One important aspect of effectively implementing cognitive control is the ability to monitor ongoing performance so that adjustments can be made when cognitive control fails. The ERN, a negative-going deflection generated in the dorsal anterior cingulate cortex (dACC; e.g., van Veen & Carter, 2002), occurs simultaneously with the commission of errors and is thought to play a crucial role in this performance-monitoring process (for review, see Weinberg, Riesel, & Hajcak, 2012). Specifically, the ERN reflects the activation of a *salience network* sensitive to conflict (e.g., between actions and intentions, or between currently implemented and optimal strategies; see Botvinick & Cohen, 2014), which is crucial for instigating performance adjustments when control is threatened (Ham, Leff, de Boissezon, Joffe, & Sharp, 2013; Hoffstaedter et al., 2014). Within this context the ERN can be said to index the degree to which errors are distressing, and therefore, salient (e.g., Bartholow, Henry, Lust, Saults, & Wood, 2012; Hajcak & Foti, 2008; Inzlicht, Bartholow, & Hirsh, 2015).

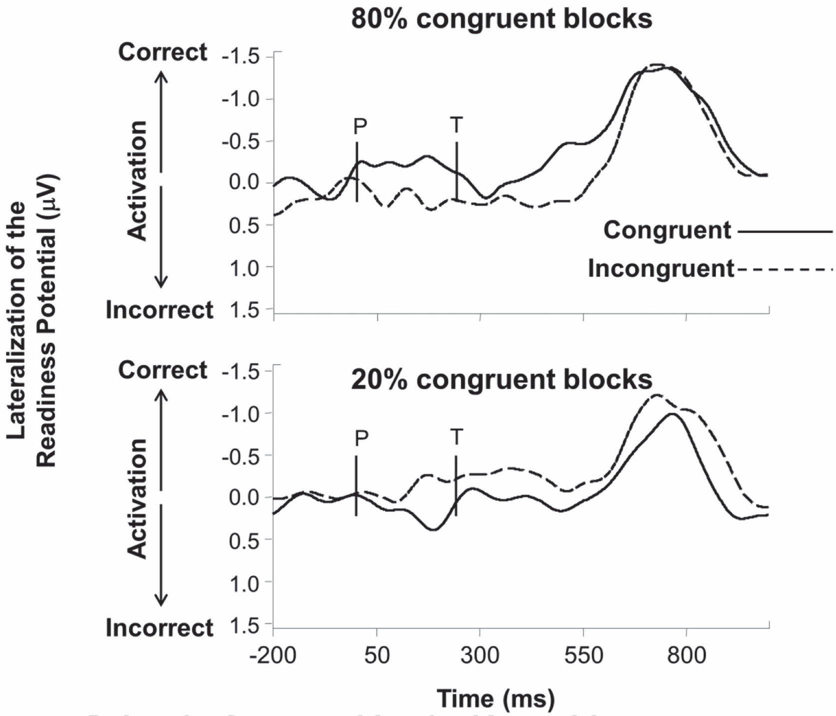


FIGURE 5.4 The Lateralized Readiness Potential (LRP) Measured on Congruent and Incongruent Trials During an Affective Priming Task (Bartholow et al., 2009)

Note: The probability of congruent and incongruent trials was manipulated across blocks, such that participants expected congruent trials in the 80% congruent blocks and expected incongruent trials in the 20% congruent blocks. The amplitude and polarity of the LRP between prime onset (P) and target onset (T) indicates relative response activation elicited by the primes, before the target has appeared. The formula used to derive the LRP is applied with reference to the correct response hand in each condition, such that negative voltage deflections indicate that participants were preparing to activate the hand needed to make the correct response, whereas positive voltage deflections indicate that participants were inadvertently preparing to activate the hand that would produce an incorrect response. These LRPs show that motor cortex was preferentially activated to initiate a valence-congruent response prior to target onset when congruent targets were expected (80% congruent blocks), but was preferentially activated to initiate a valence-incongruent response prior to target onset when incongruent targets were expected (20% congruent blocks).

The ERN has proven useful for understanding implicit racial bias. Errors indicative of unconsciously endorsing stereotypes linking Black men with armed violence elicit larger ERNs than errors that are free from biased implications (see Figure 5.5; e.g., Amodio, Devine, Harmon-Jones, 2004; Bartholow et al., 2012). This is particularly the case for individuals who are high in internal motivation to be unbiased (Amodio, Devine, & Harmon-Jones, 2008), suggesting that racially

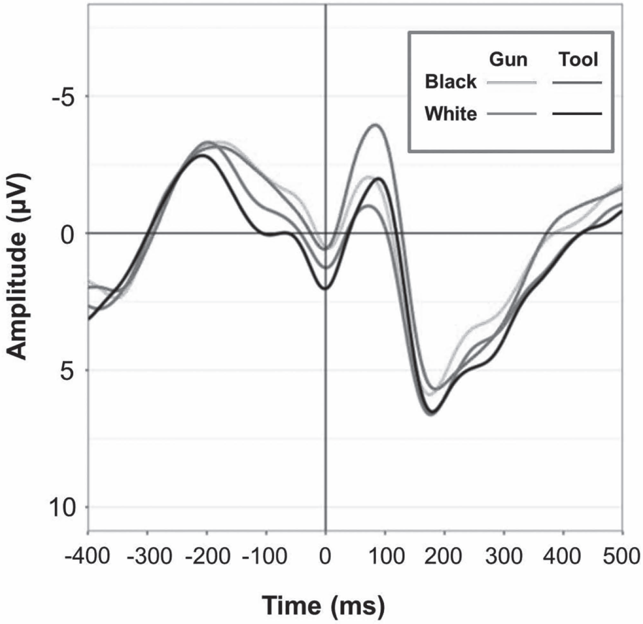


FIGURE 5.5 Response-locked ERPs Recorded on Incorrect Responses During the Weapons Identification Task (WIT; Payne, 2001)

Note: The Weapons Identification Task is a fast-paced, choice RT task where a face (Black or White race) precedes an object that participants must categorize as either a tool or a gun via button press. The ERN is the large, negative-going deflection emerging just after the button press (Time = 0 ms), and is larger when participants accidentally classify a tool as a gun following a Black face.

biased errors are particularly salient to them. Moreover, the larger the ERNs elicited on these bias-related trials, the more control of bias an individual demonstrates overall, consistent with the ERN's role in performance monitoring (see Yeung, Botvinick, & Cohen, 2004).

Considerable effort has been made to demonstrate the psychometric properties of the ERN. Overall, the internal reliability of the ERN can be variable across different tasks and age groups (*r*s = .35–.88, ICCs = .64–.76; Cassidy et al., 2012; Foti, Kotov, & Hajcak, 2013; Meyer, Bress, & Proudfit, 2014; Olvet & Hajcak, 2009a; Riesel, Weinberg, Endrass, Meyer, & Hajcak, 2013). Several researchers have examined internal agreement of the ERN as a function of the number of error trials. The recommended number of trials required to obtain adequate internal agreement (often estimated using Cronbach's alpha > .70) varies widely, from as few as 5–6 errors (Foti et al., 2013; Olvet & Hajcak, 2009b; Pontifex et al., 2010) to as many as 30 or more errors (Baldwin, Larson, & Clayson, 2015; Meyer, Riesel, & Proudfit, 2013; Meyer et al., 2014), largely depending on the type of task (see Riesel et al., 2013).

In addition to being responsive to experimentally manipulated stimuli within subjects, the ERN may help to explain inter-individual variability in the control of racial bias (Amodio et al., 2008), liberal-conservative political orientation (Amodio, Jost, Master, & Yee, 2007), high negative affect (Hajcak, McDonald, & Simons, 2004), and worry (Hajcak, McDonald, & Simons, 2003). Additionally, the ERN has been associated with anxiety (for meta-analysis, see Moser, Moran, Schroder, Donnellan, & Yeung, 2013) and obsessive compulsive disorder (e.g., Carrasco et al., 2013; Riesel et al., 2014), leading to the suggestion that the ERN could be considered a psychiatric endophenotype (Olvet & Hajcak, 2008; Proudfit, Inzlicht, & Mennin, 2013).

The ERN has demonstrated sufficient retest reliability within individuals over time (*r*s = .57–.75, ICCs = .54–.74; Cassidy et al., 2012; Meyer et al., 2014; Olvet & Hajcak, 2009a; Weinberg & Hajcak, 2011), although not in all studies (*r*s = .49 and .40 in Larson, Baldwin, Good, & Fair, 2010, and Segalowitz et al., 2010, respectively; ICC = .38 in Segalowitz et al., 2010). The ERN has shown this trait-like stability over time periods as long as two years.

Feedback Processing

RewP

When participants receive external feedback concerning the outcome of a prior choice, an apparently negative-going deflection maximal at fronto-central electrodes can be observed ~250 ms following feedback onset (Miltner, Braun, & Coles, 1997). Initially dubbed the feedback-related negativity (FRN) given its more negative voltage following negative versus positive feedback (e.g., Hajcak, Moser, Holroyd, & Simons, 2006), this component more recently has been rechristened the *reward positivity (RewP)*. Rather than being a negative-going response elicited by negative evaluative feedback, the deflection instead has been shown to represent the absence of a positive-going response when reward-related or positive evaluative information is lacking (Proudfit, 2015). RewP is hypothesized to reflect what is known as the *prediction error*; that is, the degree to which feedback deviates from expectations (e.g., Gehring & Willoughby, 2002; Holroyd & Coles, 2002). When feedback indicates that the result is worse than expected, a more "negative dip" in the positive-going RewP deflection is observed (see Figure 5.6). Relatedly, factors such as valence, magnitude, probability, and type of reinforcement all have been shown to influence RewP amplitude in reinforcement learning paradigms (see Sambrook & Goslin, 2015).

Recent work using the RewP has investigated reward expectancies in the context of social economic decision-making games. One frequently used paradigm is the Ultimatum Game (UG; Güth, Schmittberger, & Schwarze, 1982), which emphasizes judgments of fairness. During this two-player game, one player is given a sum of money to divide between him- or herself and the other player.

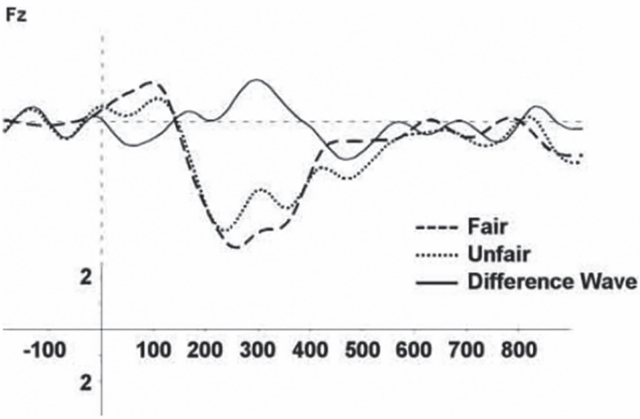


FIGURE 5.6 RewP in Response to Fair and Unfair Offers (Presented at Time 0 on the X-Axis) Made During the Ultimatum Game

Note: Unfair offers (i.e., outcomes that were worse than expected) elicited a negative dip in the positive-going deflection ~300 ms following the offer. Reprinted with permission from Boksem and De Cremer (2010).

Once an offer is made, the other player can either "accept" the offer (in which case, the money is distributed according to the proposal) or "reject" the offer, which results in both players receiving nothing. Previous research using the UG has found that RewP amplitude is more positive when participants receive fair offers compared to unfair offers (e.g., Boksem & De Cremer, 2010). Furthermore, RewP amplitude predicts both the rejection of subsequent offers and the degree of negative affect associated with unfair offers (Hewig et al., 2011).

Additionally, accumulating evidence indicates that RewP amplitude is also sensitive to social expectancies within the context of economic decision-making. For example, Osinsky and colleagues (2014) found that RewP amplitude was affected by both the magnitude of the offer received and the learned reputation of the other players based on offers they had made previously during the game. In another example, Chen and colleagues (2012) tested the effect of facial attractiveness and found a larger difference in RewP amplitude elicited by positive and negative feedback when playing against more attractive partners, consistent with the stereotype that attractive people are more trustworthy and therefore unfair offers elicit a greater prediction error.

Researchers have only recently begun to explore the psychometric properties of RewP amplitude (Bress et al., 2015; Huffmeijer et al., 2014; Levinson, Speed, Infantolino, & Hajcak, 2017; Marco-Pallares, Cucurell, Münte, Strien, & Rodriguez-Fornells, 2011; Segalowitz et al., 2010). Thus far, the RewP has demonstrated good internal reliability in response to monetary losses (*r*s = .71–.90) and gains (*r*s = .79–.89) in both undergraduates (Levinson et al., 2017) and children

(Bress et al., 2015). Acceptable internal reliability can be achieved with as few as 20 feedback trials in younger participants (Marco-Pallares et al., 2011; Levinson et al., 2017), although as many as 50 trials may be required for older participants (Marco-Pallares et al., 2011).

Individual differences reflected in the RewP are linked to trait measures of reward sensitivity (e.g., Bress, Smith, Foti, Klein, & Hajcak, 2012), and could be a biomarker for low positive affect that leads to depression (see Proudfit, 2015). However, investigations of retest reliability of the RewP have shown somewhat mixed results. In children, RewP amplitude in response to monetary losses and gains during a gambling task was found to have acceptable retest reliability for both gains (*r*s = .45–.67, ICC = .62) and losses (*r*s = .64–.71, ICC = .81) over one week to two years (Bress et al., 2015; Levinson et al., 2017). Similar retest reliability has been demonstrated when RewP is elicited during a driving simulation video game (with feedback indicating a crash; Segalowitz et al., 2010). However, when measured in response to feedback indicating response accuracy during a flanker task RewP retest reliability was poor (ICCs = .14–.40; Huffmeijer et al., 2014), possibly because the prediction error signal in tasks like the flanker is generated internally, at the time of the response, and therefore feedback is less informative (Holroyd & Coles, 2002). Some research suggests good retest reliability of RewP across experimentally manipulated temporary states, such as sleep deprivation (*r*s = .52–.84, ICCs = .55–.82; Segalowitz et al., 2010). Additionally, RewP elicited during a simulated driving task had stable retest reliability (*r*s = .53–.77) in adolescent boys across different contexts (alone vs. with friends present; Segalowitz et al., 2010).

Conclusion

ERPs represent an extremely powerful tool with unrivaled temporal specificity for examining sociocognitive processes. The rich, multivariate nature of ERP data provide numerous opportunities to address questions on the neurocognitive and affective mechanisms driving phenomena at the heart of many social and personality theories. Although the ERP technique has been used for many decades in hundreds of cognitive and clinical psychology labs, and although the prominence of ERPs—and other neuroimaging techniques—in social and personality psychology has increased dramatically in recent years, presently only a handful of social-personality labs incorporate ERPs into their research programs. In our view, the future of social cognition depends on the ability to validly and precisely probe implicit mental processes and their connections with experience and behavior, and ERPs offer the clearest path forward in this regard. Or, put another way, "Given that cognitive processes are implemented by the brain, it seems to make sense to explore the possibility that measures of brain activity can provide insights into their nature" (Rugg & Coles, 1995, p. 27).

Notes

1 Numerous other sources have elaborated the considerations needed to increase the quality of inferences in psychophysiological research (e.g., Amodio, 2010; Cacioppo, Tassinary, & Berntson, 2007; Hutzler, 2014). Because of this, we refrain from discussing it further.
2 All split-half reliability estimates of *r* presented here have been adjusted with the Spearman-Brown prophesy formula.
3 Researchers distinguish between two different P3s that occur simultaneously: the more frontally maximal P3a and the posterior P3b (for review, see Polich, 2007).
4 A related late-latency, positive-going deflection, the late positive potential (LPP), has been strongly implicated in affective stimulus processing. For a review, see Hajcak, Weinberg, MacNamara, and Foti (2012).

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