



previous judgment or expectancy stored in memory against the newly available information. For example, when we think we recognize a friend from distance we might want to approach and greet him. Only when we come closer do we see details of his face and realize that he is not the expected person. During the time between seeing the individual from afar and approaching him, we form expectations toward meeting a particular person based on partial information; the later implicit comparison between the new information and the initial expectation allows us to see whether our initial expectation or judgment was correct. It is not clear to what extent the pattern of brain responses to the new, complex feedback information is affected by the result of comparison (i.e., the consistency between the initial judgment or expectation and new information) and by the neurocognitive processes associated with the complex feedback stimulus itself.

The main purpose of this study is to investigate to what extent the neural correlates of the (implicit) outcome evaluation involving complex feedback stimuli (e.g., faces) are similar to those revealed for simple feedback in gambling or simple cognitive tasks. Answers to this question may open a new avenue for the use of the ERP technique to investigate the neural basis of outcome evaluation and performance monitoring in more complex, including social, situations. To mimic a situation in which limited information is available for decision-making and the feedback stimuli require sophisticated processing, we blurred photos of female faces and asked participants to judge whether a presented female face was attractive or unattractive. Photos of unblurred faces were presented as feedback and ERPs time-locked to the onset of the feedback were measured. Facial attractiveness is a key feature in social interactions, such as peer and mate choice (Etcoff, 1999; Thornhill and Gangestad, 1999; Johnston, 2006) and inferences about that individual's personality (Dion et al., 1972). If participants did make (implicit) comparisons between newly available information and previous judgments, then the feedback faces would carry information concerning the valence of feedback (consistent vs. inconsistent with the initial judgment), in addition to information concerning facial attractiveness. The processing of the social aspect of the feedback faces (i.e., attractiveness) becomes a necessary step in deciding whether the initial judgment or guess was right. A previous study found that the ventral occipital region including the fusiform face area (FFA) shows differential responses to attractive and unattractive faces even when the task is beauty-irrelevant (e.g., in an identity judgment task), indicating that facial attractiveness may be processed automatically (Chatterjee et al., 2009).

If the neural correlates of outcome evaluation for complex feedback stimuli with a social dimension are similar to those revealed for simple stimuli, inconsistent faces (those whose attractiveness is inconsistent with the initial judgment) should show an FRN effect relative to consistent faces. On the other hand, previous studies demonstrated that the P100 is sensitive to the reward valence in monetary gambling tasks (Hajcak et al., 2005, 2007; Wu and Zhou, 2009; Leng and Zhou, 2010), with more positive amplitudes for positive feedback than for negative feedback. If so, the P100 should be more positive to feedback faces consistent with the initial judgment than to faces inconsistent with the judgment. Moreover, previous studies also showed that ERP responses are

more positive to attractive faces than to unattractive faces on late positive potential (LPP) or P100 (Johnston and Oliver-Rodriguez, 1997; Oliver-Rodriguez et al., 1999; Werheid et al., 2007; Schacht et al., 2008). We, therefore, predict a P100 or LPP effect for facial attractiveness in this study.

## METHOD

### PARTICIPANTS

Sixteen right-handed undergraduate students (eight females, 18–24 years, mean = 21) from Peking University participated in the experiment. All the participants had normal or corrected-to-normal vision, and had no history of neurological, psychiatric, or cognitive disorders. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Academic Committee of the Department of Psychology, Peking University.

### DESIGN AND MATERIALS

This experiment had a 2 by 2 factorial design, with the first experimental factor (consistency: consistent vs. inconsistent) referring to whether the attractiveness of feedback faces were consistent with the initial judgment and the second experimental factor (attractiveness: attractive vs. unattractive) referring to the facial attractiveness of the feedback faces. The experiment included pre-test, EEG test, and post-test. In the pre-test, 170 attractive and 170 unattractive gray-scale photos of female faces were selected from the photo pools of Peking University and the Institute of Psychology, Chinese Academy of Sciences, based on a consistent rating of above five or below three on a seven-point scale by 20 participants who did not participate in the EEG test. The experimental stimuli in the EEG test comprised of five attractive and five unattractive blurred female faces and the 170 attractive and 170 unattractive unblurred female faces used in the pre-test. Given that there were variable ratings as to whether particular male faces were attractive, we did not include male faces in this study. The attractiveness of unblurred female faces was confirmed in which the EEG participants were asked to rate these faces in the same way as the pre-test. Both the attractive and unattractive faces were unfamiliar to the EEG participants to exclude the influence of familiarity.

We adjusted all photos to be approximately 218 pixels in width (SD = 10.1 pixels) and 274 pixels in height (SD = 4.6 pixels), centered on a 260 pixels × 280 pixels black background. The brightness of all photos was adjusted to about 97.8 (SD = 6.0) as indicated in the histogram after undergoing the “auto levels” function on Adobe Photoshop CS2. Five attractive and five unattractive faces were blurred by Gaussian filters with  $\sigma = 14$  pixels, maintaining all frequencies below four cycles per photo width.

In each trial in the EEG test, participants were instructed to guess the attractiveness of a blurred face, and to simply watch the subsequent unblurred face, which served as implicit feedback to the consistency of the initial judgment. The blurred faces were presented randomly while the 170 attractive and the 170 unattractive feedback faces were presented in pseudo-random orders. For each participant, each of the blurred faces was presented 14 times and each of the attractive or unattractive faces was presented only once, with the restriction that no more than three consecutive

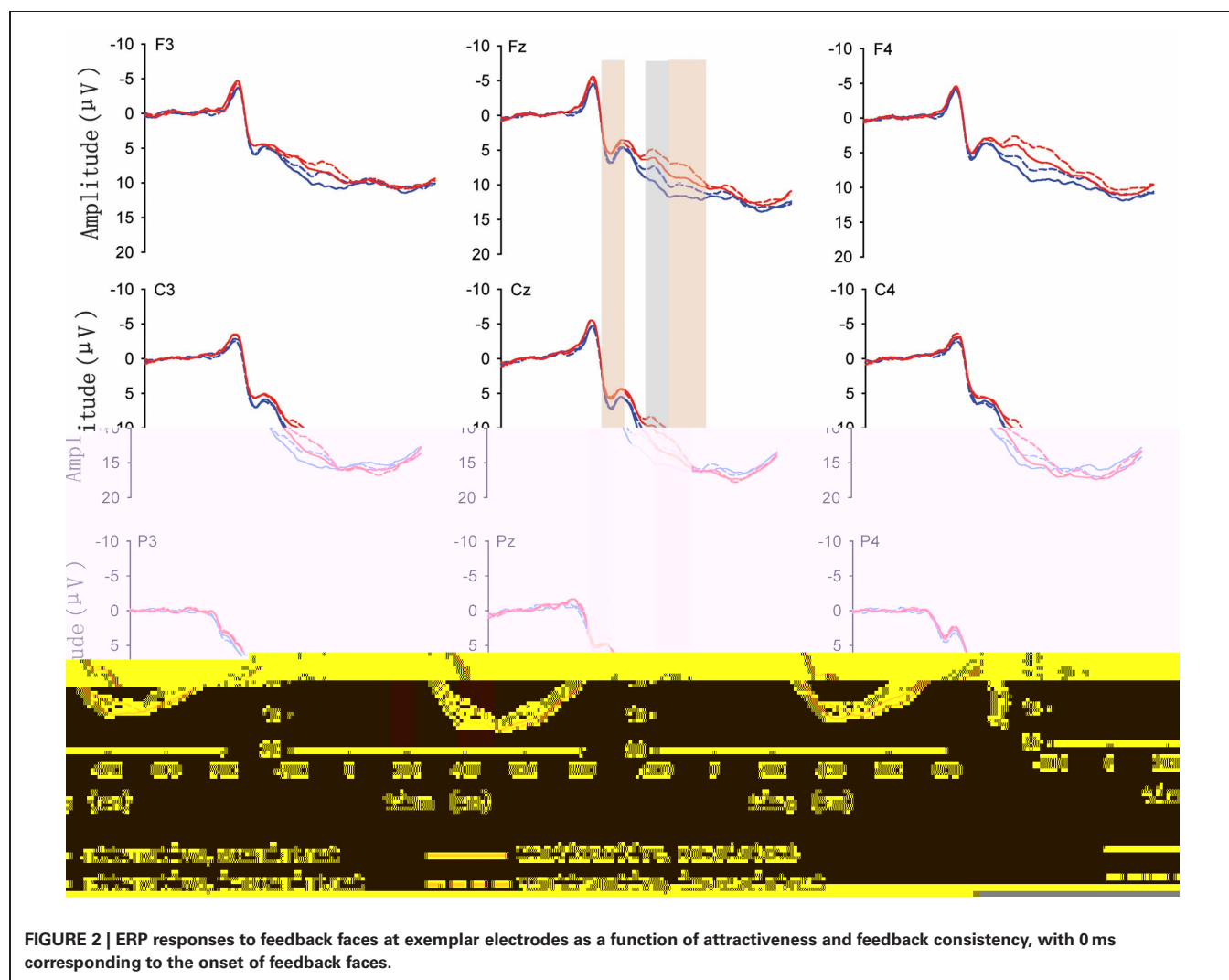
feedback faces were from the same category. Different pseudo-random orders were created for different participants. Unknown to the participants, the blurred face in each trial was not the same one as the feedback face. The purpose of this manipulation was to exclude the potential influence of the blurred faces on the percep-

algorithm which employs a regression analysis in combination with artifact averaging (Semlitsch et al., 1986). Epochs contaminated by blinks and other movement artifacts were excluded from averaging using an  $80\ \mu\text{V}$  criterion. The EEG data were low-pass filtered at  $30\ \text{Hz}$  and were baseline-corrected by subtracting the average activity of that electrode during the baseline period from each trial. After excluding trials with artifacts, each participant had at least 46 trials in each condition.

The grand-average ERP waveforms (**Figure 2**) did not show a typical pattern for ERP responses that were observed for feedback stimuli in gambling or simple cognitive tasks (e.g., no clear P<sub>300</sub> component was visible), although it appeared that inconsistent faces elicited negative-going deflections in the  $100\text{--}300\ \text{ms}$  time window. We, therefore, analyzed ERP responses in different conditions in the windows of  $150\text{--}220\ \text{ms}$  (i.e., P<sub>200</sub>),  $100\text{--}300\ \text{ms}$  (i.e., FRN), and  $300\text{--}500\ \text{ms}$  based on visual inspection. For the purposes of statistical analysis, mean amplitudes for each time window was calculated across 25 electrode locations (F<sub>3</sub>, F<sub>1</sub>, F<sub>z</sub>, F<sub>2</sub>, F<sub>4</sub>, FC<sub>3</sub>, FC<sub>1</sub>, FC<sub>z</sub>, FC<sub>2</sub>, FC<sub>4</sub>, C<sub>3</sub>, C<sub>1</sub>, C<sub>z</sub>, C<sub>2</sub>, C<sub>4</sub>, CP<sub>3</sub>, CP<sub>1</sub>, CP<sub>z</sub>, CP<sub>2</sub>, CP<sub>4</sub>, P<sub>3</sub>, P<sub>1</sub>, P<sub>z</sub>, P<sub>2</sub>, P<sub>4</sub>) that were chosen to

cover scalp areas known from previous studies to be the focus of the FRN and P<sub>300</sub>. A repeated-measures analysis of variance (ANOVA) was conducted, with attractiveness (attractive vs. unattractive), feedback consistency (consistent vs. inconsistent), anterior-posterior scalp location (frontal, frontocentral, central, centroparietal, parietal), and lateral scalp location (left, left central, midline, right central, right) as four within-subjects experimental factors. The Greenhouse-Geisser correction for violation of the ANOVA assumption of sphericity was applied in all analysis. Bonferroni corrections were used for multiple comparisons.

Given that the processing of the feedback faces and their attractiveness was likely to involve sophisticated neurocognitive processes, it is possible that the FRN and the P<sub>300</sub> components were not only overlapping in the time course, but also masked by other cognitive (and emotional) processes associated with the complex feedback stimuli. To examine whether the typical P<sub>300</sub> effects that were observed in previous studies for various aspects of the outcome evaluation could also be observed for the more complex feedback faces, we performed principal-component analysis



(PCA) on the *cleaned* ERP data (i.e., after preprocessing) in order to disentangle the overlapping and/or masked ERP components. PCA has a wide range of applications in ERP analysis, such as cleaning or filtering noises prior to data analysis, or being used in data exploration as a way to detect and summarize features of the dataset. In this study, we applied PCA on the cleaned ERP data to maximize the possibility that the PCA factors represent interpretable signals (i.e., brain activity due to experimental manipulations) as opposed to noise (i.e., artifacts or background EEG).

PCA is a common approach for decomposing an ERP dataset into its constituent factors by summarizing the relationship between variables (such as microvolt recordings at each time point in temporal PCA or at each electrode in spatial PCA; Dien and Frishkoff, 2005; Dien et al., 2005). This process consists of three main steps: (1) computation of the covariance matrix which captures the interrelationships between temporal/spatial variables; (2) extraction and retention of the PCA factors which extract linear combinations of variables (latent factors) to account for patterns of covariance in the ERP data with the fewest PCA factors; and (3) rotation to simple structure, which is used to restructure the allocation of variables to PCA factors to maximize the chance that each PCA factor reflects a single ERP component. These steps yield two matrices, which are useful in further analysis. The first one is a factor loading matrix, representing correlations between the variables and the factor scores (e.g., describing the time course of each of the PCA factors in temporal PCA). The second one is a factor score matrix that indexes the magnitude of the PCA factors for each of the observations, reflecting the contribution of each PCA factor to ERPs.

In this study, we used the spatiotemporal PCA algorithm implemented in the Matlab ERP PCA toolbox 2.2.3 (Dien and Frishkoff, 2005; <http://sourceforge.net/projects/erp-pca-toolkit/files>). In the spatiotemporal PCA, a spatial PCA was performed first on the ERP data from all the electrodes to capture spatial distribution, with the combination of 501 time points (covering the epoch from -200 to 800 ms post-onset of the feedback stimuli), 16 participants and four experimental conditions. Infomax rotation was used, and two spatial factors were extracted based on the resulting Scree plot. For each spatial factor, this analysis yielded factor scores for each combination, representing the amount of activity in the original data captured by that factor. A temporal PCA was then performed for each of the two spatial factors. Promax rotation was used, and four temporal factors were extracted based on the Scree plot, yielding eight unique factors combinations (i.e., two spatial factors by four temporal factors). The covariance relationship matrix and Kaiser normalization were used for each PCA. The waveforms for each factor combination were reconstructed (i.e., converted to microvolts) by multiplying the factor pattern matrix with the standard deviations. A PCA factor may contain one or more known ERP components, or may contain no well-defined or theoretically interesting ERP components. Following the suggestion of Dien et al. (2005) and based on visual inspection of the waveforms associated with each PCA factor, two factors that contained known ERP components involved in outcome evaluation and facial attractiveness (i.e., P100) were selected

for further statistical analysis, with attractiveness (attractive vs. unattractive) and feedback consistency (consistent vs. inconsistent) as two within-subjects experimental factors. Here we focused on electrodes that showed the largest effect for each selected PCA factor. The Greenhouse–Geisser correction was applied for violation of the ANOVA assumption of sphericity.

## RESULTS

### BEHAVIORAL RESULTS

In the post-test on the attractiveness of the feedback faces, 37 trials (6.9%) in total were inconsistent with the categorization of attractiveness based on the pretest (i.e., their rating scores were below five for attractive faces or above three for unattractive faces). After excluding the EEG trials corresponding to these faces, the remaining 506 trials were categorized into four conditions: attractive-consistent (72 trials per participant on average, ranging from 51 to 117 trials over participants), attractive-inconsistent (78 trials on average, ranging from 48 to 100 trials), unattractive-consistent (91 trials on average, ranging from 61 to 117 trials), and unattractive-inconsistent (76 trials on average, ranging from 48 to 107 trials). Overall, the percentage of trials (out of all the available trials) for each condition was 22.6%, 24.5%, 28.9%, and 24.0%, respectively. No statistically significant differences were found between the conditions.

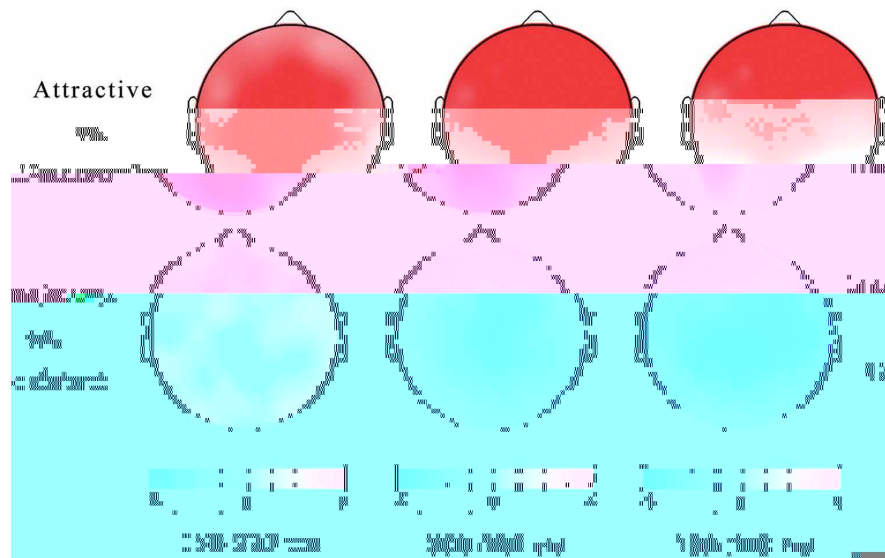
### ERP RESULTS

ERP waveforms time-locked to the onset of feedback faces and topographic distributions of the differences between conditions (e.g., ERP effects) in three time windows are illustrated in **Figures 2** and **3**, respectively.

For the 150–220 ms time window (**Figures 2, 3**), repeated-measures ANOVA showed a significant main effect of attractiveness,  $F(1,15) = 18.39$ ,  $p = 0.01$ , with more positive P200 responses to attractive faces ( $5.95 \mu V$ ) than to unattractive ones ( $4.98 \mu V$ ). The interaction between attractiveness and lateral scalp location was significant,  $F(4,60) = 5.17$ ,  $p = 0.001$ , indicating that the size of the P200 effect varied over different scalp locations. No other significant effects were found.

For the 300–380 ms window, ANOVA showed a significant main effect of feedback consistency,  $F(1,15) = 15.99$ ,  $p = 0.001$ , with ERP responses to feedback faces more negative-going following inconsistent judgments ( $9.97 \mu V$ ) than following consistent judgments ( $11.36 \mu V$ ). The main effect of attractiveness was also significant,  $F(1,15) = 20.48$ ,  $p < 0.001$ , with more negative-going responses to unattractive faces ( $9.56 \mu V$ ) than to attractive ones ( $11.78 \mu V$ ). The interaction between attractiveness and feedback consistency was not significant,  $F(1,15) < 1$ , indicating that the attractiveness effect was not affected by feedback consistency. The interaction between attractiveness and anterior-posterior scalp location was significant,  $F(4,60) = 17.66$ ,  $p < 0.001$ , as was the interaction between attractiveness and lateral scalp location,  $F(4,60) = 8.21$ ,  $p = 0.01$ . It is clear from **Figure 3** that the attractiveness effect in this time window was strongest in the frontocentral regions. No other significant effects were found.

To further verify the feedback consistency effect, we carried out statistical analyses based on peak-to-peak measurements of the feedback consistency responses (Sato et al., 2005; Wu and Zhou,



**FIGURE 3 |** Topographies of ERP effects in three time windows.

2009), with the most negative amplitudes in the 100–180 ms window and the most positive amplitudes in the 220–300 ms window as peaks. Consistent with the above analysis, the main effect of feedback consistency was significant,  $F(1,15) = 15.38$ ,  $p = 0.001$ , and this effect did not interact with attractiveness,  $F(1,15) < 1$ . The main effect of attractiveness was significant,  $F(1,15) = 20.51$ ,  $p < 0.001$ .

For the 380–500 ms window, ANOVA showed a significant main effect of attractiveness,  $F(1,15) = 11.11$ ,  $p < 0.01$ , with



**FIGURE 4 | ERP responses on the exemplar electrodes converted from factor scores in the spatiotemporal PCA and depicted as a function of attractiveness and feedback consistency.** Topographic maps on the right

side present the differential responses corresponding to the factors depicted on the left. Sketches in the upper and lower panels correspond to the first and the second selected spatiotemporal factors, respectively.

information would indicate whether the feedback stimuli had properties consistent or inconsistent with the initial judgment.

An FRN effect was observed for inconsistent feedback faces in ERP waveforms, in accordance with many earlier studies (Gehring and Willoughby, 2002; Holroyd and Coles, 2002; Yeung et al., 2005; Leng and Zhou, 2010; Zhou et al., 2010; Long et al., 2012), albeit in a delayed 100–180 ms time window. Faces inconsistent with the initial judgment elicited more negative-going responses than faces consistent with the judgment. The delay of the FRN effect was likely due to the complexity of neurocognitive processes involved in facial attractiveness and feedback consistency processing. To know whether the initial judgment or guess was a correct one, the system has to first process the perceptual structure of the feedback face, and evaluate the attractiveness of this face by appealing to experiences or schemas stored in long-term memory, and secondly to compare the result of this evaluation with information concerning the initial judgment stored in working memory. It takes time to accomplish these processes, delaying the appearance of the FRN effect, even though assessing facial attractiveness can be fairly automatic (Chatterjee et al., 2009). A previous study has also shown that the FRN effect was delayed when the sophisticated counter-factual thinking was involved in accessing the outcome valence of gambling choices (Yu and Zhou, 2009).

However, the ERP waveforms did not show the typical pattern of P100 responses; instead, sustained deflections were observed, with significant main effects for attractiveness and feedback consistency. We suspected that the usual P100 responses were masked by the sophisticated cognitive (and emotional) processes involved

in processing the feedback faces, and the observed deflections (and possibly the preceding ERP responses) contained P100 components. We, therefore, conducted spatiotemporal PCA, which revealed a clear pattern of P100 effects for both feedback consistency and attractiveness, with more positive responses to those faces consistent with the initial judgment than to faces inconsistent with the judgment, and more positive responses to attractive faces than to unattractive ones. Moreover, the P100 effects centered on centroparietal areas lasted for a short time period while the P100 effects centered on frontocentral area sustained for a long time period, indicating that facial attractiveness and feedback consistency could be processed parallel in different brain areas.

The P100 effect for feedback consistency or valence replicated previous studies using gambling tasks (Hajcak et al., 2005, 2007; Wu and Zhou, 2009; Leng and Zhou, 2010). The P100 effect for facial attractiveness also replicated many previous studies (Johnston and Oliver-Rodriguez, 1997; Oliver-Rodriguez et al., 1999; Werheid et al., 2007; Schacht et al., 2008). As attractive faces activate brain areas dedicated to reward processing such as the orbitofrontal cortex, the nucleus accumbens or the ventral striatum (Aharon et al., 2001; Kampe et al., 2001; O'Doherty et al., 2003; Bray and O'Doherty, 2007; Ishai, 2007; Winston et al., 2007; Cloutier et al., 2008), the attractive feedback faces in this study might be considered to be a form of reward, having stronger motivational significance, and capturing more attentional resources than unattractive faces (Sabatinelli et al., 2004). A large number of studies have already demonstrated that the P100 is sensitive to processes that demand attentional resources



(Polich and Kok, 1995; Polich, 2007). The independence between the P100 effect for feedback consistency and the effect for facial attractiveness, while replicating previous studies that simultaneously manipulated different dimensions of feedback stimuli (Hajcak et al., 2005, 2007; Wu and Zhou, 2009; Long et al., 2012), indicate that the evaluative processes for different dimensions of the outcome can be conducted in parallel.

Note that we also found a significant main effect of attractiveness in the 100–180 ms window. However, we do not interpret it as a kind of FRN effect because we believe this effect was very likely due to the spillover of the P100 effects for facial attractiveness.

To conclude, this study provides the first demonstration of electrophysiological responses in outcome evaluation with complex feedback stimuli (e.g., faces) that need complicated neurocognitive processing. We demonstrated that the ERP correlates of processing complex feedback stimuli with a social dimension are generally similar to those involved in processing simplex feedback stimuli; however, appropriate means of

ERP data analysis, including PCA, may be needed to uncover the underlying patterns of effects that might be masked by the sophisticated processes associated with the complex stimuli themselves. Consistent with previous studies, the present study demonstrates again that the FRN reflects early assessment of outcome valence while the P100 can encode different attributes of feedback simultaneously in outcome evaluation and performance monitoring.

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