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Event-related potential studies of emotion regulation: A review of recent progress and future directions

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Abstract

Event-related potentials (ERPs) bring many strengths to the study of emotion regulation, including: direct measurement of neural activity, high temporal resolution, affordability and suitability to a wide range of participants. Research using ERPs to study emotion regulation began approximately two decades ago, but has grown exponentially over the last 10 years. Here, we highlight progress in this body of work throughout the past decade, as well as emerging themes, novel approaches and paradigms that will likely shape the field in the coming years. While standardized picture sets are still the most commonly used stimuli in these studies, new types of stimuli (e.g., mental imagery, autobiographical memories) have become increasingly common throughout the past decade, with the potential for improved ecological validity. Cognitive reappraisal is still seen by many as the gold standard of emotion regulation, yet mixed findings suggest that its utility might be better understood by taking into account the type of stimuli and context to which it is applied. Moreover, other emotion regulation techniques, particularly for the upregulation of positive emotion (e.g., savoring), have been relatively unexamined in the ERP literature to-date, as have associations between controlled, lab-based measures of emotion generation and regulation in everyday life (e.g., as assessed using ambulatory techniques). In sum, the past decade has seen progress in a more granular understanding of emotion regulation, with ongoing and future work aimed at increasing understanding of the boundary conditions of emotion regulation; novel techniques and emotion regulation's application to everyday life.

Keywords

Emotion regulation; Event-related potentials (ERPs); Electroencephalography (EEG); Cognitive reappraisal; Late positive potential (LPP)

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1. Introduction

Just over 10 years ago, we (Hajcak et al., 2010) wrote a review paper in which we made the case that ERPs are a useful tool for studying emotion and emotion regulation. Though the majority of emotion regulation work at that time had used fMRI, ERPs provided some unique advantages, including that ERPs directly reflect brain activity, have high temporal resolution, are relatively inexpensive to collect, and may be better tolerated by certain segments of the population (e.g., children, clinical samples). Our review focused on work that had shown it was possible to modulate ERP measures of emotional salience (e.g., the late positive potential, LPP) using a variety of emotion regulation manipulations, including meaning change, task relevance and spatial attention. The findings that we reviewed reflected the state-of-the-field at the time. Now, more than a decade later, having demonstrated that participants can modulate their emotions in the lab using a variety of techniques, and that these effects can be measured using ERPs, the field's focus has shifted to a more nuanced set of questions. In what follows, we review these questions as they have featured in the ERP emotion regulation literature over the past decade.

To elicit emotion in the lab, researchers often use pictures of emotional scenes from standardized databases like the International Affective Picture System (IAPS; Lang et al., 2008). Most experimental emotion regulation work to-date has used these types of pictures. However, the past decade has also seen a proliferation of studies extending emotion regulation to novel stimuli, including unpleasant memories, smoking cues, errors elicited in a speeded response task and cues signaling monetary reward. Another area of interest in the past decade has been to characterize and compare the timing of different emotion regulation techniques, including durability of effects when stimuli are encountered later, without instructions to regulate emotional response. Still other work has recognized that although participants can often regulate their emotions in the lab, this may be more difficult in the "real world". As such, this work has sought to understand the limits and moderators of emotion regulation success. Finally, whereas the first decade of ERP emotion regulation work focused primarily on cognitive reappraisal, which involves changing the meaning of stimuli, work in the past decade has also tested previously unexamined techniques for emotion regulation.

Individual differences work on emotion regulation has also grown exponentially in the past decade. This work has examined the roles of age, gender and psychopathology in ERP studies of emotion regulation. Initial work into cultural differences in emotion regulation has also begun. In what follows, we examine how these factors can affect electrocortical measures of emotion regulation and we discuss the suitability of ERPs to assess emotion regulation in these different samples and populations.

We do not aim to cover all or even most of the studies that have emerged in the past decade, but we do hope that by the end of our review, the reader will have a sense of the ERP emotion regulation literature as it currently stands and where it has journeyed since it was first demonstrated (in the mid 2000s), that ERPs could be used to study emotion regulation. We also hope that this review will serve as a resource for readers seeking an introduction to the field or for those looking for a one-stop-shop answer to a question that has been asked in the field, as well as readers hoping to gain insight into the next generation of research questions in ERP emotion regulation work. To begin with, we briefly review ERP components most frequently used in emotion regulation research, as well as key findings in the ERP literature as it stood in 2010, before focusing on research since that time.

1.1. ERP components used to study emotion regulation

There are a number of ERP components that are larger for emotional compared to neutral stimuli. Several of these – particularly components that emerge later on during stimulus presentation (e.g., approximately 150 ms or more after stimulus onset) – have been used to measure the effects of emotion regulation. Earlier ERP components are not frequently the measure of choice in studies of emotion regulation because emotion regulation typically takes some time to enact and therefore tends to affect later reactivity to stimuli more than early sensory components. Below, we briefly introduce ERP components that have featured most prominently in emotion regulation work to-date.

1.1.1. N170—The N170 (Joyce and Rossion, 2005) is maximal between 130 and 200 ms at posterior-lateral sites, and is often largest in the right hemisphere (Bentin et al., 1996). The N170 is thought to reflect in part the structural encoding of faces, and is increased for facial compared to non-facial stimuli. Nonetheless, the N170 can also be elicited by non-face stimuli, with larger responses observed as expertise in an object category grows (Rossion and Jacques, 2011). Larger N170s are also observed for emotional compared to neutral faces, with angry, happy and fearful faces eliciting the largest amplitudes (for a meta-analysis, see Hinojosa et al., 2015). Fig. 1 depicts grand-averaged waveforms and scalp distributions of the voltage difference for the N170 elicited by neutral male faces that had been paired with shock compared to faces that had never been paired with shock (see also Bruchmann et al., 2021).

1.1.2. EPN—The early posterior negativity (EPN) is a negative-going ERP component that is maximal at occipital sites around 150–300 ms post-stimulus onset (Hajcak et al., 2012; Schupp et al., 2006). The EPN is larger for emotional compared to neutral stimuli and appears to covary with stimulus arousal level. Some evidence suggests that the EPN is especially sensitive to positive stimuli (De Cesarei and Codispoti, 2006; Flaisch et al., 2008; Frank and Sabatinelli, 2019), and potentially to discrimination of certain features often depicted in positive stimulus sets (e.g., unclothed body parts; Farkas et al., 2020). Fig. 2 depicts grand-averaged waveforms and scalp distributions of the voltage difference for the EPN elicited by positive compared to neutral pictures.

1.1.3. P300—The P300 is a positive-going, centrally or parietally maximal ERP component that is enhanced by stimulus significance, both of a non-emotional nature (e.g., target status or infrequency in an oddball paradigm; Hajcak and Foti, 2020) and of an emotional nature (e.g., emotional compared to neutral stimuli; Schupp et al., 2007; Weinberg et al., 2012). The P300 resembles the early portion of the late positive potential (LPP; described below) in terms of timing, scalp distribution and sensitivity to stimulus significance. Therefore, one possibility is that the P300 and the LPP reflect common motivational responses (Bradley, 2009; see also Nieuwenhuis et al., 2005), and that the

LPP is in fact a sustained version of the P300 (Hajcak and Foti, 2020). In affective picture-viewing tasks, the P300 is maximal approximately 300–600 ms post-stimulus onset, and tends to be maximal at centroparietal sites. Fig. 3 depicts grand-averaged waveforms and scalp distributions of the voltage difference for the P300 elicited by negative minus neutral pictures and positive minus neutral pictures.

1.1.4. LPP—The late positive potential (LPP) is a positive-going deflection in the ERP waveform that begins approximately 400 ms after stimulus onset. It is larger for emotional compared to neutral stimuli, and appears to be sensitive primarily to arousal level rather than valence (Cuthbert et al., 2000; Hajcak and Foti, 2020). Though the early LPP resembles the P300 in terms of timing and scalp distribution, it is distinguished in part by its sustained time course, persisting throughout stimulus presentation duration (e.g., 6 s or longer; Cuthbert et al., 2000) and even after stimulus offset (Hajcak et al., 2010). Nonetheless, like the P300, the LPP is also sensitive to non-emotional manipulations of stimulus significance (e.g., Weinberg et al., 2012) and indeed, the early LPP may in fact be synonymous with the P300 (Hajcak and Foti, 2020). However, because of its sustained duration, the LPP is particularly well-suited to studies of emotion regulation, and has featured most prominently in this work. The LPP is comprised of a series of overlapping positivities that are initially maximal at centroparietal sites, but may become more frontal over time (Foti et al., 2009). Fig. 3 depicts grand-averaged waveforms and scalp distributions of the voltage difference for the LPP elicited by negative minus neutral pictures and positive minus neutral pictures.

1.2. The first ERP studies of emotion regulation

Early emotion regulation work was substantially influenced by of Gross' process model (Gross, 1998b), which emphasized that emotion regulation can take place at multiple points along the temporal unfolding of emotional response. According to this model, antecedent-focused emotion regulation techniques, like cognitive reappraisal, which involves changing the meaning of stimuli, take place relatively early on during this process. By contrast, response-focused techniques, like expressive suppression, which involves inhibiting outward expression of emotion once it is generated, take place later on during the unfolding of emotion. Antecedent techniques are expected to have different (usually, preferable) consequences than response-focused techniques (Gross, 1998a). As such, this model identified an important dimension of emotion generation and regulation (time), outlined different types of emotion regulation techniques as they related to this dimension, and elevated certain ones, like reappraisal. In short, the process model helped organize and created a framework for the emotion regulation work that has followed since.

By the early 2000s, initial evidence had shown that emotion regulation could increase and decrease startle eyeblink during negative films (Gross and Levenson, 1993, 1997) and picture presentation (Jackson et al., 2000), as well as amygdala activity during picture viewing (Ochsner et al., 2004; Phan et al., 2005). Following this, the first work using ERPs to investigate emotion regulation showed that reappraisal could effectively reduce the LPP and subjective ratings of unpleasantness and arousal elicited by negative pictures (Hajcak and Nieuwenhuis, 2006; Moser et al., 2006). Soon after came studies showing that children could also use reappraisal to modulate the LPP (Dennis and Hajcak, 2009; but see DeCicco et al., 2012). To better understand the mechanisms underlying reappraisal, subsequent work provided descriptions of pictures, rather than requiring participants to generate reappraisals themselves, and thereby confirmed that meaning change alone was sufficient to modulate the LPP (Foti and Hajcak, 2008; MacNamara et al., 2009). Capitalizing on the high temporal resolution of ERPs, other studies showed that participants could dynamically modulate the LPP when instructions to reappraise were given partway through picture presentation (Parvaz et al., 2012). Moreover, this work showed that reappraisal reduced EEG frontal alpha, suggesting greater prefrontal activation (Parvaz et al., 2012), in line with findings from the fMRI literature showing involvement of the prefrontal cortex in reappraisal (Buhle et al., 2013; Morawetz et al., 2020; Ochsner et al., 2004). Together, this body of work documented the effects of reappraisal and validated purported mechanisms.

However, it quickly became clear that other mechanisms, such as visual attention, might also play a prominent role in the observed effects of emotion regulation on ERPs (Van Reekum et al., 2007). In line with this notion, some studies showed that participants could reduce the LPP by directing their gaze to less arousing picture regions (Dunning and Hajcak, 2009; Hajcak et al., 2009). Nonetheless, subsequent work showed that reappraisal explained additional variance in the down-regulation of emotional response, above and beyond effects of visual attention, and that individuals who were more successful at regulating their emotions might actually attend *more* to arousing picture regions (Bebko et al., 2011, 2014). Moreover, engagement of prefrontal brain regions via a non-affective task (i.e., working memory load; Smith et al., 1998) was shown to reduce the LPP to negative and neutral pictures (MacNamara et al., 2011a) independent of eye gaze (MacNamara et al., 2012). As such, reappraisal ultimately prevailed as a robust and beneficial emotion regulation technique that did not seem entirely dependent on visual attention. Indeed, throughout the 2000s cognitive reappraisal emerged as the “gold-standard” of emotion regulation because it was shown to be associated with a number of benefits, including improved social, cognitive, affective and physiological benefits, when compared to other emotion regulation techniques (Gross, 1998a, 2002).

2. ERP emotion regulation research in the past decade

Early work on emotion regulation aimed primarily to show cognitive reappraisal could be successfully enacted in the lab, and that these effects could be measured using ERPs, with subsequent studies beginning to interrogate the mechanisms behind reappraisal. Since this time, however, research has sought to ask more nuanced questions. These inquiries have included examination of within-subject effects, such as: emotion regulation using different types of stimuli (i.e., beyond affective pictures); the timing of the effect of various emotion regulation techniques (a list of some key emotion regulation techniques is presented in Table 1); the influence of anticipatory information, stress and cognitive load on emotion regulation, as well as the ways in which stimulus arousal level may modulate emotion regulation success. Additionally, research has begun to accrue showing that reappraisal may not *always* be the best technique for a given stimulus or situation at modulating emotion. Therefore, researchers have also started to investigate the utility of emotion regulation techniques that have not previously received much attention in the literature. Research on four of these techniques - social emotion regulation, implementation intentions, mindfulness and savoring – is reviewed below. In addition to broadening the scope of emotion regulation work beyond the types of stimuli and techniques that have been used previously, research in the past decade has also begun to investigate individual differences in emotion regulation, including examination of the effects of age, gender and psychopathology, with initial inquiries into cultural differences in emotion regulation.

2.1. Within-subject effects

2.1.1. Extension to different types of stimuli—Initial emotion regulation work in both the ERP and fMRI literatures used standardized emotional scenes with generic affective content (e.g., Lang et al., 2008). While these remain the most frequently used stimuli in emotion regulation paradigms, work over the past decade has sought to determine the boundary conditions of emotion regulation, including whether it can be used to modulate emotional responses elicited by specific picture content, and by non-pictorial stimuli.

Reappraisal has been shown to be effective at reducing face-elicited ERPs, including at earlier stages than typically observed using more complex and varied stimuli (e.g., emotional scenes). Among the ERP components shown to be sensitive to reappraisal of faces are the EPN and the LPP, with mixed results observed for the N170 (Blechert et al., 2012; Wieser et al., 2014; Zhu et al., 2019). When shown idiographic pictures of their romantic ex-partners, participants who were upset about a recent break-up were able to reduce the LPP via both reappraisal and distraction (Langeslag and Sanchez, 2018), which suggests that these emotion regulation techniques may be useful in regulating reactivity to stimuli encountered in everyday life.

Though most work has focused on the *down-regulation* of response to *negative* stimuli, some work has examined the down-regulation of response to appetitive stimuli. For example, distraction and distancing have been shown to reduce the LPP to smoking cues among smokers (Littel and Franken, 2011). By contrast, other types of appetitive stimuli may be more resistant to the effects of emotion regulation. After an overnight fast, women could increase but not reduce the LPP to pictures of high caloric food (Sarlo et al., 2013). Similarly, thinking about the short- versus long-term consequences of consumption while viewing pictures of high- compared to low-caloric food *increased* the LPP at various time points during picture presentation (Meule et al., 2013). Therefore, some types of appetitive stimuli may be resistant to down-regulation.

While emotional pictures provide a convenient and effective means of eliciting emotion, their similarity to stimuli encountered in real life is questionable. As an alternative, imagined emotional scenarios or emotional memories can elicit negative emotion and may have superior ecological validity compared to standardized pictures, because they may more closely resemble emotional experiences in everyday life. Using a novel autobiographical emotion regulation task, Speed et al. (2017) asked participants to identify neutral and emotionally-charged memories from their own lives, prior to generating keywords associated with each memory. Next, participants were reminded of their autobiographical memory, prior to viewing the associated keywords. Results showed that participants were able to reduce the LPP elicited by keywords using reappraisal, suggesting that reappraisal may be an effective means of regulating response to everyday emotional thoughts and memories (see also Baker et al., 2017).

In addition to stimuli that depict emotional content or events, stimuli that represent or pose a threat can also elicit emotion. For example, errors may represent internal threats, because they can be associated with adverse outcomes. Error-monitoring can be measured using the error-related negativity (ERN), a negative-going ERP component that peaks frontocentrally approximately 50–100 ms following response. The magnitude of the ERN varies across individuals (Imburgio et al., 2020) and tends to be larger in certain segments of the population, such as in individuals who are more anxious (Moser et al., 2013; Pasion and Barbosa, 2019). Hobson et al. (2014) found that participants could reduce the magnitude of the ERN by using reappraisal to engage less emotionally with errors in a Go-No-Go task (see also Levsen and Bartholow, 2018). This work fits with a broader literature that has sought to characterize the situational factors that may modulate the ERN (Klawohn et al., 2020; Meyer and Gawlowska, 2017; Nelson et al., 2017; Riesel et al., 2012, 2019), and – given heightened ERNs in anxiety – could have implications for the understanding and treatment of anxiety.

Monetary reward is another means of eliciting emotion. One ERP component, the reward positivity (RewP), is a positive-going, frontocentrally maximal component that peaks between 200 and 300 ms following feedback indicating a win (versus loss). The RewP has been found to be smaller in depressed individuals (Proudfit, 2015) and has been shown to predict the development of depression over time, above and beyond other predictors (Bless et al., 2013, 2015; Klawohn et al., 2021a; Kujawa et al., 2019b). Aberrant reward processing is also implicated in other forms of psychopathology, such as addiction (Hyman et al., 2006; Joyner et al., 2019; Luijten et al., 2017). Therefore, as for the ERN, insight into whether emotion regulation can modulate reward processing could not only increase understanding of the boundary conditions of emotion regulation, but might also have clinical utility. In one study, Yang et al. found that down-regulation via reappraisal reduced the RewP during a monetary reward task (Yang et al., 2013). In addition, savoring has been shown to increase the RewP (Irvin et al., 2020), and in yet another study, participants were able to willfully increase the LPP to reward-predictive cues (Langeslag and van Strien, 2013). Therefore, evidence suggests the RewP and LPP in rewarding contexts are sensitive to emotional regulatory strategies.

2.1.2. Timing effects—Part of knowing whether an emotion regulation technique is effective might involve understanding its temporal characteristics, such as how quickly it works and how long its effects last. Faster-acting techniques would seem to be preferable, though this benefit may come with some trade-offs. How emotion regulation affects response to stimuli that are later encountered outside of the initial application of emotion regulation is also central to its utility. For example, if an individual learns to use reappraisal to reduce their response to a negative event (e.g., being cut off in traffic on the way to work), it would be optimal if this meaning change (e.g., the driver was probably in a rush; they were not trying to cause a problem for me) would carry over to affect subsequent encounters with the same stimulus (e.g., being cut off in traffic on the way home from work), without the need to take the time and effort to generate a novel interpretation each time the same stimulus was encountered.

Over the past decade, these and other questions pertaining to the temporal characteristics of emotion regulation have been examined. Given their high temporal resolution, ERPs are particularly well-suited to understanding how quickly an emotion regulation technique takes effect. For example, work by Langeslag and van Strien (2018) showed that reappraisal of pictures of snakes and spiders reduced the LPP but not the EPN, suggesting modulation of motivated attention/elaborated stimulus processing, but not early selective attention. Moreover, examination of the temporal course of emotion regulation, as revealed via ERPs, may help characterize the mechanisms underlying emotion regulation's effects. For instance, increased early frontal LPPs in reappraisal, followed by smaller parietally maximal LPPs, are suggestive of an initial increase in frontal cognitive control, followed by a subsequent reduction of parietal arousal-related activity (Moser et al., 2014).

Still other work has sought to understand the comparative timing of various emotion regulation techniques. Across this body of work, distraction and suppression have been found to reduce emotional processing faster than reappraisal (Paul et al., 2013; Thiruchselvam et al., 2011; Yuan et al., 2015). However, distraction leads to larger LPPs when participants view the same pictures later, without instructions to distract (Jiang et al., 2020; Paul et al., 2016b; Thiruchselvam et al., 2011), whereas reappraisal appears to persist over time, leading to smaller LPPs 30 min later during a passive viewing task (MacNamara et al., 2011b). Nonetheless, there may be differences in the durability of reappraisal, depending on the way in which it is implemented. Detached/self-focused reappraisal, in which participants try to view stimuli from a removed perspective (e.g., bloody pictures are not real) but not positive reappraisal, in which the negative meaning of pictures is interpreted more positively (e.g., injuries are not fatal) was found to leave a lasting effect on the LPP at subsequent exposure to pictures (Qi et al., 2017). In addition, reappraisal-based implementation intention (this technique is described in Section 2.6.2) was found to have a more widespread and durable effect than controlled/standard reappraisal at re-exposure (Chen et al., 2020), suggesting that more general attempts at emotion regulation might lead to longer lasting changes in the processing of emotional stimuli.

2.1.3. Anticipatory information—One line of work over the past decade has sought to determine the conditions that may facilitate or interfere with emotion regulation. For example, are people better able to regulate their emotions when they are forewarned about an upcoming emotional event? In one study, participants received information about picture content prior to using distraction or reappraisal to reduce their emotional response. Results showed that anticipatory information interfered with distraction (which resulted in an enhanced LPP), and failed to facilitate reappraisal (Shafir and Sheppes, 2018). Interestingly, participants seem to understand this, and when given the choice, chose not to receive anticipatory information about upcoming stimuli. Nonetheless, anticipatory information has proven beneficial for emotion regulation success in other contexts. For example, when participants were informed that upcoming social feedback about themselves would be negative, they were better able to down-regulate the LPP elicited by this feedback; however, in this same sample, anticipatory information tended to interfere with the regulation of response to positive feedback (Liu et al., 2016). In addition, advance knowledge that emotion must be up- or down-regulated before viewing an affective picture has been shown to facilitate the down-regulation of emotion using reappraisal, when compared to instructions to down-regulate that were delivered partway through picture presentation (Yan et al., 2018). In sum, while the evidence is mixed regarding whether knowledge of an upcoming stimulus facilitates emotion regulation, advance knowledge that emotion regulation is upcoming may at times be helpful in achieving this goal.

2.1.4. Cognitive load and stress—Other work has sought to examine the influence of cognitive load and stress on reappraisal – factors that may impede emotion regulation success in everyday life. Work by Gan et al. (2017) found that high working memory load impaired reappraisal, as measured using the LPP. This suggests that reappraisal may be difficult to enact in the real-world, where cognitive demands are often higher than in the controlled lab environment. In addition, an unpredictable or stressful environment might compromise emotion regulation success. To test this idea in one recent study, we asked participants to use reappraisal to reduce their response to negative stimuli, while listening to a series of unpredictable, anxiety-provoking auditory tones or while they sat in silence in the lab. Results showed that starting in an unpredictable tone block increased the LPP to negative pictures throughout the task, and that starting in an unpredictable tone block or performing reappraisal while listening to unpredictable tones impaired reappraisal of negative pictures (Imburgio and MacNamara, 2019). Therefore, reappraisal might be best suited to individuals who learn to reappraise in a calm environment, and who subsequently perform reappraisal in a calm and predictable setting.

In the lab, participants are typically instructed in the use of a particular emotion regulation strategy. However, in everyday life, individuals are free to choose between several different emotion regulation techniques and receive no explicit instruction. To test the effectiveness of emotion regulation under more ecologically valid circumstances, Baur et al. (2015) did not train participants in any particular emotion regulation technique, but simply provided them with generic instructions to decrease their emotional response to stimuli using whatever technique they wished. Results showed that emotion regulation reduced subjective picture ratings and electromyographic (EMG) facial responses; however, in this study, emotion regulation *increased* the LPP. Given that the LPP reflects attentional allocation and sustained engagement, increased LPPs in this study might indicate increased attention associated with uninstructed emotion regulation, which may be more cognitively demanding than instructed emotion regulation.

2.1.5. Stimulus arousal level—Along these lines, down-regulation of emotional response via reappraisal, which is cognitively demanding, may at times increase the LPP, particularly when additional cognitive effort is required because pictures are highly arousing (Langeslag and Surti, 2017). Similarly, reappraisal may be ineffective at reducing the LPP for highly negative pictures of stigmatized (e.g., homeless people; drug addicts) but not non-stigmatized (e.g., man holding a gun, injured people) individuals (Krendl et al., 2017). Still other work has compared reappraisal to other emotion regulation techniques, finding, for example, that reappraisal is less effective than distraction when stimuli are highly arousing

(Shafir et al., 2015). When given the option to use distraction or reappraisal, participants have been shown to choose distraction more often for highly arousing pictures (Dorman Ilan et al., 2020), and pictures that elicited larger LPPs during a pre-implementation period were associated with preference for distraction over reappraisal (Shafir et al., 2016). Therefore, reappraisal's effectiveness may depend on stimulus arousal level, with distraction both better suited to and preferred when stimuli are highly arousing.

The effectiveness of expressive suppression (in which individuals inhibit outward expression of emotion) for high versus low arousing pictures has also been compared. Li et al. (2020) found that both distraction and suppression successfully reduced the early and late LPP elicited by high-intensity and low-intensity positive pictures, as well as the *early* LPP elicited by low-intensity pictures. However, only suppression reduced the *late* LPP elicited by low-intensity pictures. Therefore, suppression may be more robust than distraction to manipulations of stimulus intensity over time/picture duration.

2.1.6. Other emotion regulation techniques beyond reappraisal—The studies reviewed above have focus primarily on reappraisal, in keeping with the field's predominant emphasis on this technique (McRae and Gross, 2020). Yet while it is true that numerous studies have found evidence of the effectiveness of reappraisal in reducing ERP measures of emotional salience such as the LPP (e.g., Krompinger et al., 2008; MacNamara et al., 2009; Moser et al., 2006; Parvaz et al., 2012; Thiruchselvam et al., 2011), what is not typically noted is that numerous studies have also *failed* to find evidence that reappraisal down-regulates the electrocortical processing of emotional stimuli (Table 2). As noted above, research has also revealed that reappraisal may be less effective when participants are under situational demands such as stress or cognitive load that may divert needed cognitive resources or when stimuli are highly arousing. Therefore, while reappraisal has many benefits, it is challenging to implement, and does not always reduce the electrocortical processing of emotional stimuli. As such, an important development over the past decade has been the increasing focus on other types of emotion regulation. Below, we review work on four less-well-established techniques that have begun to be examined in the past decade: social emotion regulation, implementation intentions, mindfulness and savoring.

2.1.6.1. Social emotion regulation.: Other people's perspectives can convey important information about the emotional significance of a stimulus. Moreover, thinking about an emotional scenario from the perspective of another person can be an effective form of emotion regulation because it may provide distance from the emotional stimulus (e.g., thinking about bloody pictures from the perspective of a doctor). Though distancing is often presented to participants as one possible form of reappraisal (i.e., self-focused reappraisal; Willroth and Hilimire, 2016), distancing is not synonymous with social emotion regulation because with distancing, the goal is exclusively to *reduce* emotional response, and because distancing can be enacted in non-social ways, such as thinking, "This does not involve me" or "This does not influence me" (p. 172, Goldin et al., 2009). Among studies that have focused more specifically on *social* emotion regulation, it is apparent that the manner in which social emotion regulation is enacted determines whether the end result is increased or decreased emotional response. For example, Lei et al. (2019) showed that taking a familiar other's perspective, whether optimistic or pessimistic, reduced the P300 and LPP elicited by positive and negative pictures. Therefore, simply considering pictures from a more external, less self-focused perspective attenuated picture processing. Nonetheless, believing that other people found a picture to be emotionally arousing has been found to increase the LPP to positive and negative pictures (Willroth et al., 2017; see also Paul et al., 2016a; Xu et al., 2016; Klein et al., 2015). Therefore, whether imagining a scenario from the perspective of another individual or using social information to inform assessment of stimulus meaning, social emotion regulation can provide an effective means of modulating ERP measures of emotional processing.

2.1.6.2. Implementation intentions.: Because reappraisal is cognitively demanding, it might be challenging for individuals to quickly generate novel interpretations of stimuli in their everyday lives. More automated forms of emotion regulation could therefore permit individuals greater flexibility and a higher chance of success at regulating their emotions, particularly in stressful or cognitively demanding contexts. Implementation intention is a technique borrowed from the self-regulation literature, in which individuals set an emotion regulation implementation that they intend to enact if they encounter a particular type of stimulus (e.g., "If I see a gory picture, I will ignore it!"). The first paper to examine implementation intention for the purposes of emotion regulation included ERP data and was published just over a decade ago (Gallo et al., 2009). This paper showed that implementation intentions successfully reduced an early visual ERP elicited by pictures of spiders, the PI (but not the LPP). Over the past decade, several other papers have examined this technique. For example, Ma et al. (2019) found that compared to situation-focused implementation intentions (e.g., "If I see blood, I will think blood represents vitality and health", p. 570), self-focused implementation intentions (e.g., "If I see blood, I will take the perspective of a physician", p. 570) were more effective at reducing subjective negative emotion and the LPP elicited by disgusting pictures. Moreover, self-focused implementation intentions elicited smaller frontal LPP amplitudes, suggesting that they may have been less cognitively demanding than situation-focused implementation intentions. These results stand in contrast to results in the broader reappraisal literature, which has suggested that situation-focused reappraisals may be more effective than self-focused (e.g., Willroth and Hilimire, 2016). In sum, this work suggests that automated emotion regulation techniques such as implementation intention might be effective, and – if they consume fewer cognitive resources than conscious emotion regulation techniques such as reappraisal - could be particularly useful when cognitive resources are compromised due to situational demands or individual differences.

2.1.6.3. Mindfulness.: The down-regulation of negative emotion might also be possible through acceptance or non-judgmental awareness of emotion, rather than willful attempts to control or reduce it. Mindfulness is a type of meditation in which individuals focus on the present moment, without interpretation or judgment. It has been incorporated into various therapies for emotional disorders such as anxiety or depression, because it is thought to reduce psychological stress and negative emotion by reducing excessive orientation to the future or past. Recent work has examined mindfulness as an emotion regulation technique in the lab. Results have been mixed, with some work finding that mindfulness has no effect

(Eddy et al., 2015; Lin et al., 2016), that it increases the LPP (Egan et al., 2018) or that it decreases early ERPs, the P1 and N2, as well as the LPP (W. Zhang et al., 2019). These results may reflect in part differences in the types of instructions given to participants. For example, Egan et al. (2018) asked participants to focus their attention on pictures, whereas Zhang et al. (2019) asked participants to focus their attention on their breath (a meditative mindfulness practice), which might have reduced attention and ERPs to emotional pictures. Exposure therapy, in which participants direct their attention to fear-elicited stimuli, is effective at reducing fear and anxiety following repeated presentations of a the stimulus, and has also been shown to increase (not decrease) the LPP, at least early on during treatment (Leutgeb et al., 2009). Therefore, it also seems possible that mindfulness might initially increase the processing of emotional stimuli, but might ultimately reduce the emotional salience of pictures at subsequent encounter/over time. Along these lines, individuals higher in *trait* mindfulness showed reduced potentiation of the LPP to negative versus neutral stimuli (Eddy et al., 2015).

2.1.6.4. Savoring.: Savoring is an emotion regulation technique that, like mindfulness, involves present-moment focus and experiential absorption. However, mindfulness differs from savoring because mindfulness aims at the acceptance of all present-moment experiences and thoughts, whereas savoring emphasizes experiential absorption and amplification of pleasurable experiences, in particular. Savoring can be accomplished by sensory-perceptual sharpening/luxuriating, which can increase physical and psychological pleasure; marveling, which elicits feelings of awe; and gratitude—that is, giving thanks for what is good (Jose et al., 2012). Recently, we showed that savoring increases subjective ratings and the LPP elicited by positive pictures, and moreover, that effects persist across time to affect the same pictures when shown 30 min later in a passive picture viewing task (i.e., without instructions to savor; Wilson and MacNamara, 2020). In a follow-up study, we found that the effect of savoring may persist for as long as 24 h, at least for positive pictures (Fig. 4; $N = 68$ female participants). This work adds to a relatively small body of work that has examined the up-regulation of positive stimuli using ERPs. In prior work that permitted participants to use any technique they wanted to increase their emotional response to positive pictures, the LPP and picture ratings were increased (Baur et al., 2015; Bernat et al., 2011). However, when participants were instructed to use reappraisal to increase their response to positive pictures, the LPP was not increased (Krompinger et al., 2008). Therefore, different emotion regulation strategies, such as savoring, might provide a useful alternative to techniques that have emerged from the negative emotion regulation literature, particularly when the goal is to increase rather than decrease emotional responding. Moreover, savoring has also been shown to increase the RewP to monetary gains during a gambling task (Irvin et al., 2020), suggesting that its effects generalize beyond affective pictures, and that it may have particular relevance to disorders like depression that are characterized by deficits in reward responsivity.

2.1.7. Summary—

In sum, ERP studies of emotion regulation work in the past decade have gone beyond prior work by broadening the types of stimuli and emotion regulation techniques examined, and by assessing the factors that might qualify or modulate emotion regulation success. This work has shown that reappraisal can modulate electrocortical response to a wide variety of stimuli, but that it may be less effective for highly arousing stimuli, particularly when compared to other emotion regulation techniques, such as distraction. Additionally, our take on the literature is that reappraisal is not always as effective as typically assumed. Indeed, the literature is riddled with studies that have failed to find an effect of reappraisal on ERPs (Table 2). Therefore, it seems especially important that during the past decade, research has begun to examine a variety of previously unexamined emotion regulation techniques. This work has found that several of these techniques are quite effective at modulating electrocortical response. Going forward, it will be up to future studies to continue to work out which emotion regulation techniques are best suited to certain types of scenarios or to certain individuals. Along these lines, recent work has suggested that rather than reliance on one particular technique, *flexibility* in employing different emotion regulation techniques depending on the situation or individual may be the most important variable in effective emotion regulation (Bonanno and Burton, 2013).

2.2. Individual differences

2.2.1. Age—As it became clear throughout the 2000s that adults could successfully modulate ERP measures of emotional salience after a few minutes of training in emotion regulation, the first studies emerged showing that children could also use reappraisal to modulate ERPs (Dennis and Hajcak, 2009; but see DeCicco et al., 2012). Since this time, the developmental literature on ERP studies of emotion regulation has grown tremendously.

One question that has arisen in the field is whether the LPP can be used to track the development of emotion regulation in children and adolescents. Generally, the LPP appears to track the effects of emotion regulation in children in a manner similar to what has been shown in adults. Nonetheless, differences have been observed. For example, reappraisal appears to affect the LPP more slowly/later on during stimulus presentation in children (Dennis and Hajcak, 2009). Moreover, compared to older girls and boys of all ages, very young girls (e.g., ages 5–6 years) have been shown to exhibit larger LPPs during the down-regulation (versus passive viewing) of negative stimuli. This suggests either that girls of this age had less developed emotion regulation abilities; that they were more distressed by the negative images and/or that they might have been less engaged in the task in general (Dennis and Hajcak, 2009). Similarly, in another study, 5- to 7-year-old children were not able to reappraise their response to negative stimuli, as measured by the LPP (DeCicco et al., 2012), but an effect of reappraisal was observed in the same individuals at a follow-up when they were 8–9 years old (DeCicco et al., 2014). Therefore, regulatory effects on the LPP might provide a viable marker of developmental maturation in emotion regulation, which seems to become measurable at around school age. It is important to note, however, that failure to observe an effect of reappraisal in younger children might also be due to the specific nature of reappraisal instructions. For example, these instructions are often relatively complex and execution of reappraisal places a high demand on working memory. As such, in a study that focused on providing simplified, short interpretations to participants, children as young as 4 years old were able to regulate their response to emotional pictures, as measured using the LPP (Hua et al., 2015). Therefore, further studies and the use of child-friendly paradigms are of high importance for increased understanding of the development of emotion regulation in early childhood.

Going beyond cross-sectional approaches, some work has investigated the utility of the LPP for predicting future capacity for emotion regulation. For example, Babkirk et al. (2014) showed that reappraisal-related reductions in the LPP predicted emotion regulation strategy use in children, both cross-sectionally (i.e., at ages 5–7 and 7–9, respectively) and prospectively over the span of two years. Similarly, greater reappraisal-related reduction of the LPP in 5- to 9-year-old children was found to predict better observed emotion regulation ability (e.g., engaging in an alternate activity) during a subsequent, frustrating task (Myruski and Dennis-Tiwary, 2021). In contrast, children who were less able to modulate the LPP using reappraisal had lower (concurrent) parent-reported capacity for emotion regulation and showed higher rates of mood problems (Dennis and Hajcak, 2009). Together, these findings support the idea that reappraisal-related modulation of the LPP might provide a sensitive and even prospective measure of “real-life” developmental changes in emotion regulation capacity throughout childhood.

During adolescence, emotion regulation abilities are thought to further improve as brain development continues (e.g., Stephanou et al., 2016). For example, in a study spanning a rather wide age range of adolescents and young adults (ages 11 to 22 years), modulatory effects of distraction (i.e., counting down by three) on the LPP changed throughout adolescence. The distraction condition generally attenuated emotional modulation of the LPP relative to passive picture viewing, but in young adolescents (aged 11–14 years), distraction-related reduction of the LPP was restricted to negative pictures. By contrast, in older adolescents (aged 15–17 years) and younger adults (aged 18–23 years), modulation of the LPP was evident for both positive and negative pictures (W. Zhang et al., 2014). Similarly, in another study, reduction of the LPP via expressive suppression increased with age in a group of 12- to 17-year-old participants (Desatnik et al., 2017), pointing towards increasing effectiveness of this strategy across adolescence. Therefore, ERPs can also be used to track the development of emotion regulation abilities throughout adolescence.

In order to understand moderators of emotion regulation development throughout childhood and adolescence, some ERP work has also examined the effect of interpersonal support. For example, parental scaffolding (i.e., additional reappraisal instructions given by a parent during a directed reappraisal task), as well as passive parental presence (i.e., parent present during the recording but not verbally interacting with the child or participating in the task) have been shown to increase reappraisal-related modulation of the LPP in 5- to 7-year-old children (Myruski et al., 2019). The effect of parental support and presence on reappraisal-related modulation of the LPP has also been replicated in 5–9 year old children (Myruski and Dennis-Tiwary, 2021). Moreover, in that study, evidence that the LPP was additionally predictive of observable emotion regulation during a frustrating task further suggested transfer of parental support effects across measures.

At the other end of the age spectrum, emotional reactivity in older adults has been found to be characterized by a positivity bias and an overall decrease in negative emotion (Mather and Carstensen, 2005), which could be due to improvements in situation selection as well as attentional deployment to positive content. With regards to emotion regulation, however, older age might be associated with distinct *deficits* in emotion regulation (for a review, see Urry and Gross, 2010), potentially because of declines in fluid cognitive abilities (Opitz et al., 2014). Only a small body of work has used ERPs to examine emotion regulation in older adults, and results have been mixed. For example, one study found that positive framing (i.e., categorizing pictures more or less positive or more or less negative) reduced the LPP to negative pictures in younger adults (18–27 years, mean age 21.8), whereas no effect was observed in older adults (56–88 years, mean age 66.2), suggesting reduced malleability of the LPP in older age (Rehmert and Kisley, 2013). Nonetheless, other work found that both younger (18–26 years, mean age 20.7) and older adults (60–77, mean age 68.1) were similarly able to modulate the LPP to negative and positive pictures through willful emotion regulation (Langeslag and Van Strien, 2010). Altogether, more studies on ERP correlates of emotion regulation in older age seem necessary to resolve conflicting results.

2.2.2. Gender—Higher prevalence rates for depression and anxiety disorders in women versus men (Kessler et al., 2012), have prompted interest in investigation of gender differences in emotional reactivity and regulation. Some studies have found evidence of an early "negativity bias" in women (Gardener et al., 2013), as measured using early negative-going ERP components, the N1 and N2. Additionally, women in this study showed stronger upregulation of the LPP to negative stimuli than men, whereas no gender differences were detected with respect to instructions to decrease emotional reactivity. Therefore, women might be characterized both by exaggerated early response to negative stimuli, as well as increased potential to amplify later, more sustained processing of negative stimuli.

In another study, gender was found to moderate the association between trait mindfulness and the LPP during mindful viewing, such that higher trait mindfulness was only associated with smaller LPPs (to negative and positive pictures) during mindful viewing for men, but not women (Egan et al., 2018). This suggests that individual differences in trait mindfulness might benefit emotion regulation more for men than women. In another study, women who were in the midluteal phase of their menstrual cycle (characterized by high levels of progesterone) showed increases in the N2 (but not LPP) to negative pictures as compared to men during suppression, as well as increased self-reported distress and effort needed to suppress responses (Lusk et al., 2017). Therefore, fluctuation in gonadal hormones might be related to deficits in the early suppression of negative information and might explain in part gender differences in emotion generation and regulation. In sum, there is some evidence to suggest deficits in emotion regulation for women compared to men, though null effects have also been observed (Desatnik et al., 2017). On the whole, more work is needed to understand gender effects in the ERP emotion regulation literature.

2.2.3. Psychopathology—Emotion regulation is considered an essential prerequisite for mental health (Sheppes et al., 2015) and dysfunction in emotional reactivity and/or regulation has been implied in several forms of psychopathology. Accordingly, ERP work has found evidence of abnormalities in emotion regulation in several forms of psychopathology.

In depression, evidence points to a general insensitivity towards emotional stimuli, irrespective of valence (Bylsma, 2021). Reduced LPP amplitudes to pleasant and unpleasant stimuli have been observed in depression (Foti et al., 2010; Hill et al., 2019; Klawohn et al., 2021b; MacNamara et al., 2016; Weinberg et al., 2016, 2017), though recent work suggests that insensitivity to emotional stimuli in depression could be limited to non-self-referential contents (Benau et al., 2019). Few ERP studies have examined emotion regulation in depression, despite clinical evidence of deficits in this area (Visted et al., 2018). Nonetheless, one study found that individuals higher in depression showed more substantial increases in the LPP on trials following a reappraisal trial (compared to those that followed control trials; Parvaz et al., 2015), indicating greater post-reappraisal emotional reactivity, potentially because individuals with depression found it more difficult to regulate their emotions on the preceding trial, leading to lasting increases in emotional arousal. Another study linked emotion regulation deficits to risk for suicide, finding less reappraisal-related reduction of the LPP to dysphoric images in undergraduates with versus without a history of suicidal ideation (Kudinova et al., 2016). Therefore, the LPP might track impairments in emotion regulation associated with depression more generally, as well more specific dimensions or risk factors (e.g., history of suicidal ideation).

Though some work has also examined depression as related to reward processing in the context of a savoring manipulation, results were only observed linking individual differences in trait savoring and reappraisal with the RewP and depression, and not for the effect of savoring on the RewP (Irvin et al., 2020). Nonetheless, given well-documented evidence of positive emotion deficits in depression, further investigation of aberrant reward-related upregulation in depression, particularly in regards to more specific dimensions of depression, such as anhedonia (Craske et al., 2019), may hold promise for increased understanding of this devastating disorder.

Frequently comorbid with depression, anxiety has been associated with increased attention to unpleasant stimuli (e.g., social anxiety disorder, specific phobia), particularly using the LPP (Kolassa et al., 2005; Leutgeb et al., 2010; MacNamara et al., 2019; MacNamara and Hajcak, 2010; Moser et al., 2008). Yet despite these relatively consistent findings, different results have been observed for some anxiety disorders. For example, participants with obsessive-compulsive disorder (OCD) appear to be characterized by increased LPPs only for disorder-relevant stimuli (Paul et al., 2016c). Moreover, a different set of mechanisms may be at play with regards to generalized anxiety disorder, where high worry and autonomic arousal but also emotional avoidance are crucial to the clinical picture. Accordingly, experimental findings have shown increased early (i.e., P1), but decreased sustained (i.e., LPP) neural correlates of emotional processing following unpleasant stimuli (Weinberg and Hajcak, 2011). Beyond emotional reactivity, a smaller number of ERP studies have reported on voluntary emotion regulation in the anxiety disorders. Two studies have failed to observe evidence of social-anxiety related deficits in emotion regulation using the LPP (i.e., reappraisal, Kinney et al., 2019; reappraisal, suppression and shame- and rejection-related pictures, Kivity and Huppert, 2018), although in both studies, participants with social anxiety disorder self-reported less frequent and less effective use of reappraisal and more frequent use of suppression in everyday life, compared to psychiatrically healthy participants. Conversely, patients with OCD have been found to be unsuccessful at downregulating the LPP to negative stimuli via reappraisal, despite successful reduction in subjective arousal ratings (Paul et al., 2016c). Therefore, the majority of ERP work in the anxiety disorders has shown evidence of abnormalities in emotion generation rather than emotion regulation, with extant studies on emotion regulation revealing mixed results. Overall, more work is needed to obtain a clearer picture of emotion regulation in anxiety.

Though internalizing disorders like anxiety and depression are more commonly thought of as “emotional disorders”, other forms of psychopathology, such as schizophrenia, are also characterized by severe abnormalities in emotional response and regulation (e.g., O’Driscoll et al., 2014). Although individuals with schizophrenia often show reduced emotional expression, symptoms of anhedonia and heightened negative emotionality in daily life, lab-based investigations typically point to intact reactivity to emotional stimuli, as apparent in valence ratings and early ERP components (Horan et al., 2010). In contrast, using the LPP, schizophrenia has been found to be characterized by a diminished differentiation between negative and neutral pictures, indicating alterations in the sustained processing of emotional stimuli (for a meta-analysis, see Castro et al., 2019). Deficits in emotion regulation have also been found fairly consistently. For example, compared to controls, individuals with schizophrenia have been found to exhibit larger LPPs to reappraised negative pictures (Horan et al., 2013; Strauss et al., 2013) and larger LPPs during a directed attention task, in which participants were asked to focus on less arousing aspects of negative pictures (Strauss et al., 2015). Moreover, more impaired emotion regulation, as measured by the LPP, has been found to be associated with state and trait negative emotionality in schizophrenia (Strauss et al., 2013). Therefore, the ERP literature is in line with clinical reports of emotion regulation difficulties in schizophrenia, and indicates that the extent of emotion regulation deficits might in part explain the level of affective distress experienced by patients.

Using ERP measures in combination with eye tracking and pupil dilation, Bartolomeo et al. (2020) were also able to provide insight into the mechanisms underlying aberrant emotion regulation in schizophrenia. In line with prior work, reappraisal and distraction did not modulate the LPP in individuals with schizophrenia. Moreover, individuals with schizophrenia made relatively fewer fixations during reappraisal and increased fixations on emotional areas of pictures during distraction. In addition, pupil dilation data suggested reduced effort during reappraisal in participants with schizophrenia. Therefore, altered visual attention and reduced cognitive effort might in part explain emotion regulation impairments in schizophrenia.

Importantly, deficits in emotion regulation as indexed by reduced reappraisal-related modulation of the LPP are apparent early on in the course of schizophrenia – i.e., in individuals at high clinical risk for psychosis and in first-episode early psychosis (compared to psychiatrically healthy individuals). Furthermore, the degree of impairment in LPP modulation has been found to be associated with severity of psychotic symptoms in first-episode psychosis and with severity of disorganization in individuals at high clinical risk (Kim et al., 2021). In addition, individuals at increased risk for schizophrenia-spectrum personality disorders (e.g., individuals with perceptual aberration and/or magical ideation), have been shown to exhibit emotion regulation abnormalities compared to participants who are not at risk (Martin et al., 2017). Therefore, emotion regulation deficits may represent an early warning sign or vulnerability for schizophrenia. In addition, given that deficits in emotion regulation can have a substantial effect on the emotional and social experiences of individuals with schizophrenia (Moran et al., 2018), increased understanding of these deficits may be relevant to the development of early intervention or prevention efforts.

In sum, the ERP literature is relatively scant when it comes to depression and anxiety, but does suggest evidence of emotion regulation difficulties in depression (the literature is more mixed for anxiety). Schizophrenia, on the other hand, has been more reliably associated with emotion regulation difficulties as assessed using ERPs. Critically, in spite of several cross-sectional ERP investigations of emotion regulation in psychopathology, longitudinal investigations linking ERP evidence of emotion regulation abnormalities with clinical outcomes and treatment response are particularly understudied. Nonetheless, some work has suggested that the LPP in passive viewing paradigms might predict treatment outcome/disorder course in depression (Barch et al., 2020; Klawohn et al., 2021a) and anxiety (Bunford et al., 2017; see also Kinney et al., 2021). Furthermore, the reward positivity (RewP) – a marker of reward responsivity – might predict treatment outcome in depression (Burkhouse et al., 2016; Kujawa et al., 2019a). This gives rise to the question as to whether modulating the LPP or RewP through emotion regulation techniques might lead to symptom improvement or whether training in emotion regulation could serve as an initial or preparatory step for treatment.

2.2.4. Culture—One area of research that has only begun to receive attention in the past decade is the issue of how culture may affect emotion regulation ability, as measured using ERPs. Though the literature is still quite small, it is growing, and initial evidence suggests that emotion regulation findings may differ across cultures. These findings have significant import for all the findings described above, because they suggest that they may be bound to the specific cultures in which these data were collected (primarily in European American culture).

Some work has focused on differences in emotion regulation between Asian or Asian-American cultures and European Americans, given purported differences in "cultural training" of emotion regulation for these groups. For example, among participants at a North American university, only those who had been born in an East Asian country and not those of European American descent were able to reduce the LPP to unpleasant and neutral pictures when instructed to use expressive suppression (Murata et al., 2013). In another study, also using the LPP, Asian Americans were unable to up-regulate or down-regulate their response to positive or negative pictures when focusing on modulating their outward expression of emotion. By contrast, European Americans and Mexican Americans were able to up-regulate their response to positive and negative pictures, though participants were generally unable to down-regulate their responses to pictures, with the exception being that Mexican Americans could down-regulate their response to positive pictures (Hampton et al., 2021). Therefore, these results do not fully support the perspective that individuals from East Asian cultures are taught to value emotional inhibition/suppression and that they might therefore be better at reducing emotional responses in this way. Nonetheless, they do suggest differences in the extent to which different cultures can successfully employ emotion regulation techniques focused on outward expression of emotion (see also Kraus and Kitayama, 2019). All in all, more work is needed to test whether established emotion regulation techniques are as effective across different cultures, and until that work is accomplished, it may be prudent to assume that the majority of findings in the field are specific to European American culture.

2.2.5. Summary—In the past decade, ERPs have been used to document the development of emotion regulation abilities in childhood and across adolescence. Evidence pertaining to emotion regulation abilities in older age is scarcer, and more work is needed in this area. Research that has investigated gender differences in emotion regulation is particularly sparse, despite the potential relevance of this work to understanding why depression and anxiety occur more frequently in women compared to men. Much of the existing literature has focused on abnormalities in emotion generation as related to depression, anxiety and other forms of psychopathology, with fewer studies examining emotion regulation per se. Among work that has examined emotion regulation in these disorders, results have suggested that depression and some of its related features (e.g., history of suicidal ideation) may be characterized by abnormalities in emotion regulation, though evidence of abnormalities in positive emotion regulation have not yet been identified. The literature on anxiety is also sparse, with mixed results that have differed by disorder. Schizophrenia, though less often thought of as an emotional disorder, has been associated with relatively consistent evidence of emotion regulation deficits, which may be driven by alterations in visual attention and cognitive effort. Therefore, while more work is needed, there is initial evidence of emotion regulation abnormalities in these disorders. Further work is needed to investigate the prospective value of ERP measures of emotion regulation in predicting risk for psychopathology, disorder course or treatment outcome. Finally, the vast majority of emotion regulation work to-date has employed European American participants. Initial evidence suggests differences in the successful application of certain emotion regulation techniques, like expressive suppression, when used by individuals from European American versus East Asian American cultures. This raises the possibility that the majority of findings on emotion regulation that have been established so far should be considered specific to European American culture, and highlights the dire need for more work in this area.

3. The future – challenges and neglected areas

Despite the progress that has been made over the past decade in using ERPs to better understand emotion regulation, there are several challenges inherent to this type of research that will need to be addressed in future work. Some of these challenges are specific to ERPs, whereas others are equally applicable to the broader emotion regulation literature. This section highlights some of these challenges and notes potential avenues for future research, including topics that have been relatively neglected and provide ripe opportunities for advancing the literature.

3.1. Challenges inherent to emotion regulation work

One challenge facing psychophysiologists doing emotion regulation work lies in separating out mechanisms underlying the emotion regulation process itself from the neural processes that *support* emotion regulation. For example, cognitive neuroscience work has sought to differentiate neural signals reflecting attention versus working memory, as attention is a necessary process that supports the manipulation of information in memory but should not be confused with working memory itself (Awh and Jonides, 2001; Gazzaley and Noble, 2012; Oberauer and Hein, 2012). Similarly, inhibitory processes are often necessary for emotion regulation, but inhibitory processes likely reflect at least in part variance that can be attributed to broader, separable constructs, as well as variance specific to a particular form of emotion regulation. Along these lines, the dispositional trait of disinhibition – which shows replicable correlations with neural, physiological, and behavioral indicators of inhibitory control (Brennan and Baskin-Sommers, 2018; Venables et al., 2018; Yancey et al., 2013; Young et al., 2009) – also relates to everyday use of emotional reappraisal (Perkins et al., 2019). As such, studies seeking to find the neural correlates of reappraisal may reflect variance related to the construct of disinhibition, or other constructs and processes that *support* and *interact with* the implementation of the reappraisal in addition to those that underlie reappraisal itself.

We observe this difficulty clearly in the neuroimaging modality. For example, an activation likelihood estimation (ALE) neuroimaging meta-analysis of cognitive emotional regulation showed involvement of eight significant clusters, including the supplementary motor area, inferior frontal gyri, precentral gyri, middle temporal cortex (left), and angular gyri (Kohn et al., 2014). Similarly, another ALE neuroimaging meta-analysis of inhibitory control (categorized into two processes of interference resolution and action cancellation) also found significant clusters in all of the same areas – the supplementary motor area, inferior frontal gyri, precentral gyri (only significantly implicated in interference resolution), middle temporal cortex (only significantly implicated in action cancellation), and angular gyri (R. Zhang et al., 2017). These results highlight the degree to which the processes supporting emotion regulation rely on the same neural structures as other functions – and the degree to which it is difficult to fully parse these sources of variance. Indeed, parsing the sources of variance that contribute to ERP measures of emotion regulation will be particularly challenging. Common ERP components in emotion regulation work (e.g., the LPP) reflect both "bottom-up" (e.g., emotion generation) and "top-down" (e.g., emotion regulation) influences, making it difficult to parse the relative contribution of each to the summary ERP component. Clever experimental designs and analysis methods, as well as multiple measures (e.g., time-frequency based approaches in addition to ERPs) may be helpful in disentangling processes contributing to overall stimulus salience.

A related challenge is the assumption that the same regulatory strategies will work in the same way across emotions of differing valence. For example, perhaps because it is a cognitively demanding technique, reappraisal may be ineffective at upregulating the LPP to pleasant pictures (Krompinger et al., 2008), though it appears to be effective in upregulating peripheral psychophysiological response to positive stimuli (Gruber et al., 2014). One potential explanation for this finding is that further increases in the LPP to pleasant pictures may be limited by a "ceiling effect"; however, this seems unlikely. For example, when given non-specific instructions to upregulate positive emotion rather than instructions to use cognitive reappraisal specifically, participants were able to increase the LPP to pleasant pictures (Baur et al., 2015). As such, future studies may wish to use cognitive interviewing (Beatty and Willis, 2007) to understand what techniques individuals employ to successfully upregulate response to positive stimuli as measured using the LPP, rather than relying on strategies that have been developed and optimized for the downregulation of negative emotion.

3.2. Idiographically-inspired approaches

An emerging area of work in emotion regulation research that has received relatively little attention in the ERP literature is that of idiographic approaches and manipulations. Idiography refers to a study of individual people, at the individual level, rather than at the group level. In the context of emotion regulation, idiography refers to emotional stimuli or emotion regulation strategies that are specific to the person rather than standardized across people. Key theories of emotion regulation suggest that the personal relevance of emotional stimuli may affect emotion regulation success (Ellsworth and Scherer, 2003), and this may be particularly true for certain forms of psychopathology, such as borderline personality disorder (Kuo et al., 2014) or depression (Benau et al., 2019).

Along these lines, future work may wish to go farther in incorporating personally relevant stimuli in ERP studies of emotion regulation. The recently developed, ‘Autobiographical Emotion Regulation Task’ (Speed et al., 2017), in which participants were asked to select their own neutral and emotionally charged autobiographical memories, before cognitively reappraising (downregulating) their response to these memories is an example of initial forays in this direction. Future work could extend this task to examine the upregulation of positive autobiographical memories.

3.3. Concordance with real world behaviors

There is great value in understanding psychological processes in life as it is lived. That is, while we are able to observe that in-lab manipulations have certain effects on psychological processes, it does not *necessarily* mean that these manipulations are what drives behavior in daily life (e.g., sufficient versus necessary conditions; other manipulations may produce the same effect and may be more commonly encountered in individuals’ daily lives). Thus, ambulatory assessment (an umbrella term encompassing daily diary, ecological momentary assessment/EMA and dense longitudinal designs) holds promise for increasing the ecological validity of emotion regulation research.

Though most ambulatory data collection involves subjective/self-reported data (e.g., prompts about emotional events delivered several times a day on participants’ phones), researchers have begun to leverage cutting-edge technological advances to collect psychophysiological data in vivo during ambulatory assessment periods. Much of this work has been done in the realm of peripheral psychophysiology (e.g., heart rate and heart rate variability), often using smartwatches and other continuous recording devices (for a review of ambulatory peripheral psychophysiological devices, see Wac and Tsiourti, 2014). However, the challenge in collecting ambulatory EEG data is much greater (for a review, see Bateson et al., 2017). One of the fundamental challenges for this type of work is signal quality; however, this concern *may* be balanced with the increased ecological validity to be gained from data collection in the real world. Future work needs to carefully assess this balance and evaluate signal-to-noise ratio in mobile EEG studies. Significant innovations are being continually developed in this domain, and may eventually even provide affordable alternatives to today's in-lab EEG setups (e.g., a Raspberry Pi 2 as an alternative for administration of EEG/ERP experiments; Kuziek et al., 2017). Nonetheless, prior reviews of mobile EEG/ERP research have noted insufficient reporting of rates of unusable, lost, and noisy data in mobile EEG/ERP studies (Raugh et al., 2019), and additionally, we have not seen any reporting of internal consistency reliability of ERP components (Patrick and Hajcak, 2016) in mobile EEG studies ourselves. Therefore, it will be important to report these metrics transparently going forward.

Notwithstanding concerns about data quality, mobile EEG offers incredible promise for discovering the neural bases of emotion regulation and predicting emotion regulation success in the real world. For example, Park and Donaldson (2019) used a novel, mobile 'EEGo Sports' 32-channel system (ANT Neuro, Enschede, Netherlands) to record ERPs elicited when participants recognized real-world objects in their environment. Moreover, they found separable effects of object recency and context (i.e., whether the object was encountered in an expected or unexpected location). Using a similar approach, ERPs could be recorded during the regulation of emotions elicited by real-life stimuli in participants' environment, potentially increasing the likelihood that results would translate into improved understanding of emotion regulation in everyday life. Moreover, ambulatory ERP paradigms that track regulatory response to stimuli in individuals' daily lives may have relevance for the development of personalized treatment approaches or monitoring of treatment gains for disorders characterized by deficits in emotion regulation (Campanella, 2021), particularly given evidence that certain emotion regulation strategies may work better for some individuals than others (Cardona et al., 2021; Heiy and Cheavens, 2014).

However, in situations where mobile EEG is impractical, poorly suited to the research question, or provides unacceptable signal quality, combining laboratory EEG/ERP designs with ambulatory assessment of emotional response and regulation collected at a different time may still be advantageous, and should permit increased understanding of the dynamic nature of emotion regulation. Along these lines, Overmeyer et al. (2021) found that the magnitude of the ERN as measured in the lab predicted real-world self-regulatory failures over the following week, as assessed using EMA. Given substantial excitement about the promise of ambulatory assessment for transforming the study of emotion regulation (Brockman et al., 2017; Colombo et al., 2020), the relative lack of designs that have combined ERPs with ambulatory assessment to-date points to an area of opportunity for future emotion regulation research.

4. Conclusion

ERP research on emotion regulation has grown immensely in the past decade, bringing with it new and exciting paradigms, manipulations, and ideas. Standardized emotional pictures (e.g., the IAPS; Lang et al., 2008; Emotional Picture Set, EmoPicS; Wessa et al., 2010), particularly negative images, continue to be the most widely used stimuli for probing emotional reactivity. However, more recent work has begun experimenting with other types of stimuli (e.g., emotional imagery; MacNamara, 2018; e.g., autobiographical memories; Speed et al., 2017) that have been shown to successfully elicit ERP measures of emotional reactivity and might be well-suited to use in emotion regulation paradigms going forward. The LPP continues to be the most widely studied ERP component in the emotion regulation literature, but studies using the EPN, P300, and N170 are beginning to proliferate. The evidence-base for the effect of cognitive reappraisal on ERPs has become somewhat mixed, and new regulatory strategies, such as social and more automated forms of emotion regulation, as well as mindfulness, and savoring of positive stimuli have emerged. Key individual differences affecting emotion regulation success involve age, gender, psychopathology and potentially cultural differences. Overall, emotion regulation is more difficult for children, and is not always represented at the electrocortical level in the same way as for adults. In some clinical populations (such as OCD), reappraisal fails to modulate the LPP to emotional images, but more studies are needed across different types of disorders to better understand the impact of psychopathology on the brain basis of emotion regulation. More generally, it seems possible that many of the findings in the emotion regulation literature to-date should be considered specific to individuals from European American backgrounds, with work examining emotion regulation in other cultures sorely needed. Finally, there is ample opportunity for the next generation of emotion regulation work to move beyond the laboratory and to examine associations with real-world behaviors using ambulatory assessment approaches. All in all, it is likely that the same strengths that have made ERPs particularly useful in answering some of the more nuanced questions about emotion regulation that have emerged in the past decade (e.g., high temporal resolution, reliability, flexibility and tolerability of data collection procedures), will position them well to help overcome the challenges that remain in advancing a more ecologically valid and impactful understanding of emotion regulation in the decades to come.

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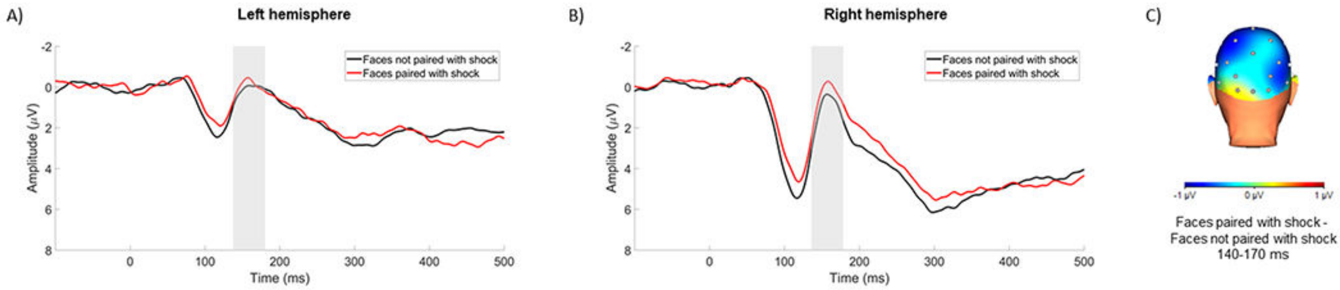

Fig. 1.

The N170. Grand-averaged waveforms at the temporo-occipital pools where the N170 was maximal, shown separately for A) left hemispheric sites (PO3, P3, P7) and B) right hemispheric sites (PO4, P4, P8) and C) headmaps depicting scalp distributions of voltage differences of faces that predicted shock onset minus faces that were not paired with shock, from 140 to 170 ms after face onset.

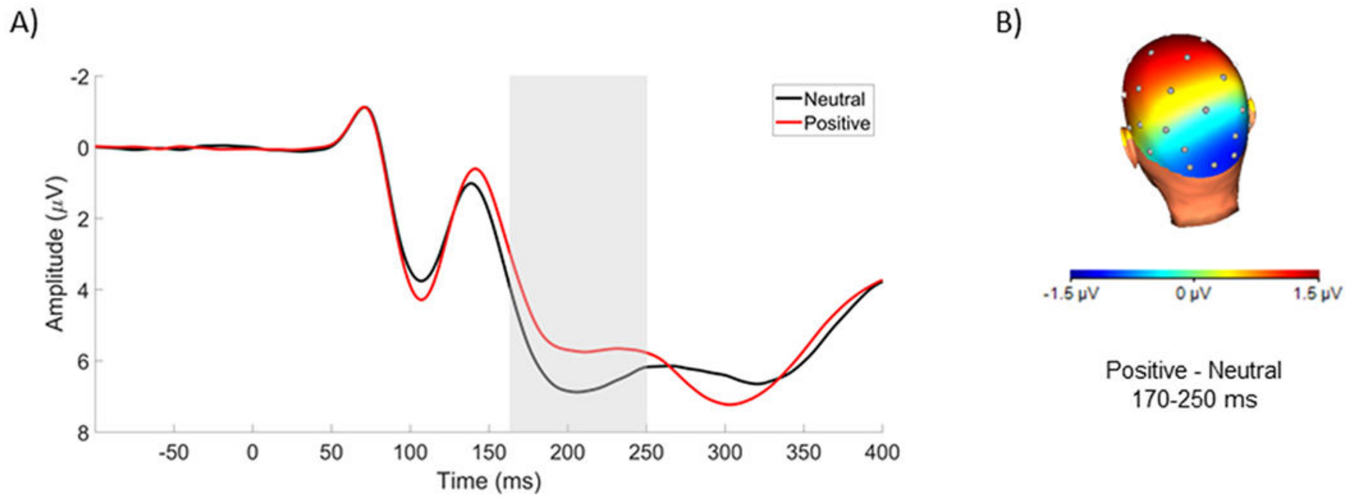

Fig. 2.

The EPN. A) Grand-averaged waveforms at Oz where the EPN was maximal and B) headmaps depicting scalp distributions of voltage differences for positive minus neutral pictures, from 170 to 250 ms after picture onset.

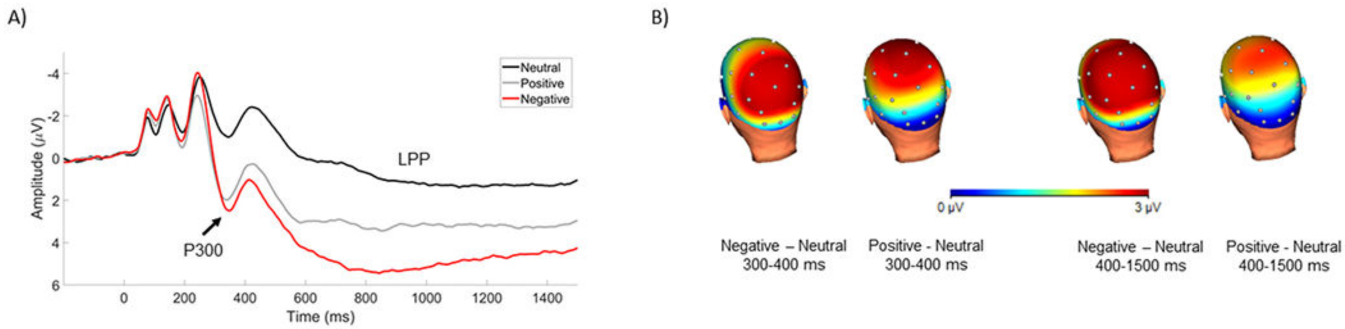

Fig. 3.

The P300 and the LPP. A) Grand-averaged waveforms at the centroparietal pooling where the P300 and the LPP were maximal (CP1, CP2, Cz, Pz) and B) headmaps depicting scalp distributions of voltage differences for negative minus neutral pictures and positive minus neutral pictures, from 300 to 400 ms (P300) and 400–1500 ms (LPP) after picture onset.

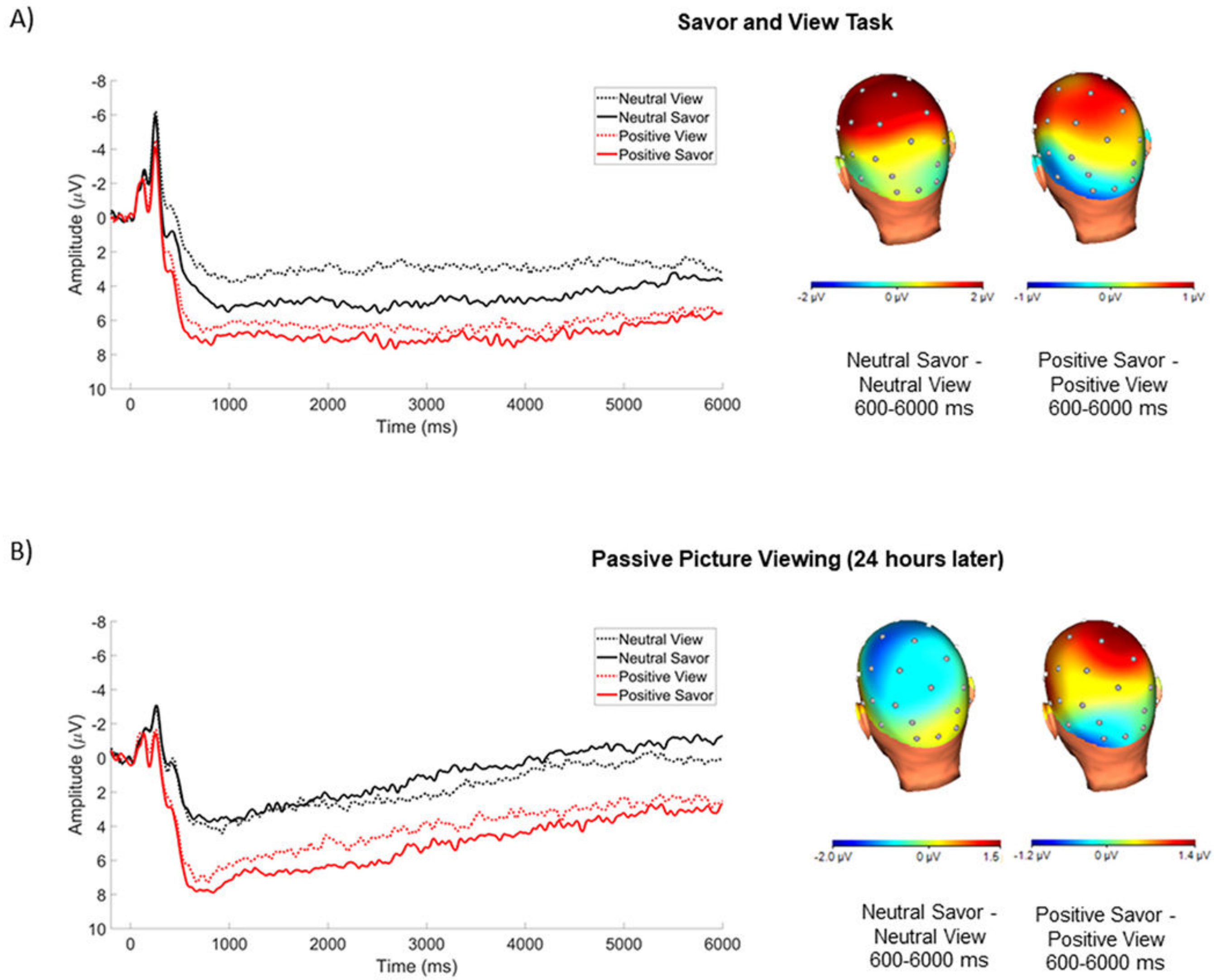

Fig. 4.

Positive pictures that were previously savored elicit larger LPPs 24 h later, in the absence of emotion regulation instructions (i.e., during passive picture viewing). Grand-averaged waveforms where the LPP was maximal (CP1, CP2, Cz, Pz) and headmaps depicting scalp distributions of voltage differences for Neutral Savor minus Neutal View and Positive Savor minus Positive View, shown separately for: A) Savor and View Task, in which participants savored and viewed neutral and positive pictures and B) Passive Picture Viewing task, performed 24 h later with the same neutral and positive pictures as previously shown.

Table 1

Emotion regulation techniques.

Technique	Description
Reappraisal	
• Distancing/self-focused	Detached perspective
• Situation-focused	Meaning change
Expressive suppression	Inhibit outward expression of emotion
Mindfulness	Present-focused awareness
Savoring	Experiential absorption in the pleasurable
Distraction	Thinking about something irrelevant
Cognitive load	Performing a cognitively demanding task
Directed or visual attention	Focusing visual attention towards or away from the emotionally arousing parts of stimuli

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Table 2

Studies that have failed to find an effect of reappraisal on ERPs.

Study	Stimuli	Main ERP findings
Baker et al. (2017)	ANEW	Benefit-focused reappraisal and compassion-focused reappraisal had no effect on the LPP.
Baur et al. (2015)	IAPS	Freely chosen emotion regulation strategies led to larger LPPs for both up- and down-regulation
Bernat et al. (2011)	IAPS	Increase and decrease reappraisal led to increased LPPs.
Cao et al. (2020)	IAPS	Decrease reappraisal had no effect on the LPP or led to larger LPPs (depending on time window).
Gan et al. (2015)	IAPS	Decrease reappraisal did not always reduce the LPP; increases sometimes observed.
Giraldo et al. (2019)	Pictures of food	Decrease reappraisal led to larger P300s and early LPPs.
Imburgio & MacNamara (2019)	EmoPicS and IAPS	Decrease reappraisal had no effect on the LPP.
Krendl et al. (2017)	Pictures of highly stigmatized individuals (e.g., homeless; drug addicts)	Decrease reappraisal had no effect on the LPP.
Kudinova et al. (2016)	IAPS	Decrease reappraisal had no effect on the LPP.
Langeslag and Surth 2017	IAPS	Decrease reappraisal of high-arousing unpleasant pictures led to larger LPPs; no effect for low-arousing pictures
Mallorquí-Bagué et al. (2020)	IAPS	Decrease reappraisal had no effect on the P300 or the LPP.
Pedersen & Larson (2016)	IAPS and NAPS	Decrease reappraisal had no effect on the LPP.
Sarlo etal. (2013)	Pictures of highly caloric food	Decrease reappraisal had no effect on the LPP.
Wu et al. (2013)	IAPS and CAPS	Decrease reappraisal led to increased P2s and LPPs

Note: ANEW, Affective Norms for English Words (Bradley and Lang, 1999); CAPS, Chinese Affective Picture System (Lu et al., 2005); EmoPicS, Emotional Picture Set (Wessa et al., 2010); IAPS, International Affective Picture System (Lang et al., 2008); NAPS, Nencki Affective Picture System (Marchewka et al., 2014).