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Event-related brain potentials and the study of reward processing: Methodological considerations☆

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A B S T R A C T

There is growing interest in using electroencephalography and specifically the event-related brain potential (ERP) methodology to study human reward processing. Since the discovery of the feedback related negativity (Miltner et al., 1997) and the development of theories associating the feedback related negativity and more recently the reward positivity with reinforcement learning, midbrain dopamine function, and the anterior cingulate cortex (i.e., Holroyd and Coles, 2002) researchers have used the ERP methodology to probe the neural basis of reward learning in humans. However, examination of the feedback related negativity and the reward positivity cannot be done without an understanding of some key methodological issues that must be taken into account when using ERPs and examining these ERP components. For example, even the component name – the feedback related negativity – is a source of debate within the research community as some now strongly feel that the component should be named the reward positivity (Proudfit, 2015). Here, ten key methodological issues are discussed – confusion in component naming, the reward positivity, component identification, peak quantification and the use of difference waveforms, frequency (the N200) and component contamination (the P300), the impact of feedback timing, action, and task learnability, and how learning results in changes in the amplitude of the feedback-related negativity/reward positivity. The hope here is to not provide a definitive approach for examining the feedback related negativity/reward positivity, but instead to outline the key issues that must be taken into account when examining this component to assist researchers in their study of human reward processing with the ERP methodology.

1. Introduction

The purpose of this review paper is to address several methodological issues that must be taken into consideration when using electroencephalography to study human reward processing – and more specifically the feedback related negativity (FRN: Miltner et al., 1997) and the reward positivity (Holroyd et al., 2008; Proudfit, 2015). It is important to emphasize that the point of this review is to address methodological concerns related to examination of the FRN and the reward positivity and not to summarize or argue for and against the theoretical and neural underpinnings of these components. Indeed, in recent years there have been multiple excellent reviews focused on the FRN and reward positivity and the factors that underlie its generation and modulation (e.g., Holroyd and Umemoto, 2016; Sambrook and Goslin, 2015; Walsh and Anderson, 2012). As such, a theoretical review is not the focus of this work. While this review will begin with a brief history of the electroencephalographic components associated with error and feedback processing the primary focus of this paper will be on ten key methodological concerns that must be taken into account when examining the FRN/reward positivity.

1.1. A brief history of the ERN and FRN

As we learn the mistakes that we make can be evaluated in two principle ways. First, early in learning we use and are reliant upon feedback – sensory information that is processed by us and indicates whether or not we have performed a given action correctly (Adams, 1971). Second, as we gain skill and learn to execute actions correctly we lose our reliance upon external feedback and gain an internal capability to evaluate the consequences of our actions via an efference copy of the motor command (Angel, 1976). Studies using electroencephalography have reported neural responses that appear to reflect both internal error evaluation (the error-related negativity) and external feedback evaluation (the feedback related negativity).

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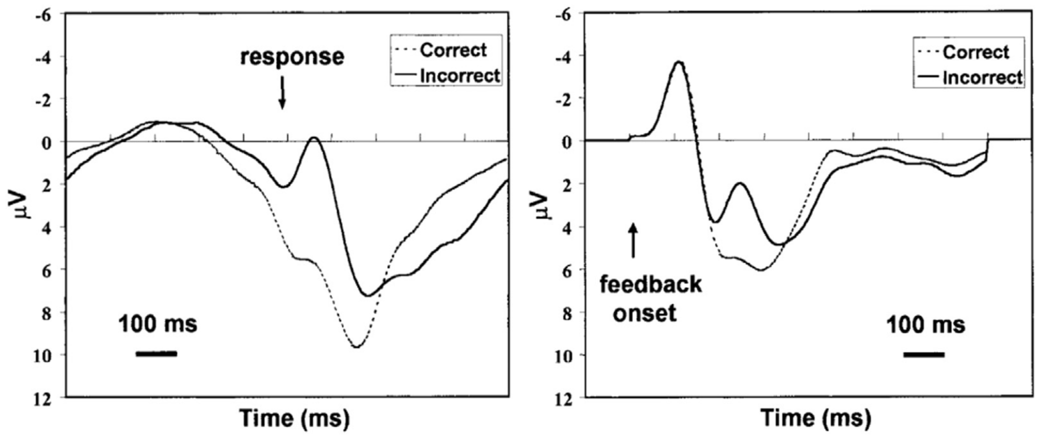

Fig. 1. Left Panel: The error related negativity shown at channel FCz where it is maximal. Right Panel: The feedback related negativity shown at channel FCz where it is maximal.
Reproduced with permission from Holroyd and Coles, 2002.

1.2. Internal error evaluation: the error related negativity (ERN)

The electroencephalographic study of error evaluation started with an examination of the event-related brain potentials (ERP) evoked by response errors – incidents during speeded response tasks when participants make an incorrect response. For example, if one contrasts the ERP response to correct and incorrect responses during performance of the Eriksen Flanker Task an error-related negativity (ERN) is observed as the difference between the average correct and incorrect waveforms time locked to the response (see Fig. 1, left panel). Within the literature, there is debate about the first reporting of the ERN but most authors now give joint credit to both Falkenstein et al. (1991) and Coles et al. (1991) for the initial observation of the ERN with a full report being made by Gehring, Goss, Coles, Meyer, and Donchin in 1993. As noted above, the ERN is typically evoked by erroneous responses in speeded response tasks. The ERN typically begins 30 ms post response and peaks at 100 ms but this latency is subject to how response onset is quantified (Burle et al., 2008). Specifically, the onset and peak of the ERN occurs at these times when the waveform is time locked to a button press or similar response. However, when response onset is defined as the onset of muscle activity using electromyography (EMG)[1] - the electrical burst of activity recorded from above the muscle belly that reflects the beginning of the contraction of the muscle – then the onset of the ERN is coincident with the onset of muscle activity and peaks around 50 ms post response (Gehring et al., 1993). The scalp topography of the ERN is typically front-central, with a maximum negativity typically occurring at electrode FCz (Burle et al., 2008; Gehring et al., 1993; Holroyd and Coles, 2002).

Perhaps the easiest way to describe the process that underlies the ERN would be to state that the ERN is the subconscious portion of the so called "oh fudge" response. However, a more precise description of the process that underlies ERN generation would be to say that the ERN reflects the evaluation of an efference copy of a motor command (Holroyd and Coles, 2002). More precisely, given that ERN onset is coincident with the onset of EMG activity it stands to reason that the evaluation process that generates the ERN is complete prior to the initiation of the physical response. As such, it has been hypothesized that when a motor command is issued a copy of the motor command – the efference copy – is sent to be evaluated almost instantaneously by a neural error detection system (see Holroyd and Coles, 2002). The ERN therefore in this framework reflects a surface-viewable signature of the detection of a response error by this underlying system. Although the ERN is an interesting and important ERP component as evidenced by the numerous studies examining it, given the scope of this review further discussion of the ERN is not warranted other than to point out to readers that it is a different ERP component from a later component associated with feedback evaluation – the feedback related negativity.

1.3. Evaluation of performance feedback: the feedback related negativity (FRN)

In 1997 Miltner and colleagues reported an ERP component evoked by performance feedback provided to participants during performance of a time estimation task. In their paradigm, participants were asked to guess the duration of 1 s. The task had a structure such that at the beginning of the task, participants had to be within ± 100 ms of 1000 ms with their guess. However, each time a participant was correct the tolerance window of ± 100 ms decreased by 10 ms (i.e., the window became ± 90 ms) and each time a participant was incorrect the tolerance window increased by 10 ms (i.e., the window became ± 110 ms). In this manner, participant performance hovered around 50% after an initial learning phase.[2] In an additional manipulation, Miltner and colleagues also manipulated how feedback was provided – in one condition it was visual, in another auditory, and in a third tactile. In all instances, a comparison of the average correct and incorrect waveforms revealed a difference at about 250 ms post stimulus onset which Miltner and colleagues referred to as the feedback-related negativity (FRN: see Fig. 1, right panel). As with the ERN, the FRN has a front-central scalp topography that is typically maximal at electrode FCz although as noted it occurs much later. Source localization of the FRN suggests a source within the human anterior-cingulate cortex (Bellebaum and Daum, 2008; Gehring and Willoughby, 2002; Gruendler, et al., 2011; Hewig et al., 2007; Mathewson et al., 2008; Miltner et al., 1997; Potts et al., 2006b; Ruchsow, et al., 2002; Tucker, et al., 2003; Walsh and Anderson, 2012; Zhou et al., 2010). The FRN is thought to reflect evaluation of performance feedback, however, there is a fair amount of debate as to the exact computations driving the difference between correct and incorrect average feedback waveforms. An abundance of recent studies have examined whether or not the FRN is sensitive outcome expectancy, outcome magnitude, and other external factors (see Holroyd & Umemoto, 2016; Sambrook and Goslin, 2015; Walsh and Anderson, 2012 for review).

As noted at the outset, a full review of the theoretical accounts that attempt to explain the FRN is beyond the scope of this review. However, briefly, perhaps the most cited account of the FRN posits that the component reflects a reinforcement learning prediction error (Holroyd and Coles, 2002). More specifically, the RL-ERN theory proposes that the anterior cingulate cortex, midbrain dopamine system, and basal ganglia compose a reinforcement learning system within the human

[1] It is worth noting from a methodological perspective that defining response onset as EMG onset is more accurate as it comes after pre-motor time and before motor time.

[2] As it turns out, this is a very important manipulation. The FRN occurs coincident with the N200 which of course is extremely sensitive to stimulus frequency (see below and see Holroyd et al., 2008).

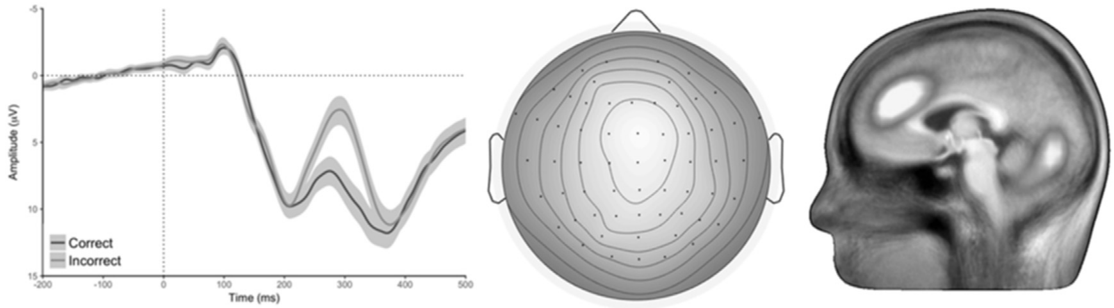

Fig. 2. Left Panel: The reward positivity shown at channel FCz where it is maximal. Middle Panel: The peak topography of the reward positivity. Right Panel: Source localization of the reward positivity using the CLARA distributed source analysis method in BESA. The source is in the anterior cingulate cortex consistent with other accounts.

medial-frontal cortex. Within this framework, the basal ganglia compute prediction errors – the discrepancies between outcomes and expectations – and then convey these prediction errors via the midbrain dopamine system to the anterior cingulate cortex to optimize response selection. This account is firmly grounded in reinforcement learning principles (i.e., Sutton and Barto, 1998) and support for the theory comes from studies that attempt to highlight that the FRN behaves in a manner that would be predicted by reinforcement learning theory. For example, in 2007 Holroyd and Krigolson demonstrated that the amplitude of the FRN was sensitive to outcome expectancy, a result in line with the predictions of reinforcement learning theory. More recently, the original Holroyd and Coles theory has been revised and now there is some evidence that the FRN may be related to a hierarchical reinforcement learning process (e.g., Holroyd and Yeung, 2012). To be fair, there are other prominent accounts that provide explanations of the FRN (e.g., the conflict monitoring hypothesis: Botvinick et al., 2001) but a full review of these accounts is not possible here (see Walsh and Anderson, 2012, for an extensive review).

2. Methodological considerations

2.1. Component naming and confusion with the ERN

Unlike the ERN, there is considerable debate about the correct name for the FRN component. The original decision to label the difference between the average correct and incorrect waveforms locked to feedback onset a feedback related negativity was due to visual inspection of the component waveforms - the difference between the correct and incorrect waveforms looked like a negativity - and to align the name of feedback locked component with the ERN (Miltner et al., 1997):

The waveforms following incorrect feedback include a negative peak, or a negative displacement, that is not evident in the waveform following correct feedback.

Thus, at the time the component was named there was no empirical evidence to support the name feedback related negativity. However, the name FRN was a logical choice given the data, the evidence to date, and the previously named ERN. Confusion about the name of the component began immediately as within this seminal paper the similarities between the ERN and FRN were discussed. Indeed, Miltner and colleagues proposed that the two components reflected a generic error evaluation process wherein both internal (ERN) and external (FRN) sources of information could be used for performance evaluation. Since the original reporting, the FRN has also been termed the feedback negativity (FN: e.g., Bress et al., 2015), the medial-frontal negativity (MFN: e.g., Gehring and Willoughby, 2002), and the feedback error related negativity (fERN: e.g., Holroyd and Coles, 2002). Moreover, based on a growing body of evidence there is now a push to refer to the FRN as a reward positivity (RewP: Proudfit, 2015) or a correct related positivity/feedback correct related positivity (Holroyd et al., 2008: see below).

Given the variety of names associated with the FRN it is important for researchers to be aware that all of the aforementioned components (FRN, FN, MFN, fERN, RewP, correct related positivity) are referring to the same ERP component. It is also worth noting that some also confuse the FRN with the considerably more well-known ERN. Indeed, some researchers are not aware of the feedback locked component and thus confuse it with the ERN. In other instances, the name ERN has been used to describe the FRN - for an example of this confusion see Holroyd et al., 2009. Finally, another naming issue arises as other researchers refer to the incorrect conditional waveform as the feedback related negativity and the correct conditional waveform as the reward positivity. This nomenclature is incorrect as the ERP component is by definition the difference between the incorrect and correct waveforms and not just one of conditional waveforms on its own (Holroyd and Krigolson, 2007; Holroyd et al., 2008; Proudfit, 2015: see below). With all of the naming confusion in mind; recommendations for researchers studying the FRN are to ensure that one clearly states that they are quantifying a feedback as opposed to response locked ERP component and to use one consistent name within their own work while acknowledging that others may refer to the same component by a different name.

2.2. It is not a negativity: the reward positivity

As noted above, in the original reporting, Miltner and colleagues referred to the feedback-related negativity as a “negativity” to align the naming of the component and the result with the previously discovered ERN (Miltner et al., 1997). However, a series of experiments by several groups (Foti et al., 2009; Holroyd et al., 2008; Krigolson et al., 2014; Proudfit, 2015) began to provide evidence that feedback evaluation did not modulate the negative conditional waveform but instead modulated the positive conditional waveform (see Figs. 2 and 3). For example, Holroyd et al. (2008) had participants complete two tasks – a simple oddball paradigm and a reward gambling task. The underlying reasoning for having participants perform both tasks was the knowledge that any visual stimulus would evoke a waveform response that included all of the typical ERP components – P100, N100, P200, N200, and P300 (Luck, 2014). Additionally, the evoked ERP components were also known to be sensitive to other underlying processes - for instance, the amplitudes of the N200 and P300 would be modulated by stimulus frequency (the oddball effect: Towey et al., 1980; Donchin and Coles, 1988). Having participants complete both an oddball and a time estimation task allowed the researchers to directly compare the oddball waveform to the correct and incorrect waveforms time locked to the presentation of the visual stimulus (see Fig. 4). Importantly, Holroyd and colleagues' data suggested that the waveform modulation brought about by the presentation of feedback modulated the correct but not the incorrect average waveform. More specifically, the researchers concluded that the process underlying the evaluation of correct feedback evoked a positivity in the N200 time range – a result paralleled by others (see also Foti et al., 2009; also Proudfit, 2015, for a full review). In any event, the aforementioned data suggested quite strongly that the

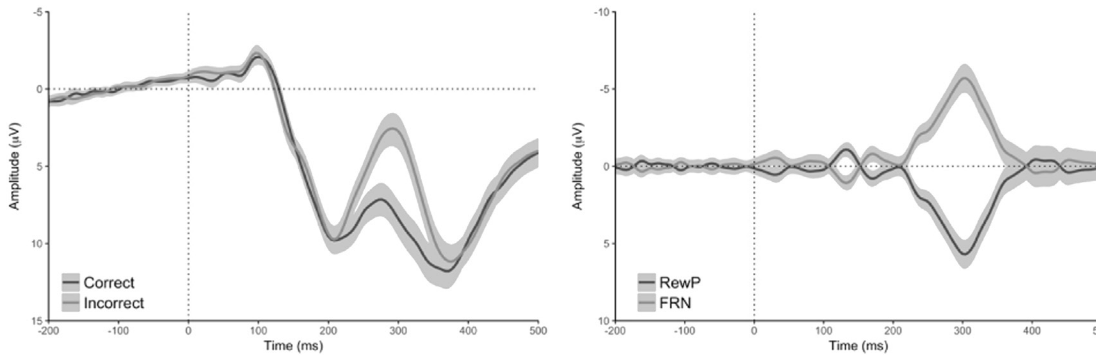

Fig. 3. Left Panel: Correct and incorrect grand average conditional waveforms. Right Panel: The difference waveform showing the mathematical subtractions that make a FRN or a reward positivity. This figure clearly shows how the two components are one and the same but the meaning is different based on the subtraction.

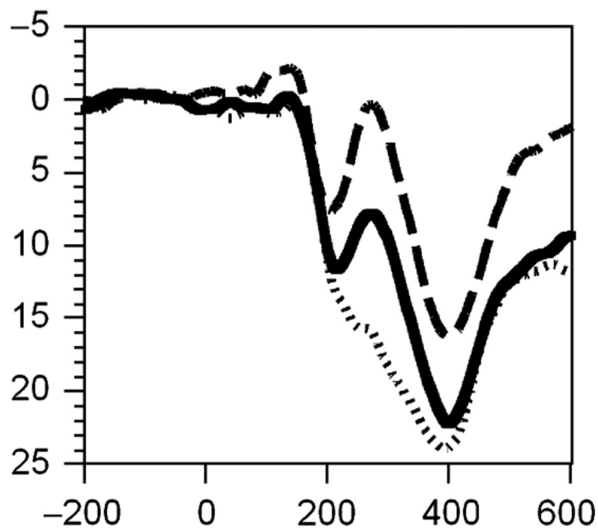

Fig. 4. Grand average waveforms for an oddball response, incorrect feedback, and correct feedback. Note the similarity in the morphology of the oddball and the incorrect feedback waveforms showing the problem with N200 frequency contamination.

FRN was actually a reward positivity and not a negativity as was originally claimed (Miltner et al., 1997) – a finding that is rapidly gaining support. For researchers studying the FRN/reward positivity it is important to be aware of the reward positivity issue and potentially address this within their work. To acknowledge this debate for the rest of this review I will refer to the FRN/reward positivity jointly.

2.3. Component identification: timing, topography, and source

While there have been many texts (Luck, 2014) and numerous papers (e.g., Picton et al., 2000) that provide an excellent summary of overall component identification here I will briefly review the important considerations with regard to component identification of the FRN/reward positivity. In general, the FRN/reward positivity is evoked by performance feedback that indicates the outcome of an event (e.g., Hajcak et al., 2006; Miltner et al., 1997) when it is not possible to determine the outcome of an action in another manner. Consider the ERN as noted above, in typical tasks that evoke the ERN performance feedback would be redundant as participants are already capable of evaluating their actions without this information and thus a FRN/reward positivity would not be elicited. The FRN/reward positivity has been reported to occur between 230 and 350 ms post feedback stimulus onset (e.g., Miltner et al., 1997) and typically has a medial-frontal scalp topography (e.g., maximal at electrode FCz: Krigolson et al., 2014). While there might be a tendency to consider the FRN/reward positivity a modulation of an incorrect average ERP waveform, this is not necessarily true. Indeed, there seems to be a growing shift to accept that the component evoked in this time range reflects a reward positivity as opposed to a feedback related negativity as outlined above.

To correctly identify the FRN/reward positivity it is important to establish at least two if not three key features of the component. One, the timing of the component should have a maximal negativity (or positivity: see below) between 230 and 350 ms post feedback stimulus onset (Holroyd and Coles, 2002; Miltner et al., 1997). With that said, it is important to note that there is evidence that the latency of the FRN/reward positivity can be modulated by factors such as cognitive load (see Krigolson et al., 2012; Krigolson et al., 2015) and thus can potentially occur later than the generally accepted time range. Two, the topography of the maximal negativity/positivity should be centered on electrode FCz (Holroyd and Krigolson, 2007; Hajcak et al., 2006). Again, there is some variance in the primary electrode site with some researchers reporting the FRN/reward positivity more frontally at Fz (Van den Berg et al., 2011) while others have reported just posterior to FCz at Cz (Holroyd et al., 2008). Three, and not a necessity given the problematic nature of source localization (Luck, 2014), a source for the FRN/reward positivity should be within the anterior cingulate cortex (Bellebaum & Daum, 2008; Gehring and Willoughby, 2002; Gruendler et al., 2011; Hewig et al., 2007; Mathewson et al., 2008; Miltner et al., 1997; Potts et al., 2006a, 2006b; Ruchsow et al., 2002; Tucker et al., 2003; Walsh and Anderson, 2012; Zhou et al., 2010). As with the prior two statements, there is some variably in the reported source of the FRN/reward positivity with some researchers finding its origin to be within the posterior cingulate cortex (Badgaiyan and Posner, 1998; Cohen and Ranganath, 2007; Doñamayor et al., 2011; Luu et al., 2003; Müller et al., 2005; Nieuwenhuis et al., 2005). In summation however, when studying the FRN/reward positivity it is important to establish a timing and scalp topography, and potentially even a neural source, consistent with previous findings as per the Picton et al. (2000) guidelines for event-related potential research.

2.4. Quantification of the FRN/reward positivity and the use of difference waveforms

Quantifying the FRN/reward positivity can be challenging. However, if one embraces Luck (2014) then this problem is somewhat easier. Specifically, Luck proposes that we should focus our analyses on the underlying ERP components and not the conditional waveforms given that, as he states, there is nothing special about the local maxima and minima on the conditional waveforms. Thus, with Luck's position in mind, computing a difference waveform to examine the underlying feedback elicited component should be done when examining the FRN/reward positivity. A further advantage with the use of difference waveforms when examining the FRN/reward positivity stems from the aforementioned debate as to whether the component reflects a negative deflection of the incorrect feedback average waveform or a positive

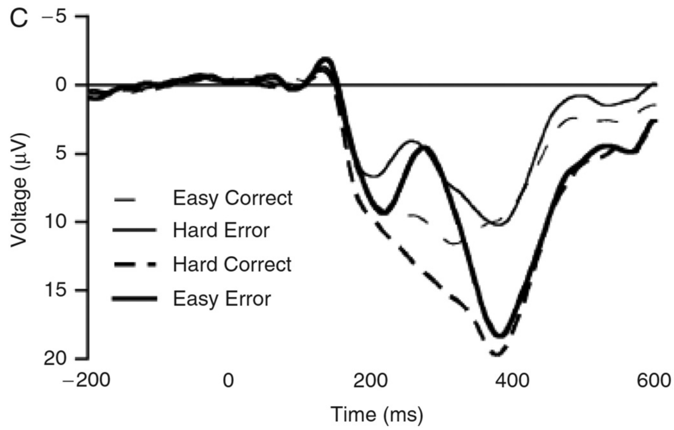

Fig. 5. The feedback related negativity in two conditions, one with frequency feedback and the other with infrequent feedback. Note here the slope of the positive aspect of the correct feedback waveforms in the time range of the feedback related negativity/reward positivity. The slope being almost a linear decrease in this time range makes peak detection on the correct conditional waveforms very problematic.
Reproduced with permission from Holroyd and Krigolson, 2007.

deflection of the correct feedback average waveform. Indeed, if one uses differences waveforms to examine the FRN/reward positivity then one does not have to decide which waveform or both should be used for peak quantification to perform statistical analyses as the use of a difference waveform renders the FRN/reward positivity argument moot – the use of a difference waveform makes the FRN the mirror opposite of the reward positivity (especially if one uses a mean voltage peak detection measure, see Fig. 3).

The use of difference waveforms is also warranted when one attempts to quantify the FRN/reward positivity for another key reason related to the actual morphology of conditional waveforms. Consider Fig. 5 and specifically the "hard correct" average positive waveform from Holroyd and Krigolson (2007). Where is the peak? Indeed, in this instance (and others, see below) a clearly defined peak is not visible on the conditional waveform thus making the implementation of global maxima, local maxima, or base to peak measures difficult.[3] Again the use of a difference waveform would be warranted here as it helps avoid the potential pitfalls of using global maxima, local maxima, or base-to-peak measures (see Luck, 2014) on a waveform without an easily identifiable maximum/minimum peak. While the reader may wonder if this is a unique data set, one has to look no further than the positive waveforms in Fig. 1 (Holroyd and Coles, 2002), Fig. 4 (Holroyd et al., 2008), or even the original figure highlighting the FRN in Miltner et al. (1997) and they will see that this problem of waveforms without an easily visible peak occurs somewhat frequently. Whether it is because one believes in the notion of underlying components (i.e., Luck, 2014), one wants to avoid or is unsure of the FRN/reward positivity debate, or one has waveforms wherein peak identification is difficult, when examining the FRN/reward positivity the use of difference waveforms is warranted. On that note, given the recommendations of Luck (2014) and what has already been stated here it also makes sense to use a mean peak quantification approach as opposed to the use of minima, maxima, or base-to-peak measures (also see Picton et al., 2000) when examining the FRN/reward positivity.

2.5. Frequency contamination: the N200

When designing an experiment with purpose of using EEG to examine feedback processing, it is important to appreciate that the timing of the FRN/reward positivity occurs coincidentally with the N200 ERP component (Holroyd, 2004).[4] It is well established that the N200 ERP component is sensitive to stimulus frequency (Patel and Azzam, 2005; Squires et al., 1975). For instance, most studies of the visual oddball paradigm have reported that the N200 (in addition to the P300) is sensitive to stimulus frequency (Patel and Azzam, 2005; Towey et al., 1980). The coincident timing of the N200 and the FRN/reward positivity however create a potential problem for researchers studying reward processing. Specifically, if a researcher wishes to design a paradigm in which learning occurs, then it is reasonable to expect that the relative frequency of positive and negative feedback will change over time. In other words, if participants improve as one would expect at task performance (e.g., the Power Law of Practice: Fitts and Posner, 1967) then the relative frequency of positive and negative feedback will change. However, as the relative frequency of feedback changes a problem occurs – if one wishes to create average ERP waveforms wherein the number of trials going into the positive and negative average ERP waveforms differ due to a relative change in feedback occurrence, then any visible difference between the positive and negative average ERP waveforms may simply be due to modulation of the underlying N200 ERP component. It is important to note that one cannot simply remove a number of trials from whatever bin of trials is "larger" – the frequency issue is in part brought about by the number of trials included in the average but more importantly occurs because of the actual difference in the frequency of the stimuli. In other words, the frequency sensitivity of the N200 reflects an underlying cognitive process and is not simply a manifestation of the number of trials going into the averaging process.

In their seminal work, Miltner et al. (1997) avoided this potential frequency contamination issue brought about by learning with their task design. Specifically, in their initial version of the time estimation paradigm participants had to guess the duration of 1000 ms second but within a ± 100 ms bandwidth. However, each time a participant guessed correctly this bandwidth was reduced by 10 ms and each time a participant guessed incorrectly this bandwidth was increased by 10 ms. The result of this manipulation had an important consequence – over the course of the experiment the relative number of correct and incorrect guesses remained relatively constant. Indeed, in this manner the average waveforms are protected from N200 contamination. However, to escape the frequency issue other researchers have relied on gambling paradigms wherein "unbeknownst to participants" the "game" was fixed such that outcomes were equiprobable. While this may seem like a logical and simple solution – there is a problem with this approach, which is outlined in a subsequent section – it seems that the amplitude of the FRN/reward positivity is impacted by the degree to which participants have control over their actions and the respective outcomes (see below). In sum, when studying the FRN/reward positivity it is important to be aware of the N200 frequency contamination issue and to account for this by using tasks wherein the frequency of correct and incorrect outcomes is equivalent or to use experimental paradigms within which the task itself balances the outcome probabilities (i.e., Miltner et al., 1997).

2.6. Component contamination: the P300

As with the N200, it is important to realize that the FRN/reward positivity can be impacted by changes in amplitude of the subsequent P300 component. Indeed, the P300 ERP component is also known to be sensitive to stimulus frequency (Duncan-Johnson and Donchin, 1977) and as such changes in amplitude of this component may simply be frequency related. Given this, and the temporal proximity of the P300 to the FRN/reward positivity, if an experimental paradigm does not equate outcome probability (win/loss or correct/incorrect) then any changes in the amplitude of the FRN/reward positivity may simply be

[3] It is worth nothing that a mean peak detection measure would potentially fail here as well.

[4] Indeed, some have posited that the FRN/reward positivity is simply a modulation of the N200 component – see Holroyd (2004) for full review.

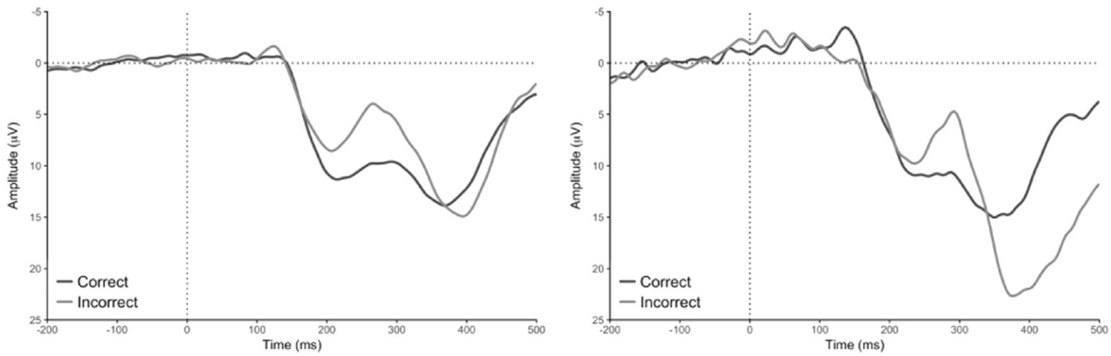

Fig. 6. Grand average correct and incorrect feedback waveforms. Note the impact of the P300 on the feedback related negativity/reward positivity in the right panel relative to the left panel.

due to changes in amplitude of the P300 component (see Fig. 6). Put another way, a large amplitude change in the P300 may have a carry-over effect on the FRN/reward positivity that "pulls down" the amplitude of the preceding component. Thus, as with the issue of N200 contamination it is important to realize that frequency issues may also bias the amplitude of the FRN/reward positivity through changes in the amplitude of the P300 ERP component.

Another factor to consider with regard to the P300 when examining the FRN/reward positivity is the relative roles of these two components in reward processing. While there is still considerable debate about what the FRN/reward positivity is encoding, the general consensus within the literature is that the FRN/reward positivity is encoding the outcome of an event (see Walsh and Anderson, 2012; see also Sambrook and Goslin, 2015) whereas the P300 is encoding reward/outcome magnitude (Yeung and Sanfey, 2004; Wu and Zhou, 2009). For example, for a given trial in a gambling paradigm it appears that the FRN/reward positivity is encoding whether the trial was won or lost whereas the P300 is encoding the relative amount that was won or lost. No matter what the "truth" is – as it is still an open question – it is important to consider the impact of the and the interaction between the FRN/reward positivity and the P300 when examining human reward processing with electroencephalography. A potential solution that may assist with dealing with P300 component overlap issues would be to use principal or independent component analysis to separate the underlying neural components - see Dien (2010) and Foti et al. (2009, 2011) for more detail on these methodologies.

2.7. Feedback timing and its impact on the amplitude of the FRN/reward positivity

Another issue that researchers need to be aware of when examining the FRN/reward positivity relates to the timing of the feedback stimulus itself. Indeed, from a behaviour learning perspective it is quite well known that for feedback to be effective there needs to be a delay between the end of a given action and the onset of feedback (e.g., Lorge and Thorndike, 1935). The impact of feedback timing has been studied with regard to the FRN/reward positivity and as such when designing experiments it is important to take into account the temporal occurrence of a feedback stimulus following an action. For example, Bismark et al., 2013 found that a FRN was not elicited when feedback immediately followed a response – a result that they suggested occurred because there was insufficient time for an expectation of the outcome to develop. In a related manner, Weinberg et al. (2012) investigated the impact of delayed feedback on the amplitude of the FRN/reward positivity. In their paradigm, participants played a forced choice gambling game in which outcome feedback was provided either 1 s or 6 s after response selection. Interestingly, Weinberg et al. found that the amplitude of the FRN was greatly diminished when feedback was provided 6 s after action selection relative to when it was provided 1 s after action selection. Recently, this finding was replicated by Arbel et al. (2017) who also found that delayed feedback (6.5 s versus 0.5 s) resulted in a reduction in the amplitude of the FRN/reward positivity. Together, these findings suggest that the timing of feedback impacts the amplitude of the FRN/reward positivity – feedback that occurs immediately or after a delay (at least 6 s) results in a reduction in the amplitude of the FRN/reward positivity. As such, the timing onset of feedback is a factor that also needs to be considered when designing experiments examining the FRN/reward positivity.

2.8. The impaction of action on the FRN/reward positivity

From a reinforcement learning perspective, the purpose of learning signals is to modify the value of antecedent actions thus optimizing decision-making behaviour by increasing the expected value of choices that lead to rewards (i.e., Rescorla and Wagner, 1972; Sutton and Barto, 1998). While it is beyond the scope of this review to argue whether or not the FRN/reward positivity reflects a reinforcement learning prediction error signals (e.g., Holroyd and Coles, 2002: see Walsh and Anderson, 2012), what is pertinent for discussion is the impact or necessity of preceding actions and/or cues on the generation of a FRN/reward positivity. In other words - is the generation of a FRN/reward positivity contingent upon there being a preceding action or choice? Interestingly, some researchers have found that a preceding action or choice is not needed for feedback to elicit a FRN/reward positivity. For example, Potts et al. (2006a, 2006b) had participants passively view a series of cues that predicted subsequent rewards and losses and found that a FRN was elicited by loss outcomes even though participants made no overt action or choice that led to the loss. As such, one might conclude that the process that leads to the generation of a FRN/reward positivity is not yoked to a specific preceding behavioural action.

However, a large body of evidence suggests that the amplitude of the FRN/reward positivity is greater when experimental participants are required to make an active choice (Holroyd et al., 2009; Martin and Potts, 2011; Yeung et al., 2005). For example, Yeung and colleagues directly compared the amplitude of the FRN between two experiments, one in which participants did not have to make a response and another in which they did. The results of this comparison demonstrated that the amplitude of the FRN was greater in the task in which participants had to make an overt response. Indirect support for the enhancement of the FRN/reward positivity when it is yoked to a preceding action comes from work wherein the amplitude of the FRN was examined in an observational learning paradigm. Specifically, Bellebaum et al. (2010) found that the amplitude of the FRN was reduced for those observing task related feedback for another as opposed to those who were actively involved in task performance. In any event, the majority of research suggests that an action is either required for a FRN/reward positivity to be observed or at the very least that the process underlying the generation of the FRN/reward positivity is reduced if the feedback evoked response is not related to a preceding action. Again, it is important for those wishing to study the FRN/reward positivity to consider the impact of choice on the amplitude of this ERP component and to potentially adjust their paradigms on this basis.

2.9. Intention and the amplitude of the FRN/reward positivity

Another factor to be considered when examining the FRN/reward positivity related to the aforementioned issue of action is the learnability of the task itself. Specifically, a key issue is whether or not the task itself can be learned and how this impacts the amplitude of the FRN/reward positivity. Given the issues with frequency contamination and the amplitude of the FRN/reward positivity (again, see above), some researchers have adopted paradigms in which they control for outcome probability (e.g., Holroyd et al., 2009). Specifically, the task structure is such that no matter what the participant does the outcomes probabilities are fixed (e.g., 50/50 or some other deterministic percentage ratio). While this manipulation has the benefit or removing N200/P300 frequency contamination from interpretation of the FRN/reward positivity it also makes the task not learnable as the outcomes for any choice are random. With this in mind, it is important to realize that the literature suggests that unlearnable tasks yield a smaller FRN/reward positivity. For instance, Holroyd et al. (2009) conducted three experiments in which participants selected from a series of doors in order to win small financial rewards. When the results of the gambling outcomes were compared across all three experiments, the researchers found that the FRN/reward positivity was greater when a given task was learnable as opposed to when it was not. In other words then, when using tasks that are not learnable to study the reward positivity the task itself may impact the amplitude of the FRN/reward positivity.

Given that the learnability of a task impacts the amplitude of the FRN/reward positivity but at the same time one has to be concerned about frequency contamination issues what does one do? Recently, Hassall and Krigolson (2013) (see also Hassall, 2013; Krigolson et al., 2017) designed a version of the standard door selection gambling task to make it learnable while at the same time equating outcome probabilities to avoid frequency contamination of the N200 and P300. Within this version of the task, participants complete multiple blocks of 20 trials of the task. On each trial, participants select from one of two differently coloured presented doors and either win or lose a financial reward. The key manipulation entails the relative probabilities of winning and losing when selecting each door. For one of the doors, the win/loss ratio is 60/40 whereas for the other door the win/loss ratio is 10/90. Over the course of the experiment, on average, assuming participants behave normally,[5] the overall win/loss ratio is approximately 50/50. However, and importantly, within each block the task is learnable – one of the doors is “better” than the other and as such over trials one should see a shift from a chance door selection ratio to a shift towards selecting the 60/40 door on a greater percentage of trials than the 10/90 door. As such, one can plot learning curves and show an increase in the percent of times the optimal door is selected and thus the task is “learnable”. Given the nature of the task, the researcher can also provide feedback after each block about performance accuracy after each experimental block which may also motivate participants and thus yield better experimental results (see Threadgill and Gable, 2016). With all of this in mind, it may be worthwhile for researchers who want to study the FRN/reward positivity to use a learnable task in their experiments.

2.10. Learning related changes in the FRN/reward positivity

Given the aforementioned discussion of the importance of action and intention on the amplitude of the FRN/reward positivity it is important to realize that if the component does truly reflect an underlying learning process then the amplitude of the component will be sensitive to learning (see Fig. 7). For instance, Krigolson, Pierce, Tanaka, and Holroyd (2009) demonstrated that the amplitude of the FRN diminished with learning for participants who were able to learn a perceptual expertise task. Paralleling this, Krigolson et al. (2014) reported that the amplitude of the reward positivity diminished with learning in a stimulus – response association task. Others have found this same result, the amplitude of the FRN/reward positivity diminishes with learning (Bellebaum and Colosio, 2014; Bellebaum and Daum, 2008; Eppinger et al., 2008; Luque et al., 2012; Sailer et al., 2010; Walsh and Anderson, 2012). In terms of experimental design and analysis, it is important to take learning related changes in the amplitude of the FRN/reward positivity into consideration. Imagine if you will a task that is very easy to learn but that is performed for a long period of time. Presumably the amplitude of the FRN/reward positivity would appear diminished simply because of task duration as participants would have quickly learned the correct actions and component amplitude would be reduced as a result of this. Another example would be a situation in which two different groups performed the same task but learned the task at different rates. Again, the amplitude of the FRN/reward positivity might be identical for both groups in reality but because of differences in learning rates the amplitude of the component might appear diminished for one group relative to the other leading to an inaccurate interpretation of the data.

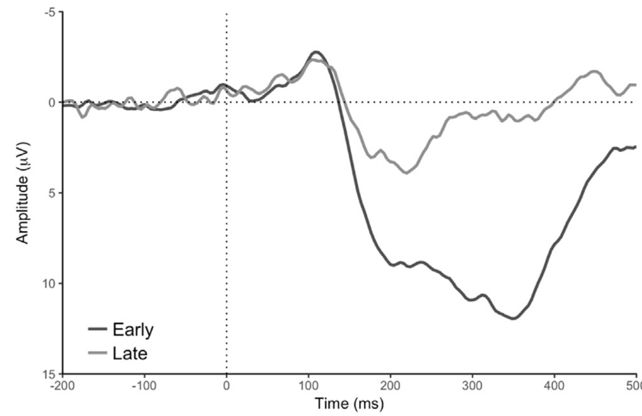

Fig. 7. Grand average correct feedback waveforms from early versus late stages of learning. The change in amplitude is obvious and quite pronounced.

When examining the FRN/reward positivity it is important to perform within-experiment temporal analyses to ensure that either the amplitude of the component is stable across task duration, or changes in component amplitude with learning are taken into account when interpreting the experimental results. At times, this can be difficult as if learning does occur then there will be a change in the number of error trials available for analysis. However, this problem can be addressed. For example, in Krigolson et al. (2014) the authors examined changes in the amplitude of the reward positivity over time. Given the lack of error trials in the later stages of learning the authors used the following approach. First, the authors demonstrated the existence of the reward positivity in the early stages of learning by showing and statistically verifying a difference between the incorrect and correct grand average waveforms in the reward positivity time range. Next, the authors scored the reward positivity as the mean voltage only on the correct average waveforms for subsequent blocks of trials using the timing of the reward positivity that they had observed in the initial stages of learning to demonstrate a decrease in the amplitude of the reward positivity with learning across all experimental blocks.[6] Given this decrease in

[5] Normal here refers to participants that are trying to learn the task. In this specific case, they should learn to pick the door that pays 60% of the time as opposed to 10% of the time.

[6] This is a departure from the recommendation for using difference waveforms. However, given the absence of incorrect trials there is not much that one can do. With that said, a difference waveform was used to guide the analysis.

Table 1
Summary of methodological consideration, problems/caveats, and solutions when examining the FRN/reward positivity.

Methodological consideration	Problems/Caveats	Solution
Component naming	Confusion with the ERN	Have a clear statement that a feedback locked ERP component is being measured
		Use consistent naming and/or the original name (FRN)
	Numerous names used (FRN, fERN, FN, MFN, RewP, CRP)	
Reward positivity	Confusion about whether the component is a negative deflection or a positive deflection	Acknowledgment of and/or agreement with the issue
Identification, timing, source	Component identified is not clearly a FRN/reward positivity	Ensure component is feedback locked
		Ensure peak timing of 250 to 350 ms
		Ensure medial-frontal topography (maximal at FCz)
Component quantification	Problems with the statistical analysis of the component	Use of difference waveforms
		Use of mean peak quantification measures
Frequency contamination	Component amplitude may be influenced by stimulus frequency	Only compare outcomes (win/loss) with equivalent probabilities
Component contamination	Component overlap with the P300	Modify paradigm to minimize changes in the P300
		Use PCA/ICA to isolate medial-frontal activity
Feedback timing	Component is impacted by feedback timing	Ensure feedback is not provided too soon (less than 500 ms) or too late (greater than 5000 ms)
Impact of action	Component may be yoked to a preceding action	Awareness of the issue – potentially ensure an action is required of participants
Impact of intention	Component may be impacted by learnability of the task	Potentially modify experimental paradigms so they are learnable
Learning related changes	Component amplitude changes with learning	Do not average across all trials, use averages for experimental blocks in addition to collapsing averages across the whole experiment

amplitude with learning, and similar results reported by others, it is then important to take learning related changes in component amplitude into account when examining the FRN/reward positivity.

3. Conclusions and future directions

There is a growing interest in the study of human reward processing using electroencephalography which is evident in the increase in the number of publications citing the FRN/reward positivity in recent years. Given this increase in interest, it is important that researchers are aware that there are several methodological considerations that must be taken into account when studying the FRN/reward positivity as outlined here (see Table 1 for a summary). While I am not suggesting that everyone should follow the approaches outlined here precisely, as in part, it reflects an opinion – albeit evidence based - it is becoming more apparent that we as researchers need to be more consistent and open with our methodologies. For example, the detailed steps of analysis utilized in the Krigolson Laboratory are available to all here http://www.neuroeconlab.com/data-analysis.html and are provided in an attempt to improve the transparency of our research. The Picton et al. (2000) paper was a seminal attempt to provide guidelines for all researchers using the ERP methodology as is the Luck (2014) book. However, to date, there has been no consistent attempt to enforce these suggestions and those outlined here. While in an ideal world all researchers examining the FRN/reward positivity would use common methodology, at a bare minimum, it is important that researchers be aware of the potential issues outlined here when examining the FRN/reward positivity and be open and transparent in their methodologies.

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