Socially Induced Negative Emotions Elicit Neural Activity in the Mentalizing Network in a Subsequent Inhibitory Task

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Abstract—Despite the growing emphasis on embedding interactive social paradigms in the field of cognitive and affective neuroscience, the impact of socially induced emotions on cognition remains widely unknown. The aim of the present study was to fill this gap by testing whether facial stimuli whose emotional valence was acquired through social learning in an economic trust game may influence cognitive performance in a subsequent stop-signal task. The study was designed as a conceptual replication of previous event-related potential experiments, extending them to more naturalistic settings. We hypothesized that response inhibition to briefly presented faces of negative and positive game partners would be enhanced on the behavioral and neural levels as compared to trials with a neutral player. The results revealed that the trust game was an effective paradigm for the induction of differently valenced emotions towards players; however, behavioral inhibitory performance was comparable in all stop-signal conditions. On the neural level, we found decreased P3 amplitude in negative trials due to significantly stronger activation in the right frontoparietal control network, which is involved in theory-of-mind operations and underlies social abilities in humans, especially memory-guided inference of others’ mental states. Our findings make an important contribution to the cognition–emotion literature by showing that social interactions that take place during an economic game may influence brain activity within the mentalizing network in a subsequent cognitive task. © 2021 The Authors. Published by Elsevier Ltd on behalf of IBRO. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Key words: event-related potentials, response inhibition, social emotion, stop-signal task, trust game.

INTRODUCTION

During our daily lives, emotional episodes are mostly triggered by social interactions (for a review, see Fischer and Van Kleef, 2010). Thus, it seems quite natural that our brains may respond differently depending on whether we are emotionally engaged and in an interaction with someone to whom we can attribute intentions and beliefs, or whether we are just adopting the attitude of a detached observer (Schilbach et al., 2013). Therefore, many authors have recently emphasized the importance of embedding interactive social paradigms in the field of cognitive and affective neuroscience (Zaki and Ochsner, 2009; Gilam and Hendler, 2016), or they have directly argued for the development of a second-person neuroscience (Schilbach et al., 2013; Redcay and Schilbach, 2019).

In spite of these recent calls for putting the social into non-social neuroscience, the majority of findings on cognition–emotion interactions and their neural correlates are still based on laboratory paradigms in which short-duration affective states are induced by emotional stimuli such as faces, pictures of scenes (e.g., attacking sharks, cockroaches on the pizza, or mutilated bodies), film clips, words or sounds (for reviews, see Dolcos et al., 2020; Okon-Singer et al., 2015). Emotional stimuli are usually retrieved from international databases, e.g., the Radboud Faces Database (Langner et al., 2010), the International Affective Picture System (Lang et al., 2008) or the International Affective Digitized Sounds (Bradley and Lang, 1999). The use of a ‘classic’ set of stimuli translates to high standardization of experimental procedures and increases reproducibility of results between and within individuals (Gilm and Hendler, 2016). However, it obscures the problem of reporting findings that are idiosyncratic to particular circumstances. These circumstances include the
brief presentation of a large set of different stimuli, lack of dynamic interaction, low psychological realism, and relatively low impact on participants’ emotional experiences. Thus, the increase of reproducibility occurs at the expense of ecological validity, which determines how applicable the results are to natural environmental contexts.

To further illustrate this problem, let us consider the influence of emotions on response inhibition. Response inhibition is defined as the ability to suppress inappropriate or irrelevant actions (Mostofsky and Simmonds, 2008; Pessoa et al., 2012), and is commonly studied using go/no-go or stop-signal tasks. An advantage of the stop-signal task is that it makes it possible to measure the ability to withhold a response after its execution has been initiated. This mainly requires effective attentional switching from the ongoing motor planning to briefly presented inhibition cues, namely stop signals. Thus, the stop-signal task is an essential tool in assessing inhibition in this context.

Stop-signal reaction time (SSRT) is a crucial variable in the stop-signal task that required withholding a response to briefly presented aversive and neutral pictures or sounds, our two recent studies performed a direct emotional relevance task. Emotional stimuli may enhance inhibitory control by improving the processing of attended signals and attracting further attention (as in our studies). How- ever, when unrelated to the task, similar stimuli may act as distractors and attenuate processing of attended signals (as in the study by Camfield et al., 2018). Thus, the effect of emotional content on cognitive processing is determined not only by subjective experiences (Sebastian et al., 2020) but also by task relevance (for the theoretical background, see Pessoa, 2009).

On the one hand, these studies have provided valuable insights into our understanding of response inhibition in the emotional context by revealing – in line with several theoretical accounts (e.g., Pessoa, 2009; Pourtois et al., 2013) – that transient affective processes may indeed dynamically modulate cognitive performance. However, on the other hand, these mixed and partly contradictory findings raised a question about the subjective relevance of emotional stimuli retrieved from international databases with established normative ratings of valence and arousal. This question was recently addressed by Sebastian and colleagues (2020), who decided to examine the influence of high- and low-threat stimuli on inhibitory control in the stop-signal task as a function of subjectively experienced threat intensity. They observed that participants who rated high-threat stimuli (previously paired with unpleasant electrodermal stimulation) as highly painful had impaired response inhibition in high-
With all of these findings, the question remains of whether transient affective processes induced by briefly presented stimuli have something in common with emotional episodes that occur within our daily routine and shape our subjective experiences, especially those emotional episodes that result from social interactions with other people in our environment. More specifically, can we be sure that we would get similar results as previously described when using more realistic and interactive induction of emotion? The aim of the present study was to answer this question by further exploring the mechanism of the emotional modulation effect on response inhibition in the stop-signal paradigm, but in more naturalistic settings.

Social interaction involves at least two agents who reciprocally influence each other through their behaviors in a time-dependent manner, thus leading to the occurrence of social emotions (Di Paolo and De Jaegher, 2012; Schilbach et al., 2013), which are defined as requiring mentalizing about other people’s minds (Burnett et al., 2009). Thus, in order to appear they do not necessitate the mere physical presence of another person, rather just the representation of another person’s mental state. An interactive social environment can be relatively easily created in laboratory settings via different types of economic games, such as the prisoner’s dilemma game, the ultimatum game, or the trust game (Rilling and Sanfey, 2011). All these games are based on the concept of mutual cooperation and defection (unfairness) and engage our ability to readily distinguish between friend and foe among conspecifics (Cosmides and Tooby, 2000). For example, the trust game involves an exchange between two players: an investor and a trustee (Berg et al., 1995). The investor is given a certain amount of money and can choose how much of this stake (if at all) he wants to transfer to the trustee. The invested money is then multiplied (doubled or tripled) and the trustee decides how much to return to their partner. The amount of money returned by the trustee can be more or less fair, therefore the trustee’s behavior may evoke differently valued emotions in the investee. Importantly, a large body of previous research suggests that economic games are reliable and valid paradigms which can be used to induce social emotions, especially negative ones such as interpersonal anger (e.g., Gilam et al., 2015, 2019; for review, see Gabay et al., 2014).

Since systematic variation of experimental situations is the only means of determining the nature of the observed effects and demonstrating their ecological validity (Wurbel, 2000), the present study was designed as a conceptual replication of previous works (Senderecka, 2016, 2018; Senderecka et al., 2018). In the present study, we aimed to further investigate the emotional modulation effect on response inhibition in the stop-signal paradigm. To achieve this goal, we used behavioral measures and ERP components. However, instead of presenting negatively valenced pictures or sounds to evoke brief affective states, this time we introduced an economic game to induce more protracted interpersonal emotions. Participants were led to believe that they were playing with three other people located in nearby laboratories and depicted in photographs presented on the screen. The interaction was based on the trust game with two active players, one of which was pre-programmed to play fairly and the other unfairly, and one passive (neutral) player who, although visible on the screen, could not take part in the game due to technical constraints. Thus, we utilized the economic game as a context for interpersonal conflict over financial resources to elicit negative/positive social emotions towards the unfair/fair player, respectively, and an emotionally neutral attitude towards the passive player. After completing the game, participants performed a stop-signal task that required response inhibition to briefly presented pictures of the players’ faces with neutral expressions while the electroencephalography (EEG) signal was recorded.

In line with their valence acquired through social learning in an interactive context, we predicted that the faces of fair and unfair players would be respectively rated as much more and much less likeable as compared to the faces of the passive player. Based on our previous results (Senderecka, 2016, 2018), we hypothesized that pictures of active players’ faces, acting as the stop signal, would dynamically improve behavioral performance in the stop-signal task by decreasing SSRT. In addition, we also predicted that stop-signal-locked ERP components related to response inhibition would show increased amplitudes for the two emotional conditions compared to the neutral one.

**EXPERIMENTAL PROCEDURES**

**Participants**

Thirty-four volunteers (19 female) aged 19–34 years old ($M = 24.1$ years, $SD = 4.3$) were recruited from the general population via internet advertisements and were compensated about 5 US dollars in Polish zloty (PLN) for their time. All participants were healthy, free of medications, declared no history of neurological or psychiatric diseases, and had normal or corrected-to-normal vision. Of the initial sample recruited for the study, two participants were excluded from the analyses: one because of technical problems with behavioral data recording, and another one due to a probable misunderstanding of the instructions which led to a lack of correct go responses in the stop-signal task. The remaining 32 participants (17 female) were 19–34 years old and had a mean age of 23.6 years ($SD = 3.9$). The sample size was estimated on the basis of our previous works (Senderecka, 2016, 2018) and power analyses. The results indicated that our sample size would allow the detection of a medium-to-large effect of emotion ($d = 0.6$ for simple effects, $\eta^2_p = 0.24$ for interaction effect) with a power 90% at an alpha level of 0.05.

**General procedure**

The study was performed in accordance with the Declaration of Helsinki (World Medical Organization, 1996) and was approved by the Research Ethics Commit-
Debriefed about the deception. The players were real; they were then thoroughly informed consent. The whole experiment took place in a dimly lit, sound-attenuated, air-conditioned testing room.

Each study session was divided into several phases, which are outlined in Fig. 1. In order to set up a cover story, participants were told that they would play an online interactive computer game with three different people located in nearby laboratories and depicted in photographs presented on the screen. Prior to the game, full-face, front-view, color pictures of each participant with a neutral facial expression were individually taken against a white background using a digital camera. Participants were led to believe that the same procedure was applied to all players and that these pictures would be edited and subsequently fed into the network so all players could see the photos of the others. In reality, participants’ photos were never processed or used and were deleted after the session. Then, the participants were instructed as to the nature and rules of the game. To make the cover story even more convincing, the participant’s roles (investor vs. trustee) in games against three other players were determined through coin tosses. The outcome of the tosses was always interpreted by the experimenter as indicating that the participant would play the investor’s role with two partners and the trustee’s role with one partner. The cover story also included the statement that one player would eventually not take part in the game due to unexpected technical constraints. To increase credibility, a fake phone call was placed to another experimenter, supposedly requesting not to postpone the start of the game. After the ostensible agreement to proceed with the experiment was witnessed by the participant, the game was performed as detailed below.

Following the game, which took about 30 min, participants were instructed to perform a short face-recognition task with 12 different faces (all facial stimuli used in the study), including those presented during the game to ensure that they could correctly identify the three faces seen before. Next, the self-report emotion-induction check was performed. Participants were asked to rate on a five-point scale to what extent they felt engaged in the game, and to what degree they liked the game and each player (1 = not at all, 5 = very much). Thus, higher scores were associated with a more positive attitude. Two first questions (concerning the game) were filler items, therefore responses to these questions were not subjected to statistical analyses. Afterwards, participants completed the stop-signal task (described in detail below), which took about 35 minutes and required response inhibition to briefly presented pictures of three players’ faces while EEG was recorded. They were instructed to restrict body movements and blinking as much as possible during the EEG recording. Directly after the end of data collection, all participants were asked whether they had believed the players were real; they were then thoroughly debriefed about the deception.

Economic game

To induce social emotion, an iterative version of the trust game was used (for a similar example, see Singer et al., 2004). Apart from the participant, the game involved two active players and one passive player: the active partners were either negative (preprogrammed to play unfairly) or positive (preprogrammed to play fairly); the passive (neutral) player allegedly could not take part in the game. It is worth noting that the passive player served as a control condition and therefore should not be associated with any affect. With this intention, participants were informed that this player could not interact with them due to technical constraints with the internet connection. All partners were depicted in photographs presented on the screen. Photographs were randomly selected for each participant from a set of 12 face stimuli (six female and six male) taken from the Radboud Faces Database (Langner et al., 2010; www.rafd.nl). All of them had equal size and presented frontal color images of Caucasian faces with frontal gaze direction and neutral facial expression. Each set of three faces contained two faces of one gender and one of another, and the same set was never repeated in the study.

The whole game included six runs consisting of three subsequent subgames with each of the three partners consecutively (6 runs × 3 subgames × 3 partners), resulting in a total of 54 subgames; however, only two-thirds of them (36 subgames) were based on a virtual money exchange between participant and active player (positive or negative). The remaining 18 subgames with the neutral player could not be completed due to the alleged connection problem. Participants were always assigned to the investor’s role when playing with active partners and to the trustee’s role when playing with the passive partner. At the beginning of each run, participants (as investors) were given 10 PLN and had to decide how much of this amount to transfer to the trustee. The money invested was tripled in the transfer. The positive partner always gave half of the received amount back to the investor. Therefore, participants could never lose such a subgame; see Fig. 2 for the illustration. In turn, the negative partner changed the strategy within the game, resending 0–35% of the received amount. Thus, participants could never win such a subgame. Participants knew that they would be rewarded according to the place achieved in the whole competition. Hence, to ensure equal payments, at the end of the game all participants were informed that they had come in second place. Importantly, participants were given detailed written information about all actions in the game and their financial consequences.

Pictures of players’ faces were displayed on the screen during the whole game. The face of the current player was framed, whereas the others were dimmed but still visible, as shown in Fig. 3. Participants were led to believe that during a network connection error two other players would perform their subgames and for this reason participants should wait for their turn. Therefore, the alleged technical constraints did not shorten the duration of the display of the neutral player’s face as
Fig. 1. Study design.

Fig. 2. Money exchange in the trust game. (A) Investor is given a sum of money. (B) Investor decides how much money to transfer to the trustee. (C) Investment is tripled. (D) Trustee decides how much money to give back to the investor. (E) In this example, investor keeps $2 from the original amount and gets $12 from the trustee, eventually earning $14.

Fig. 3. The game display. In the shown example, the participant was given the following information: he/she had received 10 PLN (point 1 in the center of the screen) and could transfer a certain amount of this stake to the current partner (point 2); the partner had received the money (point 3) and had decided how much money to return (point 4); the participant should now press the space key to continue (point 5). In addition, information on the partner’s and participant’s money was displayed in two locations: below the framed picture of the current partner (money won so far in the current run) and in the bottom corners of the screen (money won in the current subgame by the participant, left side, and by the partner, right side). This was accompanied by an illustration of a pile of coins.
compared to the other two conditions (the exposure time of each of the three players’ faces was balanced).

To emphasize the interpersonal nature of the interaction between participants and their partners, the game also included short interpersonal messages (for similar examples, see Gilam et al., 2019; Van Dijk et al., 2008). Before the first run, each player had to send a welcome message to the other players. The message sent by the positive partner contained a smiley emoticon and was more friendly as compared to the short and restrained message sent by the negative partner (“Hi! Have fun! :)” vs. “Hi.”). A similar message exchange took place once again in the middle of the competition. This time the players expressed their more or less enthusiastic opinions about the game.

Stop-signal task
The task was coded and presented using PsychoPy software (Peirce, 2007). Each trial began with a fixation point in the middle of the screen for 800 ms followed by a go stimulus. The go stimulus (one of two black arrows pointing right or left, presented randomly one at a time, each with overall 50% probability) indicated that the participant should make a right-hand or left-hand response.

This imperative cue remained on the screen for the go stimulus. The go stimulus (one of two black arrows pointing right or left, presented randomly one at a time, each with overall 50% probability) indicated that the participant should make a right-hand or left-hand response. This imperative cue remained on the screen for 100 ms and was presented on a gray background in the center of a 23” computer monitor. Participants were instructed to react to the go stimulus by pressing the left or right “ctrl” key on the computer keyboard according to the direction of the presented arrow. They were also encouraged to respond as quickly and accurately as possible.

In a random sample of 25% of the trials, a picture of an unfair, fair, or neutral player’s face followed the go stimuli (for 1300 ms or until the participant’s response). It served as the stop signal and indicated that the participant should inhibit the given response. Each face occurred 54 times as the stop signal and indicated that the participant should inhibit the given response. Each face occurred 54 times during the task. The stop-signal delay (SSD) between go and stop signals was adaptively adjusted depending on the success or failure of stopping a response: the interval increased or decreased by 50 ms (from 100 to 400 ms) following successful and unsuccessful inhibitions, respectively. The initial value of the SSD was set to 150 ms. The staircasing was done separately for each stop-signal condition. Each trial was followed by an inter-trial interval. Fig. 4 presents an outline of the stop-signal task design.

After one practice block of 40 trials (in which we used a separate set of neutral faces as stop signals), participants completed eight experimental blocks, with short breaks between them. Each experimental block consisted of 81 trials. We randomized the trial order with the restriction that any two given stop trials had to have at least one go trial between them.

EEG data recording and preprocessing
The continuous scalp EEG was recorded from 32 silver/silver-chloride (Ag/AgCl) active electrodes (with preamplifiers) using the BioSemi Active-Two system. The electrodes were secured in an elastic cap (Electro-Cap) according to the extended 10–20 international electrode placement system. Two extra electrodes called CMS and DRL formed a feedback loop that served as the ground and online reference for recordings. The signal was continuously sampled at 256 Hz. The horizontal and vertical electro-oculograms (EOGs) were monitored using four additional electrodes placed above and below the right eye and in the external canthi of both eyes.

EEG data were preprocessed using BrainVision Analyzer 2 (Brain Products, Munich, Germany). All channels were re-referenced off-line to the average of the two mastoid electrodes. The recordings were filtered off-line with a 0.05 Hz high-pass filter (slope 24 dB/oct) and a 25 Hz low-pass filter (slope 12 dB/oct). The EEG data were first segmented relative to go stimulus onset into −600 to 1900 ms segments. All trials were manually inspected to remove non-stationary artifacts (such as skin potentials or artifacts due to head movements). On average, this resulted in the rejection of less than 1% of all trials. Ocular artifacts were corrected using the Gratton, Coles and Donchin method (1983). Contaminated trials exceeding maximum/minimum amplitudes of ±65 µV were rejected by an automatic procedure. Segments with “too fast” responses (performed before stop-signal presentation, therefore not containing inhibitory activity) were excluded (less than 1% of all stop trials). Stop-signal-locked (−100 ms to 700 ms around the stop-signal onset) segments were subsequently extracted and aligned to the 100 ms pre-stop-signal baseline. Grand averages were calculated separately for negative successful, positive successful, neutral successful, negative unsuccessful, positive unsuccessful, and neutral unsuccessful stop-signal trials. The mean number of artifact-free epochs included in the ERP analysis across all participants for each of the stop-signal conditions was as follows: negative successful stop M = 28.0 (SD = 3.2), positive successful stop M = 28.1 (SD = 3.7), neutral successful stop M = 28.1 (SD = 3.3), negative unsuccessful stop M = 24.7 (SD = 3.8), positive unsuccessful stop M = 24.7 (SD = 4.5), neutral unsuccessful stop M = 24.5 (SD = 4.2).

Consistent with previous studies (Dimoska et al., 2006; Senderecka, 2016), time windows were selected around the N2 (200–250 ms) and the P3 (300–400 ms). Mean voltage amplitudes in the component-specific windows were used for statistical analysis. The N2 component was analyzed at the averaged fronto-central sites (Fz, FC1, FC2, Cz), whereas the P3 was analyzed at the averaged parietal sites (P3, P4, Pz, PO3, PO4).

Statistical analyses
We used one-way repeated-measures analyses of variance (rmANOVA) to compare inhibitory performance across the three stop-signal conditions (negative, positive and neutral). The analyses were performed on the behavioral variables: SSRT (corresponds to the latency of the inhibitory process) and inhibition rate. Following the procedure of Logan (1994), the global SSRT was obtained by subtracting the average SSD from the nth reaction time; n was calculated for each partici-
pant separately by multiplying the number of no-signal reaction times (486) by the probability of responding. The SSRTs for each stop-signal condition were obtained analogously by subtracting the negative/positive/neutral SSD from the $n$th reaction time, taking into account the condition-wise probability of responding.

Participants’ answers to questions about their emotional attitude towards players were subjected to non-parametric Friedman and Wilcoxon tests. One-way rmANOVAs were used to examine the amplitudes of the N2 and P3 components separately, with the factors being trial type (successful vs. unsuccessful) and stop-signal condition (negative, positive and neutral). The critical $p$ value was set at 0.05 for all the analyses. To interpret significant findings, global analyses were followed by restricted post-hoc $t$-tests. All data and supporting materials are available online at https://osf.io/zyejc/.

**RESULTS**

**Self-report and behavioral findings**

The means and standard deviations of self-report and behavioral measures for emotional conditions in the stop-signal task are summarized in Table 1. All participants correctly identified three players’ faces during the short face-recognition task performed between the game and the stop-signal task. The results of the emotion induction check (as revealed by the Friedman test) indicated significant differences between participants’ emotional attitudes towards the negative, positive and neutral players ($p < .001$). Paired comparisons between the likeability ratings using the Wilcoxon test showed that all the differences were significant beyond the 0.001 level. Likeability ratings were lower for the negative player than for the neutral ($\Delta M = 1.0$, 95% CI: 0.62–1.32) and positive ($\Delta M = 1.8$, 95% CI: 1.41–2.16) players. They were also lower for the neutral player than for the positive one ($\Delta M = 0.8$, 95% CI: 0.52–1.11). During the final debriefing, only two participants claimed that they had not fully believed the other players were real.

Regarding the stop-signal task, the mean reaction time of the correct go trials was 449.9 ms ($SD = 103.1$). The global SSRT was 195.3 ms ($SD = 23.6$); the global SSD was 226.8 ms ($SD = 63.2$). As expected, because of the staircasing procedure, stop performance was approximately 50%

| Table 1. Means and standard deviations of self-report and behavioral measures for emotional conditions |
|---------------------------------------------------------------|
| **Attitude towards players (range 1–5)**                     |
| Negative  | Positive  | Neutral |
| 2.2 (0.8)  | 4.0 (0.5)  | 3.2 (0.5)  |

| **Stop performance**                                      |
|----------------------------------------------------------|
| Inhibition rate (%) | 52.2  | 52.4  | 52.5  |
| (5.8)              | (6.8) | (6.3) |
| SSD (ms)          | 226.0 | 228.9 | 225.5 |
| (63.5)            | (63.4) | (65.6) |
| SSRT (ms)         | 198.3 | 193.6 | 197.0 |
| (27.7)            | (32.3) | (27.0) |

Note. SSD = stop-signal delay; SSRT = stop-signal reaction time.

* Higher scores are associated with more positive attitude.

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1. We checked that there was no difference in self-report, behavioral, and ERP measures between males and females and there was no interaction between these measures and the sex of participants.

2. We checked that excluding these participants from the analyses did not significantly impact the results, therefore we report data for the whole sample.
correct in all three conditions and no main effect of emotion was observed in the mANOVA analysis, \( F(2,62) = 0.15, p = \text{ns} \). The SSRT did not differ significantly between the three stop-signal conditions, \( F(2,62) = 0.56, p = \text{ns} \), indicating that inhibitory performance was comparable in the negative, positive and neutral stop-signal trials. The SSD was also comparable in all conditions, \( F(2,62) = 0.62, p = \text{ns} \).

**ERP findings**

The mean amplitudes and standard deviations for the N2 and P3 components in all experimental conditions are shown in Table 2. Fig. 5 presents the grand-average ERPs to the stop signal with scalp distribution maps for difference waves.

**N2 component (200–250 ms)** The global analysis revealed that the main effect of trial type (successful vs. unsuccessful) was statistically significant, \( F(1,31) = 24.75, p < .001, \eta^2_p = 0.44 \). The ERPs time-locked to the stop signal in unsuccessfully inhibited trials showed a sharp negative peak which was attenuated in successfully inhibited trials (\( \Delta M = 3.6 \mu V, 95\% \text{ CI: 2.17–5.11} \)). The N2 amplitudes were statistically comparable, \( F(2,62) = 1.38, p = .26, \eta^2_p = 0.04, \) in the negative, positive and neutral trials (all \( \Delta M < 1.0 \mu V \)). The interaction effect (trial type \( \times \) stop-signal condition) did not reach significance, \( F < 1.0 \).

**P3 component (300–400 ms)** The ERPs time-locked to the stop signal in successfully inhibited trials displayed sustained positive activity (following the N2), which was less pronounced in unsuccessfully inhibited trials (\( \Delta M = 2.5 \mu V, 95\% \text{ CI: 1.59–3.34} \)). Indeed, ANOVA showed the main effect of trial type, \( F(1,31) = 32.97, p < .001, \eta^2_p = 0.52 \). Statistical analysis revealed that the main effect of the stop-signal condition was also significant, \( F(2,62) = 6.74, p = .002, \eta^2_p = 0.18 \). The P3 amplitudes time-locked to the stop signal in the negative condition were smaller than in the other two stop-signal conditions: positive, \( t(31) = 3.04, p = .005, d = 0.13 \) (\( \Delta M = 0.9 \mu V, 95\% \text{ CI: 0.28–1.44} \)); neutral, \( t(31) = 3.55, p = .001, d = 0.21 \) (\( \Delta M = 1.4 \mu V, 95\% \text{ CI: 0.58–2.16} \)). The P3 amplitudes did not differ between the positive and neutral stop-signal conditions, \( t(31) = 1.23, p = \text{ns} \) (\( \Delta M = 0.5 \mu V, 95\% \text{ CI:} -0.34–1.36 \)). The interaction effect (trial type \( \times \) stop-signal condition) did not reach significance, \( F < 1.0 \). Thus, the P3 amplitude reduction in the negative stop-signal trials was significant in both successfully and unsuccessfully inhibited trials.

**Exploratory source-localization analyses**

The results of our analyses raised the question of which regions of the brain might have contributed to the P3 amplitude reduction in the negative stop-signal trials. To answer this question, we examined the configuration of the neural generators underlying the difference in the P3 amplitude between the negative and the other two stop-signal conditions averaged together, since they did not statistically differ from one another. We used a distributed linear inverse solution, namely standardized low resolution brain electromagnetic tomography (sLORETA; Pascual-Marqui, 2002).

In sLORETA, estimations are made using the realistic three-shell head model, which is based on the Montreal Neurological Institute (MNI) 152 template provided by the Brain Imaging Center of the MNI (Mazziotta et al., 2001; Fuchs et al., 2002). The three-dimensional solution space is restricted to cortical gray matter and hippocampi. The intracerebral volume is divided into 6239 voxels with a spatial resolution of 5 mm. Neuronal activity is expressed as current density (\( \mu A/mm^2 \)). The number of active sources is not predefined. The localization accuracy of sLORETA has been repeatedly validated in studies that combined LORETA with functional magnetic resonance imaging (e.g., Mulert et al., 2004; Olbrich et al., 2009).

We compared the log-transformed power of the estimated electric current density over the P3 component’s time window (300–400 ms) between the negative and the other two conditions averaged together using a dependent-sample two-sided \( t \) test. The analysis was performed using statistical non-parametric mapping (Holmes et al., 1996). We adopted a bootstrap method with 5000 randomized samples. As a result, we obtained the exact significance threshold, regardless of non-normality and corrected for multiple comparisons. The level of significance was set to \( p < .05 \) for \( t \)-values above 4.36.

The analysis revealed that the P3 amplitude reduction in the negative stop-signal trials was surprisingly associated with significantly stronger activation in two widely distributed networks located in the right hemisphere\(^3\). One of them encompassed the inferior parietal lobule, including the angular and supramarginal gyrus, whereas the other extended over the lateral and dorsal surface of the frontal lobe, including the inferior, middle and superior frontal gyrus; see Fig. 6. The coordinates of local maxima are provided in Table 3. No cortical regions displayed a significantly stronger activation in the other two stop-signal conditions.

**DISCUSSION**

The aim of the present study was to test whether facial stimuli whose emotional valences were acquired through social learning during an interactive game may influence response inhibition in a subsequent cognitive task. The study was designed as a conceptual replication of previous experiments (Senderecka, 2016, 2018; Senderecka et al., 2018), but extended them to more naturalistic settings. We used the trust game to create a context for interpersonal competition over financial resources and consequently induced negatively and positively valenced emotions towards the unfair and fair partner, respectively, and an emotionally neutral attitude towards the passive player. Pictures of players’ faces with neutral expressions were subsequently used as stop signals in the stop-signal task. We hypothesized that response inhibition in trials with briefly presented faces of negative and

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\(^3\) No significant voxels were obtained with the analogous comparison performed over the N2 component’s time window (200–250 ms).
positive partners would be enhanced on the behavioral and neural levels as compared to the trials with the neutral player. The results revealed that the trust game was an effective paradigm for inducing differently valenced emotions towards players; however, behavioral inhibitory performance was comparable in all stop-signal task conditions. On the neural level, contrary to our hypothesis we found decreased P3 amplitude in negative trials. As revealed by our sLORETA analysis, this was due to significantly stronger activation in two right-lateralized networks: one encompassing the inferior parietal lobule; the other extending over the lateral and dorsal surface of the frontal lobe.

In line with our hypothesis and previous research (e.g., Gilam et al., 2015, 2019; Singer et al., 2004), the economic game turned out to be a valid paradigm for inducing social emotions. Compared to pictures of neutral players, faces of positive and negative partners were rated as significantly more and less likeable, respectively. Importantly, given that all faces displayed on photographs had neutral expressions and were randomly distributed across participants, affective ratings cannot be attributed to differences in facial features.

The behavioral outcomes of the stop-signal task revealed that faces of negative and positive partners did not influence the SSRT as compared to faces of neutral players. These findings stand in opposition to those reported in many previous studies ( Pessoa et al., 2012; Pawliczek et al., 2013; Senderecka, 2016, 2018; Xu et al., 2016; Litman and Takacs, 2017; Williams et al., 2020; Zheng et al., 2020), in which emotional, arousing scenes, faces, or sounds improved response inhibition by decreasing SSRT. At the same time they are in line with the results of other studies, however much less numerous, in which the presentation of affective stimuli did not elicit an emotional facilitation effect on inhibitory performance as compared to the neutral condition ( Sagaspe et al., 2011; Camfield et al., 2018; Senderecka et al., 2018). In these works, the lack of emotional facilitation was due to either the low arousing power of the stimuli or their irrelevance to the main task in which participants were engaged. In the present study, an affective context was formed by task-relevant stop-signals. This suggests that the lack of emotional enhancement was probably due to the insufficient arousing power of the stimuli used in the economic game. Specifically, their influence could be time- and context-limited in such a way that it did not prospectively generalize to the subsequent task, which did not involve social interactions and interpersonal competition.

As for the stop-signal-related brain activity, the N2 component was larger in unsuccessful than successful stop-signal trials, which is in line with the findings of previous studies (e.g., Kok et al., 2004). The N2 in the stop-signal task is implicated as an index of an evaluative process that detects the conflict between go and inhibitory responses ( Nieuwenhuis et al., 2003; Yeung et al., 2004). In unsuccessful stop trials, the inhibitory response cannot override the go response before it is executed, therefore the conflict is greater and consequently evokes enhanced N2 amplitudes. In our previous experiment (Senderecka, 2016), we observed a relatively large difference between the N2 amplitudes evoked by threatening and neutral pictures in both successful and failed stop trials. In the present study, the lack of significant discrepancies in the N2 amplitude between negative, positive and neutral trials suggests that the likeability of the three players’ faces did not influence the strength of the conflict between the go and inhibitory processes in the stop-signal task. Apart from this inhibitory framework, it is worth noting that the N2 component has also been used in the field of social cognition to examine the process of social categorization. In this context, several findings suggest that the N2 component reflects attention to individuating information and vigilance for faces of in-group members ( Dickter and Bartholow, 2007, 2010; Lucas et al., 2011; Willadsen-Jensen and Ito, 2008; for review, see Ito and Bartholow, 2009). Specifically, N2 amplitude is typically larger for more familiar individuals. Thus, from a social cognition perspective the lack of significant differences in N2 amplitude between the three conditions may also indicate that the faces of negative, positive and neutral game partners were equally familiar to participants.

With regard to the second component of the N2-P3 complex, we observed a higher P3 amplitude for successfully inhibited trials than for unsuccessfully inhibited ones, which aligns with the results of other research (e.g., De Jong et al., 1990). The P3 in the stop-signal task context is considered a marker of cognitive control mechanisms; in particular, monitoring of the outcome of inhibitory processes is more effective in successful stop trials (e.g., Nieuwenhuis et al., 2003). The crucial finding of the present study is that the processing of negatively valenced stop signals, as compared to positive and neutral ones, was associated with a reduced P3 amplitude in both successfully and unsuccessfully inhibited trials, despite the balanced behavioral performance across task conditions. This observation stands in opposition to our predictions and to the results of our previous study (Senderecka, 2018), in which aversive auditory stop

| Components’ mean amplitude results (µV) | Global | Negative | Positive | Neutral |
|-----------------------------------------|--------|----------|----------|---------|
| N2 component                            |        |          |          |         |
| Successful stop                         | -5.1 (8.6) | -5.5 (8.2) | -5.1 (9.1) | -4.6 (9.4) |
| Unsuccessful stop                       | -8.7 (8.3) | -9.0 (8.0) | -8.5 (8.5) | -8.4 (9.0) |
| P3 component                            |        |          |          |         |
| Successful stop                         | 17.7 (7.0) | 16.9 (7.3) | 17.9 (7.2) | 18.2 (7.1) |
| Unsuccessful stop                       | 15.2 (6.3) | 14.4 (6.3) | 15.3 (7.2) | 15.9 (6.2) |
signals elicited a larger P3 relative to neutral tones, thus reflecting an enhancement of cognitive control in the emotional condition. It also stands in contrast to many previous studies in which increased P3 was typically observed following the presentation of emotional (both pleasant and unpleasant) compared to neutral stimuli (for reviews, see Hajcak et al., 2010; Olofsson et al., 2008). The present pattern of results indicates that pictures of negative players’ faces adversely impacted the recruitment of the brain mechanisms responsible for the

Fig. 5. ERP results. N2 component (A): stop-signal-locked grand-average waveforms at pooled electrodes Fz, FC1, FC2, Cz for successful and unsuccessful stop trials (left part), negative, positive and neutral successful stop trials (middle part), negative, positive and neutral unsuccessful stop trials (right part). P3 component (B): stop-signal-locked grand-average waveforms at pooled electrodes Pz, P3, P4, PO3, PO4 for successful and unsuccessful stop trials (left part), negative, positive and neutral successful stop trials (middle part), negative, positive and neutral unsuccessful stop trials (right part). Topographic maps for difference waves in the N2 time window 200–250 ms (A) and in the P3 time window 300–400 ms (B) illustrate the most important effects. Neg = negative, neu = neutral, pos = positive, succ = successful stop trials, unsucc = unsuccessful stop trials.
evaluation of inhibitory processes (as indexed by decreased P3 amplitude). However, this impact was not sufficient to increase the latency of reactions to the stop signal on the behavioral level.

This finding becomes particularly interesting when compared with the results of several ERP studies that indicated an association between P3 amplitude and reward processing (for review, see Proudfit, 2015). The P3 component (in this context more frequently called reward positivity) is typically more pronounced for stimuli that signal personal benefits and therefore have high value and enhanced motivational significance. This association is most evident in gambling tasks (e.g., Wu and Zhou, 2009) and economic exchanges (e.g., Moser

Table 3. Brain regions showing significantly stronger activation for negative stop signals as compared to the other two stop-signal conditions over the P3 component’s time window (300–400 ms). Maximum t values, coordinates of local maxima in MNI space, their respective Brodmann areas, and number of significant voxels are listed

| Brain area                                      | Number of significant voxels | BA  | Coordinates$^a$ | $p$   |
|------------------------------------------------|-----------------------------|-----|-----------------|-------|
| Right angular gyrus, right supramarginal gyrus, right inferior parietal lobule | 10                           |     | 39               | 50X, −70Y, 30Z | 5.20 |
|                                                 |                              |     | 40               | 60X, −55Y, 35Z | 4.71 |
| Right inferior frontal gyrus, right middle frontal gyrus, right superior frontal gyrus | 16                           |     | 10               | 35X, 60Y, −5Z  | 4.72 |
|                                                 |                              |     | 11               | 40X, 55Y, −10Z | 4.42 |

Note. BA = Brodmann area; X, Y, Z, coordinates in MNI space; X corresponds to the left–right, Y to the posterior–anterior, Z to the inferior–superior dimension.

$^a$ Coordinates of local maxima.

$^b$ df = 1,31.
et al., 2014) in which advantageous offers elicit higher P3 amplitudes than disadvantageous ones. In this vein, it is certainly worth noting a study by Ruz and colleagues (2013) in which P3 amplitude was measured in response to the faces of several trustworthy and untrustworthy players taking part in an interpersonal game in which participants received good or bad economic offers. Interestingly, the analysis revealed that P3 was significantly smaller for untrustworthy than trustworthy players, regardless of their facial expressions. This suggests that faces of untrustworthy players were processed as signals of personal loss, in contrast to rewards that typically evoke larger P3 amplitudes. Similarly, in our study, pictures of negative players’ faces could have lower rewarding value, which in turn could decrease the amplitude of P3 in both conditions of the stop-signal task.

Thus, an important implication of our findings is that multiple neural mechanisms (other than those underlying inhibitory control) may modulate ERP generation in the emotional stop-signal task. A reduced P3 component in response to negatively valenced stop-signals raised the question of which brain regions might have specifically contributed to this effect. To shed some additional light on this area, we performed source-localization analysis. The configuration of the neural generators underlying the difference in the P3 amplitude between the negative and the other two stop-signal conditions revealed that the effect was due to more extensive involvement of two cortical networks in the right hemisphere: one of them extended over the inferior parietal lobule, including the angular and supramarginal gyrus; the other encompassed the lateral and dorsal surface of the frontal lobe, including the inferior, middle and superior frontal gyrus in the prefrontal cortex. These findings have important consequences for the interpretation of our study. The right inferior parietal lobule constitutes an essential part of the right temporoparietal junction, a region which is believed to be involved in theory-of-mind operations. A number of functional magnetic resonance imaging studies have indeed demonstrated that these structures are engaged when individuals are attempting to access others’ mental states (for review, see Patel et al., 2019). In addition, the temporoparietal junction is one of the most expanded cortical regions in humans compared to macaques (Hill et al., 2010); it is also one of the last to develop, maturing in young adulthood at a similar time as the prefrontal cortex (Sotiras et al., 2017). Based on its functional involvement, evolutionary expansion and ontogenetic development, Patel and colleagues (2019) have recently proposed that the temporoparietal junction (along with the posterior superior temporal sulcus) works as a hub that coordinates and integrates the activities of the numerous brain networks that are necessary for complex social functioning. Specifically, the right inferior parietal lobule, in conjunction with the prefrontal cortex, plays a crucial role in the frontoparietal control network. This frontoparietal processing stream underlies the increased social abilities in humans, e.g., memory-guided inference of others’ mental states (Spreng and Mar, 2012), and maintenance of the balance between the processing of external information and internally stored models of social agents and situations (Dixon et al., 2018). In addition, the dorsolateral prefrontal cortex itself (in particular, in the right hemisphere) has often been implicated in the implementation of fairness norms and social moral judgment (Moll et al., 2003, 2005; Greene et al., 2004; Spitzer et al., 2007).

Thus, in our study pictures of unfair players’ faces, in contrast to those of fair and neutral players, led to higher engagement of the neural network, which supports inferring the mental states of others based on personally reexperiencing the past. Going a step further, we can assume that participants possessed a mental history of past interactions with the unfair player that were acquired during the game and were re-experienced and rejudged during the subsequent inhibitory task. Mentalizing about the unfair player exceeded that for the fair player, thus pointing to an enhanced saliency of deception in human interaction as compared to mutual cooperation, which is in line with evolutionary considerations (Cosmides and Tooby, 2000). Since the function of memory retrieval is not only to recall the past but to construct flexible models of the future (Schacter et al., 2008), higher activity in the mentalizing network for unfair than fair players seems particularly adaptive, especially given that the costs of making inaccurate predictions in the social domain are usually very high.

To sum up, this study examined for the first time the influence of emotion elicited within an interactive social context on response inhibition in the subsequent cognitive task. Taken as a whole, our findings indicate that facial stimuli whose negative valence was acquired through social learning during an interactive economic game were able to evoke neural activity in the frontoparietal network, supporting social knowledge retrieval, in the subsequent inhibitory task. This process was reflected in the ERPs by a decreased stopping-related P3 amplitude. However, although the activity of the frontoparietal network was significantly higher in the negative as compared to the two other conditions of the stop-signal task, it did not interfere with inhibitory processing on the behavioral level. In a broader perspective, the present findings suggest that pictures of unfair players’ faces elicited mentalizing rather than basic bottom-up emotional responses. This discrepancy may, in turn, explain why they had a different effect on response inhibition than previously observed for aversive pictures and sounds (Senderoecka, 2016, 2018). An issue for future research will be to examine whether these effects differ by individual characteristics. Since social cognitive deficits are well recognized in some psychiatric and developmental disorders, such as schizophrenia or autism (e.g., Pinkham et al., 2008), it would surely be worthwhile to replicate the present results after controlling for the subclinical symptoms of these conditions. Such studies may offer valuable insight into what may be driving our findings.

In conclusion, despite the growing emphasis on embedding interactive social paradigms in the field of cognitive and affective neuroscience, the impact of socially induced emotions on cognition still remains...
widely unknown (for an exception, see Matyjek et al., 2021). Our study makes an important contribution in this respect by showing that emotionally charged social interactions that take place during an economic game may influence brain activity within a mentalizing network in a subsequent inhibitory task. Future studies are surely needed to assess whether similar results can be obtained for cognitive processes other than response inhibition.

DECLARATIONS OF INTEREST

None.

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