

Performance monitoring of self and other in a turn-taking piano duet: A dual-EEG study

Madeline Huberth, Tysen Dauer, Chryssie Nanou, Irán Román, Nick Gang, Wisam Reid, Matthew Wright & Takako Fujioka

To cite this article: Madeline Huberth, Tysen Dauer, Chryssie Nanou, Irán Román, Nick Gang, Wisam Reid, Matthew Wright & Takako Fujioka (2018): Performance monitoring of self and other in a turn-taking piano duet: A dual-EEG study, *Social Neuroscience*, DOI: [10.1080/17470919.2018.1492968](https://doi.org/10.1080/17470919.2018.1492968)

To link to this article: <https://doi.org/10.1080/17470919.2018.1492968>



Accepted author version posted online: 24 Jun 2018.
Published online: 09 Jul 2018.



[Submit your article to this journal](#)



Article views: 121



[View Crossmark data](#)

ARTICLE



Performance monitoring of self and other in a turn-taking piano duet: A dual-EEG study

Madeline Huberth^a, Tysen Dauer^a, Chryssie Nanou^a, Irán Román^a, Nick Gang^a, Wisam Reid^a, Matthew Wright^a and Takako Fujioaka^{a,b}

^aCenter for Computer Research in Music and Acoustics, Department of Music, Stanford University, Stanford, CA, USA; ^bStanford Neurosciences Institute, Stanford University, Stanford, CA, USA

ABSTRACT

During joint action tasks, expectations for outcomes of one's own and other's actions are collectively monitored. Recent evidence suggests that trait empathy levels may also influence performance monitoring processes. The present study investigated how outcome expectation and empathy interact during a turn-taking piano duet task, using simultaneous electroencephalography (EEG) recording. During the performances, one note in each player's part was altered in pitch to elicit the feedback-related negativity (FRN) and subsequent P3 complex. Pianists memorized and performed pieces containing either a similar or dissimilar sequence as their partner. For additional blocks, pianists also played both sequence types with an audio-only computer partner. The FRN and P3a were larger in response to self than other, while P3b occurred only in response to self, suggesting greater online monitoring of self- compared to other-produced actions during turn-taking joint action. P3a was larger when pianists played a similar sequence as their partner. Finally, as trait empathy level increased, FRN in response to self decreased. This association was absent for FRN in response to other. This may reflect that highly-empathetic musicians during joint performance could use a strategy to suppress exclusive focus on self-monitoring.

ARTICLE HISTORY

Received 11 January 2018
Revised 16 May 2018
Published online 10 July 2018

KEYWORDS

Performance monitoring; electroencephalography (EEG); empathy; joint action; event-related potentials (ERPs)

Introduction

In everyday life, humans carry out tasks with others. Whether it be cooking with a partner, playing in a music ensemble, or cooperating to carry a heavy object, we monitor the actions of others and coordinate with them. In the past decade, studies in social cognitive neuroscience have investigated neural mechanisms of social interactions. Specifically, research examined how our predictions for both our own and another's actions, based on shared representations with integrated feedback, all enable the successful and flexible achievement of joint tasks (Sebanz, Bekkering, & Knöblich, 2006; Vesper et al., 2017). Further, factors such as knowledge about a partner's task and the social context of the task may influence action representations, revealing important sensitivities of our action representation system.

A key process in understanding and representing the actions of others is *performance monitoring*. According to the reinforcement-learning theory, performance monitoring reflects neural processes that are used to guide subsequent behavior (Holroyd & Coles, 2002), and can be based both on internal representations of actions and

subsequently-available external feedback (for a review, see Ullsperger, Fischer, Nigbur, & Endrass, 2014). Neural activity examined via event-related potentials (ERPs) in response to externally-provided feedback, especially when the feedback does not match the expected outcome, exhibits the frontocentral feedback-related negativity (FRN) occurring at ~200 msec latency, followed by a P3 complex with two subcomponents: the frontocentral P3a and parietal P3b. The FRN is thought to reflect prediction errors, and is sensitive to motivational salience (Talmi, Atkinson, & El-Derey, 2013) and goal relevance (Walentowska, Moors, Paul, & Pourtois, 2016), with the tendency to respond more strongly to worse-than-expected, compared to better-than-expected outcomes (Nieuwenhuis, Holroyd, Mol, & Coles, 2004). The subsequent P3 components are not specifically related to the feedback itself but relate generally to any perceptually significant stimulus processing. The first subcomponent P3a is typically elicited by either novel and highly deviant or task-irrelevant yet salient stimuli (Comerchero & Polich, 1999), reflecting early attentional, fast orienting neural processes that update frontal working memory. The later, more sustained P3b subcomponent, reflects

further cognitive processing of such stimulus events such as memory encoding or decision making (Polich, 2007).

When monitoring actions, brain responses to external feedback could occur for one's own actions, another's actions, or a joint action (e.g. Bellebaum, Kobza, Thiele, & Daum, 2010; Koban, Pourtois, Bediou, & Vuilleumier, 2012; Loehr, Kourtis, & Brazil, 2015). However, differences between the agencies have consistently been observed. When observing another person perform a task, FRN and P3 amplitudes are reduced, compared to when performing the task oneself (Bellebaum et al., 2010; Koban et al., 2012; Loehr et al., 2015; Yu & Zhou, 2006). Similarly, reduced control over one's own action outcomes reduces both FRN and P3 amplitudes (Li, Han, Lei, Holroyd, & Li, 2011; Li et al., 2010). Importantly, the FRN can be elicited even when the feedback is given a moment later, suggesting the prediction can be made and sustained for at least a couple of seconds (Chase, Swainson, Durham, Benham, & Cools, 2011; Loehr et al., 2015; Walentowska et al., 2016).

Performance monitoring can also reflect nuanced social contexts such as the animacy of an agent, as shown in Fukushima and Hiraki (2009), in which FRNs were larger when observing actions made by a human compared to a computer actor. Actor animacy related to action representation is, in fact, of wide interest in behavioral studies as well as human and animal neural studies regarding the mirror neuron system (MNS). Broadly, the MNS refers to a network of brain areas responding to both performed and perceived actions (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996; for a review, see Rizzolatti & Craighero, 2004). It is thought to help us understand the actions and intentions of other people (Iacoboni et al., 2005) and facilitate empathy (Iacoboni, 2009). Regarding actor animacy, studies reveal mixed results, including similar activation in the MNS for human and non-human movements (Cross, Ramsey, Liepelt, Prinz, & Hamilton, 2016; Gazzola, Rizzolatti, Wicker, & Keysers, 2007), that motor priming can be attenuated for non-human movements (Liepelt & Brass, 2010; Press, Gillmeister, & Heyes, 2007), and still others find effects only for actions produced by human agents (Kilner, Paulignan, & Blakemore, 2003; Obhi & Hall, 2011; Tai, Scherfler, Brooks, Sawamoto, & Castiello, 2004; for a review, see Press, 2011). Despite the initial findings that our performance monitoring system reflects differences in animacy (Fukushima & Hiraki, 2009), the topic remains underexplored in ERP-based studies.

In addition to partner animacy, the integrity of internal action representations clearly influences the system's prediction quality. Observers of an action use a

model of their own kinematic production to generate predictions (Colling, Thompson, & Sutton, 2014; see also Knoblich & Flach, 2003). In Colling et al. (2014), participants viewed biological motions with only kinematic identifying information made by themselves or another actor. Their task was to identify a target timepoint (e.g., the peak of the motion) by pressing a button. The accuracy was higher if an observed agent moved similarly to the observer's kinematic model of that action. This raises the possibility that online predictions of those action outcomes would be modulated when the similarity of action sequences between the observer and performer are manipulated. An additional factor contributing to the internal representation of another's action may be personality traits in social interactions; studies found links between performance monitoring and personality traits such as perspective taking and empathy (Fukushima & Hiraki, 2009; Koban et al., 2012; Rak, Bellebaum, & Thoma, 2013; for reviews, see Koban & Pourtois, 2014; Thoma & Bellebaum, 2012).

Music performance can be seen as a task with a variety of social contexts that engages actors in ecological and goal-oriented actions. Several studies have examined performance monitoring during music performance, both in solo and ensemble contexts. To elicit the FRN-P3 response, these studies have used the tactic of altering pitch feedback in pianists' parts (Katahira, Abla, Masuda, & Okanoya, 2008; Loehr, Kourtis, Vesper, Sebanz, & Knoblich, 2013; Maidhof, Vavatzanidis, Prinz, Rieger, & Koelsch, 2010). Trained pianists form expectations of pitch outcomes over years of practice (Zatorre, Chen, & Penhune, 2007), and hearing an unexpected pitch outcome when pressing a piano key reliably elicits an FRN-P3 complex. Maidhof et al. (2010) revealed that when pianists are engaged in solo performance of a familiar melodic sequence, FRN and P3a amplitudes to pitch alterations were larger compared to when only listening to the sequence, consistent with the greater performance monitoring literature. They also found that a P3b was only reliably elicited during action. However, when two pianists are engaged in duet performance and play two notes each (four as a whole) simultaneously, pitch alterations in one of the notes in one's own and a partner's part elicit comparable FRNs, but larger P3 (with a posterior distribution, resembling a P3b) in response to one's own part (Loehr et al., 2013). This raises a question as to whether pianists equivalently monitored their partner's actions without the clear segregation of self and other, or alternatively, that the pianists reacted equivalently in the early stage of performance monitoring only because their actions were always synchronous, and thus similar to each other. Other studies using musical joint tasks have not

specifically investigated the effects of timing and action similarity separately on the FRN and P3 components.

The present study used a melodic turn-taking task in a piano duet to examine how performance monitoring may be influenced by factors of agency, animacy of the partner, and similarity between partners' action sequences. Pianists alternately played 6-note sequences with a duet partner while their brain activity was recorded using electroencephalography (EEG). We altered the pitch of the auditory feedback in both players' parts to observe the FRN-P3 response. Half of the time, pianists alternated a similar (same melodic contour) or a dissimilar (different melodic contour) sequence with the partner. Further, pianists played each of these sequence types with a human and a computer partner. We hypothesized that, overall, FRN and P3a would be larger in response to pitch alterations from self- compared to other-produced actions, with a P3b present only during action, consistent with the performance monitoring literature. Further, we hypothesized that sharing a similar sequence would result in larger FRN and P3a amplitudes in response to the partner's part when compared with the dissimilar sequence, and that FRNs would be larger to the human compared to computer partner. Finally, we also obtained questionnaire data on participants' trait empathy levels using the Empathy Quotient (EQ; Baron-Cohen & Wheelwright, 2004) to examine potential trait empathy correlations with neural activities.

Methods

Participants

Twenty-four pianists, comprising twelve pairs, were recruited. Amongst those recruited, only two pairs knew each other and had played duets prior to the experiment; the remainder met for the first time at the experiment. The EEG was not obtained from one pianist due to technical failure, and 5 pianists were removed from data analysis for high behavioral error rate ($N = 2$), technical failure ($N = 2$), and excessive movement artifacts ($N = 1$). Thus, the final sample included 18 pianists ($M_{\text{age}} = 22.4$ years, $SD_{\text{age}} = 3.2$ years, 7 female). They had on average, 13.7 years of musical experience ($SD = 4.7$ years). All but one pianist was right-handed. Since removal of the left-handed pianist did not change the pattern of results or their statistical significance, subsequent analyses included the data from all 18 pianists. Pianists provided written informed consent and were paid \$20/hour. The study protocol was approved by the Stanford University Internal Review Board.

Apparatus and procedure

Two Yamaha Axiom-61 digital keyboards were placed in a sound-shielded room face-to-face, while all auditory feedback was played through two loudspeakers placed on either side of the keyboards (see Figure 1). Presentation of metronome ticks (three count-ins for all trials) and auditory feedback to the pianists was controlled by a custom-made module implemented in Max/MSP 7.0.1 software run on a Macintosh computer (OSX 10.9.5). Trigger codes were sent from Max/MSP through an Arduino Uno to the EEG acquisition computer. Piano and drum timbres for the metronome clicks were both built-in sounds of AU DLS Synth, the default OSX MIDI sound synthesizer. Piano tones were played at a constant volume of approximately 75 dB SPL.

The latency of the overall apparatus was evaluated by comparing the onset latency of the press of a piano key, the subsequent trigger code sent by Max/MSP, and the resulting auditory feedback using simultaneous three-channel audio recording of all three events (Wright, Cassidy, & Zbyszyński, 2004). The mean latency from key press to trigger code onset ($N = 175$ key presses) was 27 msec ($SD = 4.0$ msec), and from trigger code onset to pitch feedback was 21 msec ($SD = 3.3$ msec). The latter was compensated in the ERP analysis such that time zero represents the pitch feedback onset (see below 'EEG recording and data analysis' section).

Each pianist spent half of the recording time playing with a human partner and the other half with a computer partner (audio only). For each pair, one pianist started the session with the computer partner. During this time, the second participant arrived and was prepared with electrodes. When the first participant completed the computer partner portion, they played the portion requiring a human partner together. The second participant then completed the portion requiring a computer partner.

Upon arrival, pianists were shown the music (see below 'Stimuli and task' section), and were told to memorize it as soon as possible, although the score was kept close at the side of keyboard during the recording session so that pianists could use it as needed. During the instructions, they were informed of the feedback manipulations, and were instructed to continue playing upon hearing altered pitches. During the recordings, they were asked to keep a fixed gaze at a comfortable location. Recordings took place in a sound-attenuated chamber and the participants' compliance was verified by monitoring from an adjacent room through a window. Pianists were permitted to take brief breaks between blocks as needed.

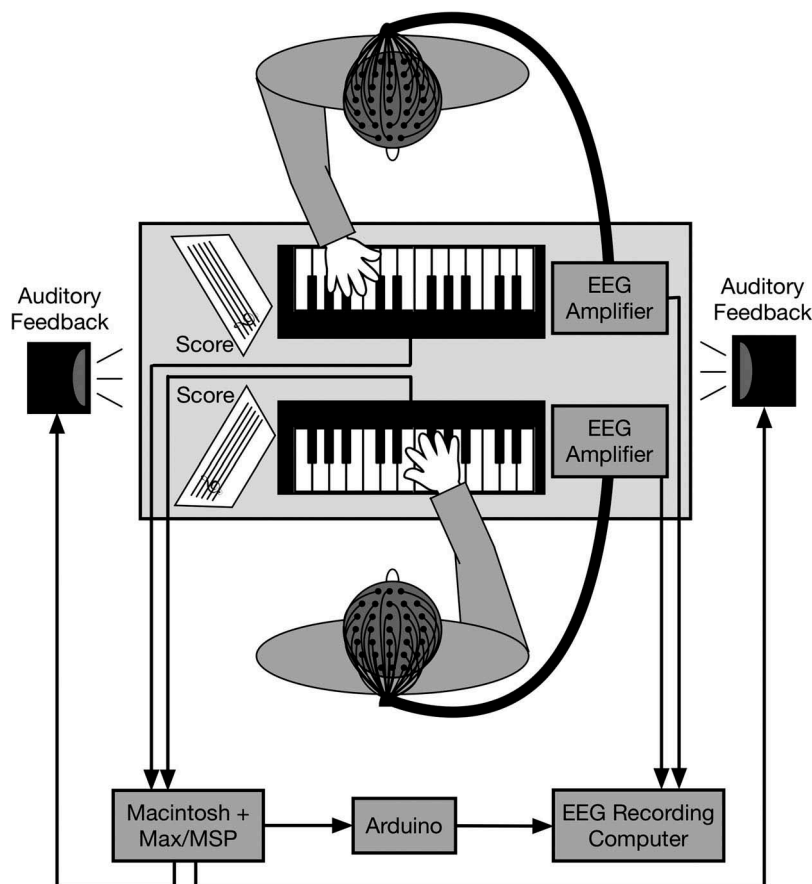


Figure 1. Experimental apparatus. This depicts a case in the human partner condition. The music scores were written in double staves separating two parts into two lines. They were identical for both partners.

After eight blocks were completed by a pianist (four each with a computer and human partner), he or she completed two questionnaires: the 40-question version of the Cambridge Empathy Scale yielding the Empathy Quotient (EQ; Baron-Cohen & Wheelwright, 2004), as well as a 10-question customized questionnaire asking for details of prior familiarity with the human partner and task difficulty. The total time involvement for each participant was 3.5–4 hours.

Stimuli and task

Four 31-note piano duets were composed for the study (Figure 2). All four duets were identical in time signature, pitch range, rhythmic pattern, manner of turn-taking, and contained only isochronous notes. Pianists alternated playing each bar with their partner during the first four bars. In two duets, partners alternated melodies with the same contour, thus performing *similar* action sequences, while in the other two duets partners alternated different contours, resulting in *dissimilar* action sequences. To control for overall

pitch distance between the duet parts, the pitch distance between the last note of one bar and the first note of the next was controlled to be either 6 or 7 scale notes until the end of the fourth bar. There was a 5th bar that used identical notes across the four duets; data from this bar will not be analyzed in the present paper. Which two duets were played with the human or computer partner were counterbalanced across pairs, and within pairs, counterbalanced factors included whether the pianist began with a *similar* or *dissimilar* duet, and whether he or she played bars 1 and 3 as the first player (P1, Figure 2), or 2 and 4 as the second player (P2, Figure 2). Thus, a pianist performed each score for a total of two blocks, once as the first player, another as the second player. During each block, pianists played one score with a fixed order of the players over the repeated trials. The duets were composed so that each part could be played with the right hand alone, and no bar required the performer to change overall hand position. To ensure consistency and minimal movement across participants, fingering numbers were given on the score.

Similar Melody

The figure shows two musical staves for a 'Similar Melody' in 6/8 time with a key signature of two sharps (F# and C#). The top staff, labeled 'Correct', shows a sequence of notes for Player 1 (P1) and Player 2 (P2) alternating every bar. The bottom staff, labeled 'Altered', shows the same sequence, but with arrows pointing to the 4th and 5th notes of the first four bars, indicating where altered feedback pitches could occur.

Dissimilar Melody

The figure shows two musical staves for a 'Dissimilar Melody' in 6/8 time with a key signature of two sharps (F# and C#). The top staff, labeled 'Correct', shows a sequence of notes for Player 1 (P1) and Player 2 (P2) alternating every bar. The bottom staff, labeled 'Altered', shows the same sequence, but with arrows pointing to the 4th and 5th notes of the first four bars, indicating where altered feedback pitches could occur.

Figure 2. Two examples of similar and dissimilar conditions in the duet task. For the first four bars, pianists alternated bars; Player 1 = P1, Player 2 = P2. Correct versions represent both the notes printed on the score, and thus what pianists played and expected for pitch feedback. Potential positions for which altered-feedback pitches could occur are 4th or 5th note in 1st-4th bar, marked here in grey on the correct versions. Note that the scores given to the participants did not have this color modification. Altered versions depict examples of altered pitch feedback, occurring at the rate of one note per partner per trial. Altered pitches are indicated by arrows.

Each block began with two practice trials during which no pitch alterations took place. The practice trials proceeded automatically into the trials in which pitch alterations occurred at the rate of one note in each partner's part per trial. Altered pitch feedback could occur during the 4th or 5th notes of each of the first four bars. Alterations always produced only in-key notes and were \pm two scale notes from the printed score note. The pitch alteration position included 16 possibilities (2 note positions in each bar \times 4 bars \times 2 possible pitch change directions). We collected 3 of each of these possibilities during a block, for a total of 48 target trials (~15–16 minutes). This way, each trial always contained an altered pitch for each player, but its position or direction of alteration was never predictable.

To set the tempo and cue the start of the trial, each trial began with three isochronous metronome ticks with 500 msec inter-onset interval (IOI) corresponding to the eighth note, after which the partners played through the instructed score. The computer partner's IOI was always exactly 500 msec. The next trial began by starting the metronome ticks after a random duration (1.5–2.5 seconds) of silence following the final note

onset of a trial. The accuracy of pianists' performance on each trial was monitored in real time: the Max/MSP module compared the pressed piano keys against the score in a note-by-note fashion and monitored IOIs. A trial was deemed incorrect when an incorrect key was pressed or if the IOI was 125 msec shorter or longer than the expected IOI (500 msec). Incorrect trials had to be correctly performed again and were appended to the end of each block. When a trial was identified as incorrect, the feedback was stopped to notify pianists so that they could prepare for the next trial. After a short period of silence, the next trial started.

Data recording and analysis

Behavioral data analysis

The music performances (including key press timing, velocity, and pressed key in MIDI number as well as produced pitch in MIDI number) were recorded using Max/MSP. IOIs were calculated from correctly-completed trials. To test whether participants showed performance slowing after feedback manipulations, IOIs

from altered pitches to the next note were statistically compared to IOIs of correct pitches for the 4th and 5th notes of each of bars 1–4.

EEG recording and data analysis

The EEG was recorded using the Neuroscan SymAmpRT amplifier with Curry 7 acquisition software and one or two whole-head 64-channel Quikcaps (all three from Compumedics Neuroscan Inc.) at a 500 Hz sampling rate. Because the amplifier was built for simultaneous recordings from up to four caps, no temporal synchronization mechanism was needed. Horizontal and vertical electrooculogram (EOG) were also recorded in each participant. Electrode impedances were kept below 10 k Ω . For each cap, scalp electrodes were referenced to an electrode located between the CPz and the Cz electrodes at the recording and were re-referenced using the common average reference per cap during the offline analysis after the data from each individual participant were separately saved from the original raw data files. Eye artifacts were removed from the obtained continuous EEG data using source space projection implemented in the Brainstorm toolbox (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011). Specifically, vertical and horizontal EOG were used to detect stereotypical eye-artifacts (blink and movement) and a 400 msec epoch centered around the detected events was used to construct a set of projectors. These projectors were applied to each of the eight data blocks per participant when extracting 1500 msec epochs beginning 500 msec before the onset of the 4th or 5th note of each of the first four bars in correctly-completed trials. According to the trigger code, which was recorded alongside the EEG, epochs were separated by the presence/absence of the pitch alteration, and by self/other parts with respect to each participant. Trials including channels with peak-to-peak amplitude exceeding $\pm 250\mu\text{V}$ were rejected. While participants were generally compliant in minimizing movement, the trial-rejection threshold was chosen to obtain enough EEG trials free of large amplitude changes. The data were then time-corrected such that the timepoint zero corresponded to the onset of auditory feedback, and were baseline-corrected using a 100 msec pre-stimulus window.

Difference waves were calculated on individual averages by subtracting the ERPs in response to correct pitches from the ERPs in response to altered pitches. We averaged data for the ERP waveforms and difference waves into electrode groups. For the FRN and P3a, amplitudes for the frontocentral electrodes (F1, Fz, F2, FC1, FCz, FC2) were averaged as the

responses for FRN and P3a were maximal at this site. We observed a right-lateralized P3b maximal around Pz, P2, and P4, and thus averaged these electrodes. For statistical analysis of FRN and P3a, amplitudes of difference waves were taken around the peak latencies of the grand average for each stimulus condition. These latencies were determined through the minima and maxima of the grand average difference waveforms for each condition, searching from 150–300 msec for the FRN, and 200–350 msec for the P3a. A 70 msec window was used for averaging for the FRN, and a 50 msec window for P3a. Due to the long duration of the P3b, a 300–500 msec window for amplitude averaging was used. These amplitude values were then subjected to statistical analysis using repeated-measures analysis of variance tests (ANOVAs) with three within-participants factors (*Agency* [Self, Other], *Partner* [Human, Computer], and *Similarity* [Similar, Dissimilar]). Here, we combined all participants because an additional between-subjects factor of gender (male/female) did not yield significant main effects. Post-hoc tests included Bonferroni corrections. For the purpose of visualization of grand-average waveforms, lowpass filtered data (100 Hz) were used for Figures 3 and 4.

Results

Behavioral performances

IOIs following correct and altered pitches in the 4th and 5th positions of each bar were entered into a three-way repeated-measures ANOVA using three within-participants factors (*Partner* [Human, Computer], *Similarity* [Similar, Dissimilar], and *Feedback Type* [Correct, Altered]). The ANOVA revealed a main effect of *Partner*, $F(1,17) = 100.12$, $p < .001$, $\eta^2 = .51$, reflecting that IOIs when playing with a human ($M = 470.0$ msec, $SD = 9.8$ msec) were significantly shorter than when playing with the computer ($M = 489.0$, $SD = 4.9$ msec), $p < .001$. A one-tailed t -test revealed that, overall, IOIs were shorter than the initial metronome ticks of 500 msec, $t(17) = -13.17$, $p < .001$. Thus, pianists played more closely to tempo with a computer partner and faster with a human partner; however, performances overall were faster than the prescribed tempo, commensurate with prior studies (Loehr et al., 2013; Mathias, Gehring, & Palmer, 2017). There was also an interaction between *Similarity* and *Feedback Type*, $F(1,17) = 41.87$, $p < .001$, $\eta^2 = .004$, reflecting that IOIs were slightly longer in response to altered pitches only during performances of similar melodies; however, no post-hoc tests were significant.

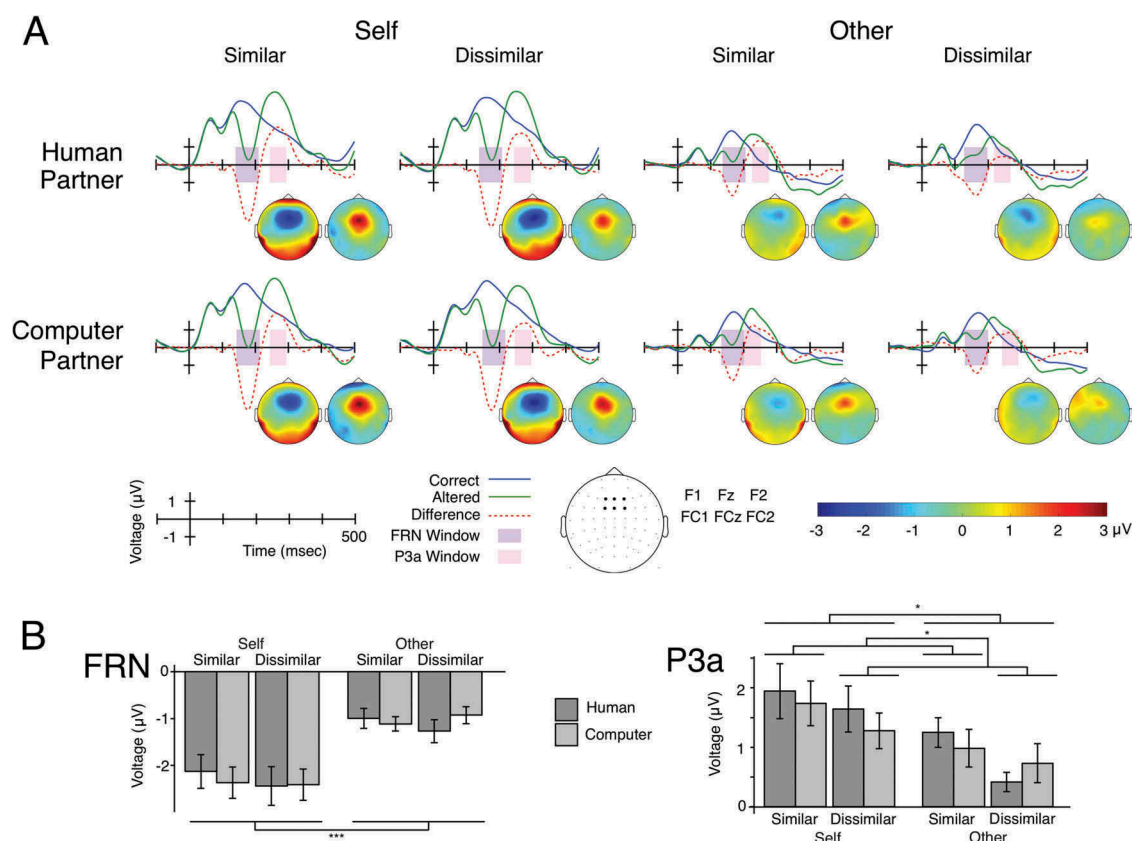


Figure 3. (a) Grand-average waves (correct, altered, and difference) for each condition, time-locked to pitch feedback onset. Shaded areas show the time windows used for statistical analysis based on grand average peak latency for each condition. Topographies from FRN and P3a time windows depicted for each condition, on the left and right respectively. (b) Mean amplitude for FRN (left panel) and P3a (right panel) time windows. Error bars depict S.E.M. *: $p < 0.05$, ***: $p < 0.001$.

ERPs

We first examined whether altered auditory outcomes elicited an FRN and if so, whether FRN amplitude differed across conditions. Figure 3 shows the grand-averaged ERPs and difference waves (altered minus correct) averaged over F1, Fz, F2, FC1, FCz, FC2 electrodes and topographies using the time windows for ANOVAs. Note that the ERPs are time-locked to the feedback onset of correct and altered pitches for each condition. As expected, altered pitches (compared with correct pitches) elicited a negative deflection with a frontocentral scalp distribution in all eight conditions. FRN amplitudes were calculated using the difference waveforms and were entered into a repeated-measures ANOVA using three within-participants factors (*Agency* [Self, Other], *Partner* [Human, Computer], and *Similarity* [Similar, Dissimilar]). The ANOVA revealed a significant main effect of *Agency*, $F(1, 17) = 33.32$, $p < .001$, $\eta^2 = .21$, reflecting that responses to altered feedback in one's own part elicited a larger FRN than in response to the partner's part ($p < .001$). No other effects were significant.

We next examined if altered auditory outcomes elicited a P3 and if so, whether its amplitude differed across conditions. We observed two components, an early frontocentral positive wave peaking at approximately 250 msec, thought to be P3a, and a subsequent, sustained, right-lateralized parietal wave, thought to be P3b. Amplitude values for each component were again analyzed with a three-way repeated measures ANOVA with within-participants factors (*Agency* [Self, Other], *Partner* [Human, Computer], and *Similarity* [Similar, Dissimilar]).

Regarding the P3a component indicated in Figure 3, which was examined at the same 6 frontocentral electrodes as the FRN, there was a significant main effect of *Agency*, $F(1, 17) = 11.12$, $p < .01$, $\eta^2 = .08$, reflecting a larger P3a in response to one's own part than to a partner's part ($p < .01$). There was also a significant main effect of *Similarity*, $F(1, 17) = 6.82$, $p < .05$, $\eta^2 = .03$, reflecting a larger P3a when playing a similar compared to a dissimilar melody ($p < .05$). No other effects were significant.

Figure 4 shows the grand-averaged ERPs and difference waves, as well as topographies, of the P3b response, pooled over electrode sites Pz, P2, and P4.

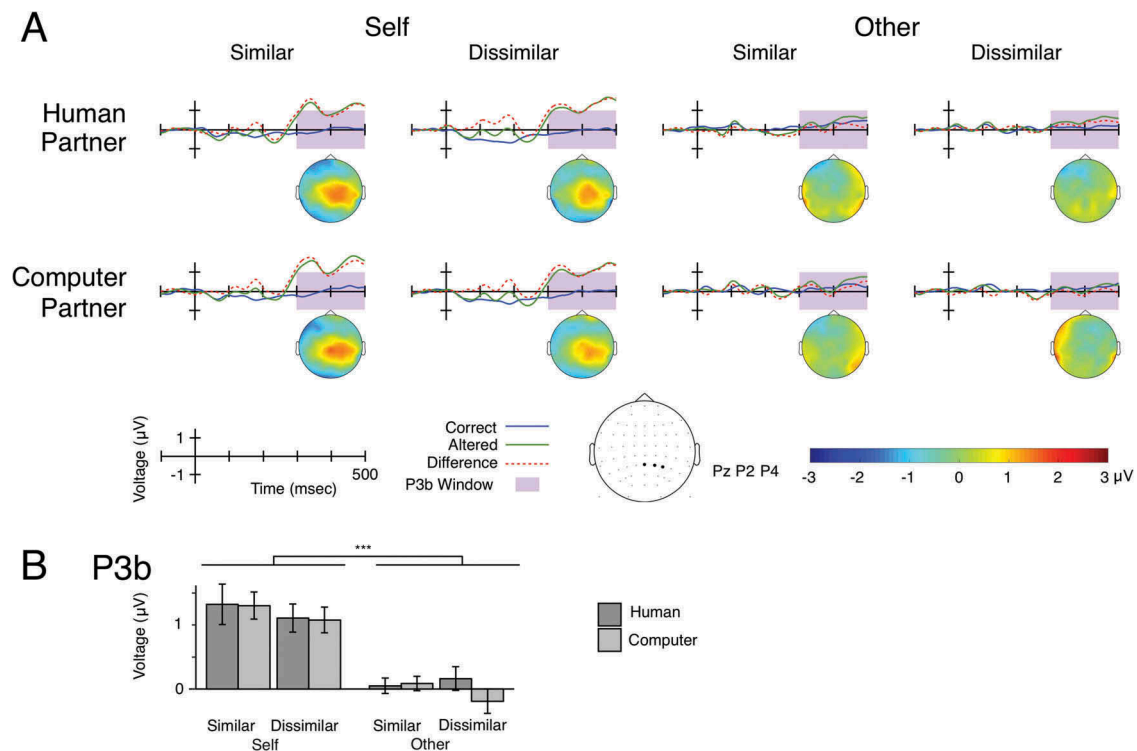


Figure 4. (a) Grand-average waves (correct, altered, and difference) for each condition at electrode group Pz, P2, P4, time-locked to feedback onset. Shaded areas show the time windows used for statistical analysis of P3b (300 – 500 msec). Topographies from these time windows also presented. (b) Mean amplitude for P3b time window. Error bars depict S.E.M. ***: $p < 0.001$.

Compared with correct pitches, altered pitches elicited a positive deflection with a right-lateralized parietal scalp distribution only in response to altered pitches in one's own part, reflected in a significant main effect of *Agency*, $F(1, 17) = 51.79$, $p < .001$, $\eta^2 = .33$. No other effects were significant.

Correlations to empathy

In a final analysis, we investigated the relationship between pianists' trait empathy scores (as measured by the 40-item Empathy Quotient, $M = 42.9$, $SD = 11.9$) and FRN amplitude using Spearman rank-order correlations. Correlations between empathy score and FRN amplitude in response to the other, either with partner types combined or separated, were not significant. However, the analysis revealed a significant positive correlation between empathy score and FRN amplitude in response to self, $r_s = .48$, $p < .05$, shown in Figure 5. There was an outlier (large FRN amplitude, $z\text{-score} = -3.03$)¹; when this outlier was removed, the correlation was strengthened, $r_s = .67$, $p < .01$.

When split by partner type, the correlation between empathy score and FRN amplitude in response to self

while playing with a human was marginally significant, $r_s = .45$, $p = .06$; with a computer partner, it was not significant, $p > .15$. Again, there was an outlier in the correlation with a human, which was the same instance as above. When this was removed, the correlation became significant, $r_s = .63$, $p < .01$.

Amplitudes from altered-note ERPs and correct-note ERPs in response to self were extracted from the same time window and electrode group that the FRN was investigated in to understand if the correlation was driven by increased amplitudes to altered pitches or decreased amplitudes to correct pitches. Neither correlation was significant.

There was no significant correlation between FRN amplitude and years of piano playing, nor between P3a amplitude and empathy scores.

Discussion

The present study investigated the neural correlates of performance monitoring in the context of a musical joint-action task, a piano duet. Pitch alterations occurred with equal frequency in both players' parts, eliciting the FRN-P3 complex. As predicted, performance monitoring

¹The outlier participant was a right-handed female participant.

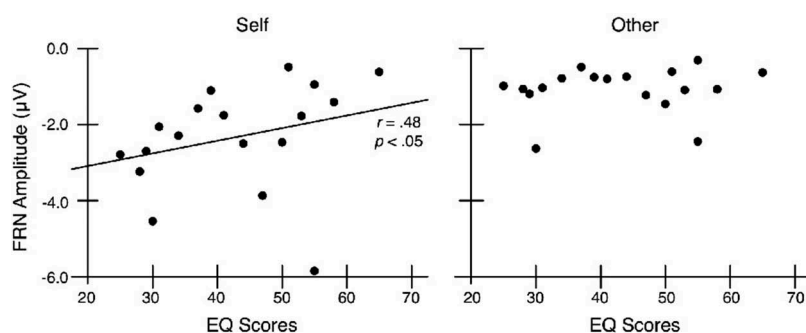


Figure 5. Correlation between Empathy Quotient (EQ) Scores and FRN amplitude in response to pitch alterations in pianists' own part (self) and the partner's part (other).

processes were modulated by agency, with greater pre-attentive and attentive resources devoted to self-generated feedback compared to other-generated feedback, as indexed by FRN, P3a, and P3b responses. Specifically, FRN and P3a amplitudes were larger in response to pitch alterations in one's own part compared to a partner's part, and the P3b was elicited only in response to alterations in one's own part. This pattern is similar in amplitude and peak latency to those found in Maidhof et al. (2010), in which pianists exhibited larger FRN and P3a during their own actions compared to those in perception tasks. Maidhof et al. (2010) also observed a P3b evident during action, but it was not present when pianists engaged in perception tasks irrelevant to pitch alteration. In contrast, Loehr et al. (2013) found that when two pianists played notes simultaneously, FRN amplitudes to altered pitches were equivalent between parts. Interestingly, in Loehr et al. (2013), both FRN and P3 deflections exhibited slightly later latencies than those in the present study, although it is not clear whether this delay is related to neural delays in feedback processing due to the simultaneous key presses, or partly to the delay between the keyboard control and trigger timing, or the asynchrony between the pianists in key press timing. Nonetheless, unless entirely synchronized action is required as in Loehr et al. (2013), our results clarify that in a piano duet task, performance monitoring of one's own action is distinguishable from and more salient than that of a partner's. For both cases, however, more replication would be desirable. Our results are also in line with other studies using non-musical tasks in which a larger FRN was found for one's own than for observed performance feedback (Bellebaum et al., 2010; Fukushima & Hiraki, 2009; Koban et al., 2012; Loehr et al., 2015). This enhanced FRN is likely related to higher salience of feedback about one's own performance (Bellebaum et al., 2010) as well as greater importance of feedback in subsequent behavioral adjustment (Holroyd & Coles, 2002).

Our study found equivalent FRN amplitudes to the partner's part regardless of whether the partner was a human or a computer. The result failed to confirm our hypothesis on the possible enhancement of FRN for a human compared to a computer (Fukushima & Hiraki, 2009). The explanation for this result could be that the active nature of our duet task may have reduced the social distance between human and computer partners. Social distance felt for a stranger and for a friend has been found to influence FRN. During observation of friends and strangers, FRNs were larger to friends than to strangers (Kang, Hirsh, & Chasteen, 2010; Ma et al., 2011; but see Leng & Zhou, 2010). However, this difference disappears when a participant simultaneously plays a game together with friends and strangers (Chen, Lu, Wang, Feng, & Yuan, 2017; Ma et al., 2011). Thus, it appears that the influence of social distance on the FRN decreases in general during active task participation. Importantly however, it is noteworthy that these studies still observed P3 differences between partner types (Chen et al., 2017; Ma et al., 2011). Their results may mean that because the FRN during active participation captures only the early part of the monitoring process, it may fail to reflect the nuances of the participant's interpersonal relationship. We observed no P3 differences between human and computer partners; thus, our musical task, based on well-controlled and defined musical roles, may involve a fundamentally different representation of social distance between the duet partners compared to that of friends and strangers engaged in reward-related gaming activity. It highlights the need for increased research into how the animacy of a partner is relevant in various music-specific contexts.

Our second manipulation was that of the similarity of action sequences between partners to probe if increased auditory and kinematic similarity between action sequences during a musical joint task resulted in more accurate online predictions of the partner's part. This was partly confirmed by the increased P3a

for the similar compared to the dissimilar condition, but differences were absent in the FRN. Since this increased P3a occurred not only in response to the partner but also to the self, it is possible that sharing a sequence with a partner increases the motivational saliency of altered feedback in that action, which is known to alter P3a amplitudes (Pfabigan, Alexopoulos, Bauer, Lamm, & Sailer, 2011). Alternatively, such sharing may increase the saliency of the expected pitches in working memory, resulting in a larger P3a (Polich, 2007). The observed increase in P3a for the similar condition was accompanied by slightly delayed key presses after pitch alterations compared to the dissimilar condition. This may reflect an increased attentional demand for processing of pitch alterations when sharing a similar sequence with a partner. This type of slowing down after error or altered feedback has been observed in music performance (Mathias et al., 2017), and in flanker (Debener et al., 2005) and Stroop tasks (Hajcak, McDonald, & Simons, 2003). It is also possible that because our participants are all trained pianists, the FRN, reflecting the long-held action-outcome expectations developed in pianists, may not be sensitive enough for our similarity manipulations, unlike later processing of the reorientation of attention as indexed by the P3a.

Finally, we found that higher trait empathy scores corresponded to smaller FRNs in response to the self. This result adds to the mounting evidence linking performance monitoring processes and trait empathic tendencies by offering data based on the FRN, which few studies have done (see Thoma & Bellebaum, 2012, for a review). However, our result is unique in that higher trait empathy was associated with smaller *self*-FRN amplitudes. This may sound odd at first, since previous studies found that increases in trait empathy are associated with larger FRN amplitudes when observing others (Fukushima & Hiraki, 2009; Koban et al., 2012). However, there is some evidence that FRN during observation of others may decrease with increasing empathy scores (Kobza, Thoma, Daum, & Bellebaum, 2011). This pattern was observed only during trials in which feedback was difficult to predict. The authors posited that those with higher levels of trait empathy directed attention to the behavior of the observed person, or to the emotional consequences for the other person, rather than feedback outcomes themselves.

What would be an integrative framework needed here for our present result and previous findings? According to a recent theory, proposed by Walentowska et al. (2016), a critical dimension in performance monitoring at the level of the FRN is that of *goal relevance* (see also Gentsch, Grandjean, & Scherer,

2013; Osinsky et al., 2017). Goal relevance refers to the degree to which a stimulus is informative about the satisfaction status of pursued goals (see Moors, 2007) such that the stimulus is deemed more or less relevant if its impact on the goal is larger or smaller (Roseman & Smith, 2001). Whether the FRN is sensitive to goal relevance was directly tested in a within-subjects study (Severo, Walentowska, Moors, & Pourtois, 2017). In the high-impact condition, participants were told their performance was diagnostic of their academic abilities, and that their score would be compared directly to a group of peers, whereas in the low-impact condition, the test was not diagnostic and no such social comparison would be made. The results showed that feedback in the high-impact condition elicited *smaller* FRN amplitudes compared to the low-impact condition. The authors proposed that in the high impact condition, participants may have resorted to a self-protective strategy because the impact of the predominantly negative feedback was too high for their self-image (Hoefer et al., 2015; Sherman & Cohen, 2006). In an fMRI study, Hoefer et al. (2015) found that activation of the anterior cingulate cortex (ACC) was attenuated when participants evaluated personality trait statements as being applicable to themselves, and this attenuation was even greater for personality trait statements that were negatively valenced. That the FRN is also thought to reflect ACC activity (Holroyd & Coles, 2002; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004; see also Knutson & Cooper, 2005) may further suggest a closer link between these related phenomena.

In piano playing, producing a wrong note is undesirable, a value often engrained in pianists from their very first lessons. In the present study, increases in trait empathy scores were also associated with self-reported increases of disruption to their playing by altered feedback, ($r_s = -.58, p < .05$). This rating in the post-task questionnaire was obtained by asking "How disruptive were the wrong notes to your playing?" (1 = Extremely disruptive ... 5 = Not at all disruptive). It may be that higher trait empathy individuals processed these pitch feedback alterations less strongly when they occurred in their own part. Furthermore however, because we observed a significant correlation only between empathy score and FRN amplitudes, not specific to either correct or altered ERP waveforms that comprise the FRN, higher empathy individuals may have more greatly suppressed both types of external feedback. Fukushima and Hiraki (2009) reported a similar, but marginal association of empathy with smaller self-FRNs. The above speculation still does not offer an explanation for different patterns of empathy influence when

performance monitoring is examined for self-produced genuine error. For example, Severo et al. (2017) found no effect of goal relevance on error-related negativity (ERN) or correct-related negativity (CRN), and higher trait empathy levels are associated with larger ERNs in response to self (Larson, Fair, Good, & Baldwin, 2010; Santesso & Segalowitz, 2009). Additionally, increases in motor-evoked potentials (MEPs) reflective of a piano duet partner's part are associated with increases in trait empathy levels (Novembre, Ticini, Schütz-Bosbach, & Keller, 2012). Future research could explicitly test how empathy levels interact with performance monitoring during joint tasks with conditions for self-caused errors and simple feedback alteration.

One limitation of our study is that it does not account for changes in familiarity between one's own and the partner's part, which may affect performance monitoring processes. Specifically, our block design was such that in the first block of each melody, partners had not played the other duet part before, whereas in the second block, they had, resulting in an increase in familiarity between blocks. We could not repeat the blocks and counterbalance the block order due to the long recording time. Activation of motor areas by action observation is sensitive to long-term familiarity with action sequences, as exemplified in dancers observing different dance genres or type of dance movement (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005; Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006), as well as trained athletes observing different types of serves (Balsler et al., 2014). Regarding sound-action associations, it appears that they can be learned relatively quickly. Nonmusicians show increased neural activation in the posterior interior frontal gyrus and Broca's area when listening to learned piano sequences when compared to listening to shuffled sequences after only a 5-day training (Lahav, Saltzman, & Schlaug, 2007), exhibit evidence of auditory-sensorimotor coactivation within only 20 minutes of piano training (Bangert & Altenmüller, 2003), and show neuroplastic changes when listening to sounds after 30 minutes of playing a novel instrument (Ross, Barat, & Fujioka, 2017). For trained pianists, greater activation in the motor region is seen in response to a duet partner's part when the part is previously rehearsed within the experimental session, compared to unrehearsed, both during simultaneous actions (Novembre, Ticini, Schütz-Bosbach, & Keller, 2014) and turn-taking actions (Hadley, Novembre, Keller, & Pickering, 2015). Together, these studies suggest that action simulation of movement sequences within one's own motor repertoire is involved in predicting others' actions as well, and that only brief training is required to obtain greater activation to motor sequences. Investigating the extent to which motor training on a

sequence impacts performance monitoring-related prediction processes is an interesting research area to explore for pedagogical and therapeutic applications. It is noteworthy that, while these studies address action-perception associations either in experts or after training, the findings, including ours, are likely not specific to experts; nonexperts can hold a range of action-perception associations involving sounds, such as how the act of walking or clapping one's hands involves expectation and recognition of familiar sounds. Varying neural representations based on general "action similarity" (for which melodic similarity is a surrogate in the present study) may hold true among a general population when observing or perceiving an action outcome, and paradigms testing the effects of action similarity between partners on performance monitoring during non-musical tasks in everyday situations could evaluate this generalizability.

To conclude, our results indicate that during turn-taking joint action, both early- and late-stage processes of performance monitoring reflect greater monitoring of oneself than of a partner, regardless of the animacy of the partner. We also found that increases in trait empathy levels are associated with decreases in FRN amplitude in response to the self, and speculate that this underscores the goal-related importance of pitch feedback to individuals in musical tasks influenced by empathy. Finally, our study suggests that the performance monitoring system, as indexed by P3a, may be sensitive to within-task similarity between action sequences. Our musical duet task employs an ecologically valid social task, with manipulations on factors frequently experienced in actual music scenarios. Thus, our study contributes to the idea that joint music-making not only offers great promise in studies of social interactivity (D'Ausilio, Novembre, Fadiga, & Keller, 2015), but can also reveal complexities of neural processes of performance monitoring in operation at the intersection of perception and action.

Acknowledgments

We are grateful to Amanda Lauren Sussman for her help in data collection, and to Jay Kadis and Sasha Leitman for their technical advice in building the experimental apparatus.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

- Balsler, N., Lorey, B., Pilgramm, S., Naumann, T., Kindermann, S., Stark, R., ... Munzert, J. (2014). The influence of expertise on brain activation of the action observation network during

- anticipation of tennis and volleyball serves. *Frontiers in Human Neuroscience*, 8, 568.
- Bangert, M., & Altenmüller, E. O. (2003). Mapping perception to action in piano practice: A longitudinal DC-EEG study. *BMC Neuroscience*, 4, 26.
- Baron-Cohen, S., & Wheelwright, S. (2004). The empathy quotient: An investigation of adults with asperger syndrome or high functioning autism, and normal sex differences. *Journal of Autism and Developmental Disorders*, 34(2), 163–175.
- Bellebaum, C., Kobza, S., Thiele, S., & Daum, I. (2010). It was not MY fault: Event-related brain potentials in active and observational learning from feedback. *Cerebral Cortex*, 20, 2874–2883.
- Calvo-Merino, B., Glaser, D. E., Grèzes, J., Passingham, R. E., & Haggard, P. (2005). Action observation and acquired motor skills: An fMRI study with expert dancers. *Cerebral Cortex*, 15, 1243–1249.
- Calvo-Merino, B., Grèzes, J., Glaser, D. E., Passingham, R. E., & Haggard, P. (2006). Seeing or doing? Influence of visual and motor familiarity in action observation. *Current Biology*, 16, 1905–1910.
- Chase, H. W., Swainson, R., Durham, L., Benham, L., & Cools, R. (2011). Feedback-related negativity codes prediction error but not behavioral adjustment during probabilistic reversal learning. *Journal of Cognitive Neuroscience*, 23(4), 936–946.
- Chen, Y., Lu, J., Wang, Y., Feng, Z., & Yuan, B. (2017). Social distance influences the outcome evaluation of cooperation and conflict: Evidence from event-related potentials. *Neuroscience Letters*, 647, 78–84.
- Colling, L. J., Thompson, W. F., & Sutton, J. (2014). The effect of movement kinematics on predicting the timing of observed actions. *Experimental Brain Research*, 232, 1193–1206.
- Comerchero, M. D., & Polich, J. (1999). P3a and P3b from typical auditory and visual stimuli. *Clinical Neurophysiology*, 110, 24–30.
- Cross, E. S., Ramsey, R., Liepelt, R., Prinz, W., & Hamilton, A. F. D. C. (2016). The shaping of social perception by stimulus and knowledge cues to human animacy. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371, 20150075.
- D'Ausilio, A., Novembre, G., Fadiga, L., & Keller, P. E. (2015). What can music tell us about social interaction? *Trends in Cognitive Sciences*, 19(3), 111–114.
- Debener, S., Ullsperger, M., Siegel, M., Fiehler, K., von Cramon, D. Y., & Engel, A. K. (2005). Trial-by-trial coupling of concurrent electroencephalogram and functional magnetic resonance imaging identifies the dynamics of performance monitoring. *Journal of Neuroscience*, 25(50), 11730–11737.
- di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V., & Rizzolatti, G. (1992). Understanding motor events: A neurophysiological study. *Experimental Brain Research*, 91, 176–180.
- Fukushima, H., & Hiraki, K. (2009). Whose loss is it? Human electrophysiological correlates of non-self reward processing. *Social Neuroscience*, 4(3), 261–275.
- Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain*, 119, 593–609.
- Gazzola, V., Rizzolatti, G., Wicker, B., & Keysers, C. (2007). The anthropomorphic brain: The mirror neuron system responds to human and robotic actions. *NeuroImage*, 35, 1674–1684.
- Gentsch, K., Grandjean, D., & Scherer, K. R. (2013). Temporal dynamics of event-related potentials related to goal conduciveness and power appraisals. *Psychophysiology*, 50, 1010–1022.
- Hadley, L. V., Novembre, G., Keller, P. E., & Pickering, M. J. (2015). Causal role of motor simulation in turn-taking behavior. *The Journal of Neuroscience*, 35(50), 16516–16520.
- Hajcak, G., McDonald, N., & Simons, R. F. (2003). To err is automatic: Error-related brain potentials, ANS activity, and post-error compensatory behavior. *Psychophysiology*, 40, 895–903.
- Hoefler, A., Athenstaedt, U., Corcoran, K., Ebner, F., Ischebeck, A., & Siegel, A. (2015). Coping with self-threat and the evaluation of self-related traits: An fMRI study. *PLoS ONE*, 10(9), e0136027.
- Holroyd, C. B., & Coles, M. G. H. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*, 109(4), 679–709.
- Iacoboni, M. (2009). Imitation, empathy, and mirror neurons. *Annual Review of Psychology*, 60, 653–670.
- Iacoboni, M., Molnar-Szakacs, I., Gallese, V., Buccino, G., Mazziotta, J. C., Rizzolatti, G., & Ashe, J. (2005). Grasping the intentions of others with one's own mirror neuron system. *PLoS Biology*, 3(3), e79.
- Kang, S. K., Hirsh, J. B., & Chasteen, A. L. (2010). Your mistakes are mine: Self-other overlap predicts neural response to observed errors. *Journal of Experimental Social Psychology*, 46, 229–232.
- Katahira, K., Abba, D., Masuda, S., & Okanoya, K. (2008). Feedback-based error monitoring processes during musical performance: An ERP study. *Neuroscience Research*, 61, 120–128.
- Kilner, J. M., Paulignan, Y., & Blakemore, S. J. (2003). An interference effect of observed biological movement on action. *Current Biology*, 13(6), 522–525.
- Knoblich, G., & Flach, R. (2003). Action identity: Evidence from self-recognition, prediction, and coordination. *Consciousness and Cognition*, 12, 620–632.
- Knutson, B., & Cooper, J. C. (2005). Functional magnetic resonance imaging of reward prediction. *Current Opinion in Neurology*, 18, 411–417.
- Koban, L., & Pourtois, G. (2014). Brain systems underlying the affective and social monitoring of actions: An integrative review. *Neuroscience and Biobehavioral Reviews*, 46, 71–84.
- Koban, L., Pourtois, G., Bediou, B., & Vuilleumier, P. (2012). Effects of social context and predictive relevance on action outcome monitoring. *Cognitive, Affective, & Behavioral Neuroscience*, 12, 460–478.
- Kobza, S., Thoma, P., Daum, I., & Bellebaum, C. (2011). The feedback-related negativity is modulated by feedback probability in observational learning. *Behavioural Brain Research*, 225, 396–404.
- Lahav, A., Saltzman, E., & Schlaug, G. (2007). Action representation of sound: Audiomotor recognition network while listening to newly acquired actions. *The Journal of Neuroscience*, 27(2), 308–314.
- Larson, M. J., Fair, J. E., Good, D. A., & Baldwin, S. A. (2010). Empathy and error processing. *Psychophysiology*, 47, 415–424.
- Leng, Y., & Zhou, X. (2010). Modulation of the brain activity in outcome evaluation by interpersonal relationship: An ERP study. *Neuropsychologia*, 48, 448–455.
- Li, P., Han, C., Lei, Y., Holroyd, C. B., & Li, H. (2011). Responsibility modulates neural mechanisms of outcome processing: An ERP study. *Psychophysiology*, 48, 1129–1133.
- Li, P., Jia, S., Feng, T., Liu, Q., Suo, T., & Li, H. (2010). The influence of the diffusion of responsibility effect on outcome evaluations: Electrophysiological evidence from an ERP study. *NeuroImage*, 52, 1727–1733.
- Liepelt, R., & Brass, M. (2010). Automatic imitation of physically impossible movements. *Social Cognition*, 28(1), 59–73.

- Loehr, J. D., Kourtis, D., & Brazil, I. A. (2015). It's not just my fault: Neural correlates of feedback processing in solo and joint action. *Biological Psychology*, *111*, 1–7.
- Loehr, J. D., Kourtis, D., Vesper, C., Sebanz, N., & Knoblich, G. (2013). Monitoring individual and joint action outcomes in duet music performance. *Journal of Cognitive Neuroscience*, *25*(7), 1049–1061.
- Ma, Q., Shen, Q., Xu, Q., Li, D., Shu, L., & Weber, B. (2011). Empathic responses to others' gains and losses: An electrophysiological investigation. *NeuroImage*, *54*, 2472–2480.
- Maidhof, C., Vavatzanidis, N., Prinz, W., Rieger, M., & Koelsch, S. (2010). Processing expectancy violations during music performance and perception: An ERP study. *Journal of Cognitive Neuroscience*, *22*(10), 2401–2413.
- Mathias, B., Gehring, W. J., & Palmer, C. (2017). Auditory N1 reveals planning and monitoring processes during music performance. *Psychophysiology*, *54*, 235–247.
- Moors, A. (2007). Can cognitive methods be used to study the unique aspect of emotion: An appraisal theorist's answer. *Cognition and Emotion*, *21*(6), 1238–1269.
- Nieuwenhuis, S., Holroyd, C. B., Mol, N., & Coles, M. G. H. (2004). Reinforcement-related brain potentials from medial frontal cortex: Origins and functional significance. *Neuroscience and Biobehavioral Reviews*, *28*, 441–448.
- Novembre, G., Ticini, L. F., Schütz-Bosbach, S., & Keller, P. E. (2012). Distinguishing self and other in joint action. Evidence from a musical paradigm. *Cerebral Cortex*, *22*, 2894–2903.
- Novembre, G., Ticini, L. F., Schütz-Bosbach, S., & Keller, P. E. (2014). Motor simulation and the coordination of self and other in real-time joint action. *Social Cognitive and Affective Neuroscience*, *9*, 1062–1068.
- Obhi, S. S., & Hall, P. (2011). Sense of agency in joint action: Influence of human and computer co-actors. *Experimental Brain Research*, *211*, 663–670.
- Osinsky, R., Ulrich, N., Mussel, P., Feser, L., Gunawardena, A., & Hewig, J. (2017). The feedback-related negativity reflects the combination of instantaneous and long-term values of decision outcomes. *Journal of Cognitive Neuroscience*, *29*(3), 424–434.
- Pfabigan, D. M., Alexopoulos, J., Bauer, H., Lamm, C., & Sailer, U. (2011). All about the money? External performance monitoring is affected by monetary, but not by socially conveyed feedback cues in more antisocial individuals. *Frontiers in Human Neuroscience*, *5*, 100.
- Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148.
- Press, C. (2011). Action observation and robotic agents: Learning and anthropomorphism. *Neuroscience and Biobehavioral Reviews*, *35*, 1410–1418.
- Press, C., Gillmeister, H., & Heyes, C. (2007). Sensorimotor experience enhances automatic imitation of robotic action. *Proceedings of the Royal Society B: Biological Sciences*, *274*, 2509–2514.
- Rak, N., Bellebaum, C., & Thoma, P. (2013). Empathy and feedback processing in active and observational learning. *Cognitive, Affective & Behavioral Neuroscience*, *13*, 869–884.
- Ridderinkhof, R. K., Ullsperger, M., Crone, E. V., & Nieuwenhuis, S. (2004). The role of the medial frontal cortex in cognitive control. *Science*, *306*(5695), 443–447.
- Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Review of Neuroscience*, *27*, 169–192.
- Rizzolatti, G., Fadiga, L., Gallese, V., & Fogassi, L. (1996). Premotor cortex and the recognition of motor actions. *Cognitive Brain Research*, *3*, 131–141.
- Roseman, I. J., & Smith, C. A. (2001). Appraisal theory: Overview, assumptions, varieties, controversies. In K. R. Scherer, A. Schorr, & T. Johnstone (Eds.), *Appraisal processes in emotion: Theory, methods, research* (pp. 3–19). New York, NY: Oxford University Press.
- Ross, B., Barat, M., & Fujioka, T. (2017). Sound-making actions lead to immediate plastic changes of neuromagnetic evoked responses and induced beta-band oscillations during perception. *The Journal of Neuroscience*, *37*(24), 5948–5959.
- Santesso, D. L., & Segalowitz, S. J. (2009). The error-related negativity is related to risk taking and empathy in young men. *Psychophysiology*, *46*, 143–152.
- Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: Bodies and minds moving together. *TRENDS in Cognitive Sciences*, *10*(2), 70–76.
- Severo, M. C., Walentowska, W., Moors, A., & Pourtois, G. (2017). Goal impact influences the evaluative component of performance monitoring: Evidence from ERPs. *Biological Psychology*, *129*, 90–102.
- Sherman, D. K., & Cohen, G. L. (2006). The psychology of self-defense: Self-affirmation theory. In M. P. Zanna (Ed.), *Advances in experimental social psychology* (Vol. 38, pp. 183–242). San Diego, CA: Academic Press.
- Tadel, F., Baillet, S., Mosher, J. C., Pantazis, D., & Leahy, R. M. (2011). Brainstorm: A user-friendly application for MEG/EEG analysis. *Computational Intelligence and Neuroscience*, *2011*, 1–13.
- Tai, Y. F., Scherfler, C., Brooks, D. J., Sawamoto, N., & Castiello, U. (2004). The human premotor cortex is 'mirror' only for biological actions. *Current Biology*, *14*(2), 117–120.
- Talmi, D., Atkinson, R., & El-Dereby, W. (2013). The feedback-related negativity signals salience prediction errors, not reward prediction errors. *The Journal of Neuroscience*, *33* (19), 8264–8269.
- Thoma, P., & Bellebaum, C. (2012). Your error's got me feeling – How empathy relates to the electrophysiological correlates of performance monitoring. *Frontiers in Human Neuroscience*, *6*, 135.
- Ullsperger, M., Fischer, A. G., Nigbur, R., & Endrass, T. (2014). Neural mechanisms and temporal dynamics of performance monitoring. *Trends in Cognitive Sciences*, *18*(5), 259–267.
- Vesper, C., Abramova, E., Bütepage, J., Ciardo, F., Crosse, B., Effenberg, A., ... Wahn, B. (2017). Joint action: Mental representations, shared information and general mechanisms for coordinating with others. *Frontiers in Psychology*, *7*, 2039.
- Walentowska, W., Moors, A., Paul, K., & Pourtois, G. (2016). Goal relevance influences performance monitoring at the level of the FRN and P3 components. *Psychophysiology*, *53*, 1020–1033.
- Wright, M., Cassidy, R. J., & Zbyszyński, M. F. (2004). Audio and gesture latency measurements on Linux and OSX. In *Proceedings of the International Computer Music Conference* (pp. 423–429). Miami, FL: International Computer Music Association.
- Yu, R., & Zhou, X. (2006). Brain responses to outcomes of one's own and other's performance in a gambling task. *NeuroReport*, *17*(16), 1747–1751.
- Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: Auditory-motor interactions in music perception and production. *Nature Reviews Neuroscience*, *8*, 547–558.