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Xukai Zhang

Pursuit of Interpersonal Relationships

Behavioral and Brain Response Correlates of Social Acceptance and Rejection

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF EDUCATION AND PSYCHOLOGY

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ABSTRACT

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Pursuing and building social connections is important for people's well-being. However, the neural underpinnings of a range of decision-making behaviors and social interactions in the pursuit of social relationships remain unclear. To explore these behaviors and interactions, I designed three studies using a novel online speed dating task, along with the recording of brain activity using electroencephalogram (EEG) technology. In **Study I**, I explored the behavior and EEG responses of participants in the stages of decision-making, anticipation, and outcome evaluation in pursuit of romantic relationships. In **Study II**, I further explored how waiting time affects the outcome evaluation stage, as social feedback is not always immediate in social context. In **Study III**, I examined the effect of oxytocin on social rejection because the previous studies showed oxytocin to be a promising candidate for regulating social behavior and reducing negative emotions. The results show that, in **Study I**, participants exhibited more negative stimulus preceding negativity (SPN), when they waited for social evaluation from important compared to unimportant others. The largest reward positivity (RewP) was observed when participants received acceptance from important others and the greatest theta power was observed when participants received a rejection from important others. Furthermore, the burst of theta power was source-localized to the anterior cingulate cortex and frontal pole, which is related to physical pain processing. In **Study II**, the reduced RewP was observed for the feedback from unimportant others in the long wait condition. On the contrary, the increased RewP was observed for the feedback from important others in the long wait condition. In **Study III,** the oxytocin group showed significantly lower theta power than the placebo group when they received a social rejection. Also, the negative correlation between theta power and self-reported pleasantness ratings was found only in the placebo group, not in the oxytocin group. Taken together, my dissertation highlights the role of SPN, RewP, and theta oscillations in social relationship pursuit, reveals the effects of subjective preference and wait time on the processing of social feedback, and provides pharmacology-electrophysiological evidence that oxytocin alleviates social pain induced by social rejection.

Keywords: interpersonal relationship, EEG, social rejection, social acceptance, oxytocin, outcome evaluation

TIIVISTELMÄ (FINNISH ABSTRACT)

Xukai Zhang
Ihmissuhteiden tavoittelu: Käyttäytymis- ja aivovasteet korreloivat sosiaalisen hyväksynnän ja hylkäämisen välillä
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Sosiaalisten yhteyksien tavoitteleminen ja rakentaminen on tärkeää ihmisten hyvinvoinnille. Kuitenkin useiden päätöksentekokäyttäytymisten ja sosiaalisten vuorovaikutusten hermoperustat sosiaalisten suhteiden tavoittelussa ovat edelleen epäselviä. Tutkiakseni näitä käyttäytymismalleja ja vuorovaikutuksia suunnittelin kolme tutkimusta käyttämällä uutta online-pikatreffitehtävää sekä aivojen toiminnan tallentamista elektroenkefalogrammi (EEG) -tekniikalla. Tutkimuksessa I tutkin osallistujien käyttäytymistä ja EEG-vasteita päätöksenteon, ennakoinnin ja tulosten arvioinnin vaiheissa romanttisten suhteiden tavoittelussa. Tutkimuksessa II tutkin edelleen, miten odotusaika vaikuttaa tulosten arviointivaiheeseen, koska sosiaalinen palaute ei ole aina välitöntä sosiaalisessa kontekstissa. Tutkimuksessa III tutkin oksitosiinin vaikutusta sosiaaliseen hylkäämiseen, koska aiemmat tutkimukset osoittivat oksitosiinin olevan lupaava ehdokas sosiaalisen käyttäytymisen säätelyyn ja negatiivisten tunteiden vähentämiseen. Tutkimuksessa I koehenkilöillä oli enemmän negatiivista ”ärsykettä edeltävää negatiivisuutta” (stimulus preceding negativity), kun he odottivat sosiaalista arviointia tärkeiltä vs. ei-tärkeiltä osapuolilta. Suurin palkintopositiivisuus (RewP) ja suurin theta-teho havaittiin, kun koehenkilöt saivat hyväksynnän ja hylkäämisen tärkeiltä osapuolilta. Lisäksi theta-tehon purkauksen lähde paikannettiin etukuoreen ja frontaaliseen napaan, mikä liittyy fyysisen kivun käsittelyyn. Tutkimuksessa II alentunutta RewP:tä havaittiin tapuaksissa, joissa paluate saatiin ei-tärkeiltä osapuolilta pitkän odotusajan jälkeen. Vastaavasti tätä suurempia RewP-arvoja havaittiin, kun palaute saatiin tärkeiltä osapuolilta pitkän odotuksen jälkeen. Tutkimuksessa III oksitosiiniryhmällä oli merkittävästi pienempi theta-teho sosiaalisen hylkäämisen tilanteissa verrattuna verokkiryhmään. Negatiivinen korrelaatio theta-tehon ja ahdistuksen välillä havaittiin vain verokkiryhmässä, mutta ei oksitosiiniryhmässä. Kaiken kaikkiaan tutkimuksemme valaisee parisuhteen etsimiseen liittyviä neurokognitiivisia mekanismeja ja tuo esiin mahdollisia terapeuttisia lähestymistapoja sosiaalisiin suhteisiin liittyvien negatiivisten kokemusten hoitoon.

Keywords: ihmissuhde, EEG, sosiaalinen hylkääminen, sosiaalinen hyväksyntä, oksitosiini, tulostenarviointi

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FIGURES

FIGURE 1 Schematic representation of the novel online speed dating task 34
FIGURE 2 Schematic representation of Study II.. 36
FIGURE 3 Behavioral data and Self-reported questionnaires in Study I....... 46
FIGURE 4 Stimulus preceding negativity (SPN) in Study I 47
FIGURE 5 Reward positivity (RewP) in Study I....... 48
FIGURE 6 Results of PCA to extract RewP in Study I. 49
FIGURE 7 Time-frequency theta oscillation in Study I. 50
FIGURE 8 Source maps of theta oscillation in Study I 51
FIGURE 9 Statistical differences of theta source activity in Study I....... 52
FIGURE 10 Behavior and self-reported ratings in Study II 54
FIGURE 11 Results of reward positivity (RewP) in Study II....... 56
FIGURE 12 Self-reported pleasantness in Study III 59
FIGURE 13 Time-frequency theta oscillation in Study III....... 60
FIGURE 14 Source maps of theta oscillation in Study III....... 62
FIGURE 15 The Pearson correlation between self-reported pleasantness and theta power in the Rejection condition for the placebo (PLC) and oxytocin (OT) groups 63

TABLES

TABLE 1 Basic information of the participant in StudyI, II and III 29
TABLE 2 Participant demographic and trait information in Study III 31
TABLE 3 The parameters of the stimulus presented in the experiment....... 33
TABLE 4 Summary of parameters for event-related potentials, time-frequency analysis, and source localization analyses in EEG data 40
TABLE 5 Average response time for making judgments and the number of trials for each possible outcome for Study I 42
TABLE 6 Average response time for making judgments and the number of trials for each possible outcome for Study II....... 43
TABLE 7 Average response time for making judgments and the number of trials for each possible outcome for study III....... 44
TABLE 8 Summary of behavioral results from StudyI, II and III 64
TABLE 9 Summary of questionnaire results from StudyI, II and III....... 65
TABLE 10 Summary of EEG results from StudyI, II and III 68

CONTENTS

ABSTRACT
TIIVISTELMÄ (FINNISH ABSTRACT)
ACKNOWLEDGMENTS
LIST OF ORIGINAL PUBLICATIONS
FIGURES AND TABLES
CONTENTS

1 INTRODUCTION 13
1.1 Interpersonal relationships 13
1.1.1 The need to belong 13
1.1.2 Social feedback in the interpersonal relationship 14
1.2 Neuroimaging in human relationships 15
1.2.1 Electrophysiological indices 16
Stimulus preceding negativity (SPN) 17
Reward positivity (RewP) 17
Frontal-midline theta oscillation 18
1.3 Behavioral indices related to the pursuit of relationships 19
1.4 Social acceptance and rejection 20
1.4.1 Social acceptance 20
1.4.2 Social rejection 21
Social pain 21
1.5 Social feedback delay 22
1.5.1 Waiting time as the cost 24
1.6 Oxytocin and social bonding 24
1.6.1 The effects of oxytocin on social bonding 25
1.6.2 The pain-reducing effects of oxytocin 25
1.7 Purpose and hypothesis of the research 26
1.7.1 Study I 27
1.7.2 Study II 28
1.7.3 Study III 28

2 METHODS 29
2.1 Participants 29
2.2 Experimental design 31
2.2.1 Cover story 31
2.2.2 Stimuli 32
2.2.3 Procedure 33
2.3 EEG data acquisition and processing 37
2.4 EEG data analyses 37
2.4.1 Event-related brain potential analyses 37
2.4.2 Time-frequency power analyses 38
2.4.3 Source localization analyses 38

2.5 Statistical analysis 40
2.5.1 Study I 40
2.5.2 Study II 42
2.5.3 Study III 43

3 SUMMARY OF THE RESULTS 45
3.1 Study I 45
3.1.1 Behavioral results 45
3.1.2 Questionnaire results 45
3.1.3 EEG results 46
Stimulus preceding negativity (SPN) 46
Reward positivity (RewP) 47
Theta oscillation 49
Source localization 50
3.2 Study II 53
3.2.1 Behavioral results 53
3.2.2 Questionnaire results 53
3.2.3 EEG results 55
Reward positivity (RewP) 55
3.3 Study III 57
3.3.1 Behavioral results 57
3.3.2 Questionnaire results 57
3.3.3 EEG results 59
Theta oscillation 59
Source localization 61

4 DISCUSSION 70
4.1 Behavior patterns of seeking for interpersonal relationships 72
4.2 Emotional responses to social evaluations 73
4.3 Brain responses to social evaluations 74
4.4 Waiting time reshapes the value of social evaluations 76
4.5 Oxytocin alleviates social pain 79
4.6 General discussion 81
4.7 Limitations 83
4.8 Future directions 84

YHTEENVETO (SUMMARY) 86

REFERENCES 88

ORIGINAL PAPERS

1 INTRODUCTION

1.1 Interpersonal relationships

Humans are essentially a social species that relies on building and maintaining relationships for survival and mental health (Baumeister & Leary, 1995; Lieberman, 2013; Linden & Maercker, 2011). Whether in novels, movies, songs, plays, or poems, interpersonal relationships are a universal topic that describes the happiness and despair of human beings (Aron et al., 2005; Fisher & Garcia, 2019; Jackson-Dwyer, 2013). Good interpersonal relationships play a decisive role in our satisfaction with life, work, and play (Agnew & South, 2014; Saeri et al., 2018; Umberson & Karas Montez, 2010). When asked, ”What makes your life meaningful?”, almost all respondents gave ”being loved and needed” as one of their answers (Klinger, 1977). In addition, choosing someone who is willing to share life in an intimate way is one of the most important decisions we make in our lives (Jackson-Dwyer, 2013; Joel, Plaks, & MacDonald, 2019). This is mate selection, which is a basic human endeavor, but also one of the most influential life behaviors. A romantic relationship offers love, affection, sexual activity, social support, and importantly, emotional intimacy that is often not found in other relationships, no matter how intimate they are (Jackson-Dwyer, 2013). Friendship, on the other hand, is another important social relationship throughout our lifespan. In a survey, Bibby (2001) showed that 85 percent of people think friendship is more important than power, recognition, excitement, and having a comfortable life. This result indicates the supreme status of interpersonal relationships.

1.1.1 The need to belong

We have a strong sense of belonging and an even greater avoidance and aversion to rejection (Baumeister & Leary, 1995). Not only do we spend most of our lives being close to others – living, working, studying, eating, and talking – but we also want to be accepted by others at some minimum level (Leary, 2001).

Alfred Adler (1930) was the first to propose that humans have a basic need for belonging, and stated that social feeling is the key and decisive factor in normal development. Later, Baumeister and Leary (1995) completed a landmark article in which they systematically reviewed the evidence to support the view that belonging is a basic human need. The belonging hypothesis argues that ″to form and maintain strong, stable interpersonal relationships is a human motivation,″ and that the motivation is ″powerful, fundamental, and extremely pervasive.″ According to this hypothesis, humans have an innate need to form attachments – that is, to seek the companionship of others – and to establish and maintain some number of enduring, positive, and essential relationships. Baumeister and Leary (1995) compared the need to belong to hunger and thirst, which can be solved by searching for food and water. The criteria for satisfying belongingness, therefore, are relatively frequent and affectively positive interactions with other people, and sustained and stable interpersonal relationships and mutual affective care are other important criteria.

According to the belongingness hypothesis (Baumeister & Leary, 1995), the characteristics of human belonging need are as follows. (A) The process of forming social groups is natural and applies to people of all cultures. (B) Early in life, babies form attachments that are innate (with caregivers). Attachment forms eagerly and rapidly throughout human life, and people hate and resist breaking it. (C) Human cognitive functions focus on social connections to maintain and promote social relationships. (D) Forming a group is spontaneous, even if there are no emotional or material rewards. (E) Changes in relationships can lead to strong emotional responses. Good relationships lead to feelings of happiness and contentment, while poor relationships lead to negative emotional responses such as anxiety, depression, and loneliness. (F) Lack of attachment can adversely affect people’s health with an increased risk of mental and physical illness.

1.1.2 Social feedback in the interpersonal relationship

From an evolutionary perspective, social acceptance and social rejection serve as important social signals in the formation of interpersonal relationships (Baumeister & Leary, 1995; Gere & MacDonald, 2010; Leary & Acosta, 2018). One idea is that humans’ strong and universal drive for social acceptance may have been an adaptive behavior, because early humans who lived in groups and supported each other were more likely to survive and reproduce than those who lived alone, which led to establishing and maintaining contact with others becoming a driving force (Baumeister & Leary, 1995; Gere & MacDonald, 2010). Conversely, social rejection is a potentially threatening social signal, and humans are more sensitive to monitoring and avoiding the possibility of being rejected by others (Leary & Acosta, 2018).

With the development of human society, when people consider peer selection or forming groups in modern social relationships, they at least try to determine how these individuals or groups perceive and evaluate them (Baldwin, 2006). When two people go on a first date and want to get to know each other, they may also want to know each other's first impressions and feelings about each other. Similarly, in the process of building a new social relationship, with the interaction between people, we may learn more about each other, and we may also pay attention to others' evaluation of ourselves (Baldwin, 2006). Therefore, social feedback provides people with a window into how others view them.

The behaviors that we colloquially call ″acceptance″ and ″rejection″ seem to reflect differences in the relational evaluation; that is, how valuable, important, or intimate an individual thinks an actual or potential relationship with another person is (Leary, 2006; Leary & Acosta, 2018). In addition, the feelings of being ″accepted″ occur when the individual perceives that the relational evaluation is considered valuable for others, and the feelings of being ″rejected″ occur when the individual perceives that the relational evaluation is worthless to others or perceived as devalued compared to previous relational values they had (Leary, 2001). In other words, received social acceptance and rejection from others serve as social feedback signals that convey an assessment of the value of actual or potential social relationships.

People do not simply respond to objective ″acceptance″ and "rejection," but their subjectively perceived relational evaluation in the eyes of others (Leary, 2001). However, an essential factor that influences perceived relational evaluation and the reaction to events is a personal preference (Kelly, 2001; Leary, 2001). For example, when faced with different individuals, some people need to perceive greater relational evaluation than others before they can feel accepted. In different relationships, the same low relational evaluation may make us feel rejection in a relationship, but not in another one (Kelly, 2001; Leary, 2001). Similarly, for the reaction to the events, for example, the forgotten birthday is clearly an event in which people can infer that they are treated in low relational evaluation, but we do not have strong reactions to everyone who does it because we do not care about the relational evaluation of the person who offends us. Therefore, individual preferences and the nature of relationships should be taken into account when studying how people respond to social evaluation by others.

1.2 Neuroimaging in human relationships

With the development of neuroimaging technology, neuroimaging provides us with an important opportunity to explore the complexity of brain function in human relationships and social evaluation (Eisenberger, 2015; Gere & MacDonald, 2010; Leary & Acosta, 2018). In social life, common separation and negative social evaluation often threaten the sense of belonging (Leary, 2006; Leary & Acosta, 2018). Therefore, the negative effects of negative evaluation and poor social relations have also been concerned by many researchers.

A series of functional magnetic resonance imaging (fMRI) studies have examined how brain responses to different types of belonging are treated. In the social exclusion study, in a ball-tossing game (cyberball task), some participants were excluded (rarely passed to by other peers). By using the cyberball task, the first fMRI study revealed that the dorsal anterior cingulate cortex (dACC) and the anterior insula (AI) were activated when the participants were excluded during the game (Eisenberger et al. 2003). The result also found a positive correlation between the activation of dACC and self-reported feelings during social exclusion. Subsequent studies replicated similar results, showing increased dACC and AI activity in response to social exclusion (Bayer et al., 2018; Chester, DeWall, & Pond, 2016; Kawamoto et al., 2012; Masten, Telzer, & Eisenberger, 2011; Masten, Telzer, Fuligni, Lieberman, & Eisenberger, 2012; see Eisenberger, 2015, for a review). The activities of dACC and AI were positively correlated with self-reported feelings of social exclusion (DeWall et al., 2012; Eisenberger, Gable, & Lieberman, 2007; Onoda et al., 2009). Similar results were found in other experiments that threatened belonging; for example, by viewing pictures of social rejection (Kross et al. 2007; He et al., 2020), recalling romantic rejection (Fisher et al. 2010, Kross et al. 2011), and recalling a lost loved one (Gundel et al. 2003, Kersting et al. 2009, O'Connor et al. 2008).

In addition, electroencephalogram (EEG) technology with high temporal resolution (at the millisecond level) provides additional useful information to help us understand brain processes in human relationships. One research group completed a series of EEG studies by using a social evaluation task, in which the participants received social evaluation based on first impressions (like or dislike) from their peers. The results showed that 200 ms before the social evaluation, participants showed increased stimulus preceding negativity (SPN), a slow negative potential (Van der Molen et al., 2014). They also found an increased EEG theta response (4–8 Hz) at a 200–400 ms time window after participants received negative feedback (that is, social rejection) (Van der Molen et al., 2017; 2018). Furthermore, Van Noordt et al. (2015) found a positive correlation between late EEG theta power (400–800 ms) and self-reported distress during social exclusion in the cyberball paradigm.

However, most previous studies have focused on established relationships (such as romantic relationships, kinship, and friendship). Few studies have looked at the stage of relationship pursuit that precedes relationship formation (Cooper et al., 2014; van der Veen et al., 2019). Moreover, there is not just one stage in the process of pursuing interpersonal relationships. The present dissertation includes the decision-making stage (choosing important others), the anticipatory stage (waiting to receive others' feedback), and the outcome evaluation stage (processing of others' feedback). Therefore, I used high time-resolution EEG technology to capture individual brain dynamics at these different stages of interpersonal pursuit.

1.2.1 Electrophysiological indices

The high temporal resolution of electroencephalography (EEG) provides a way to study the dynamics of brain activity at different stages of pursuing interpersonal relationships in the laboratory. We focused on event-related potentials representing the anticipated stage and the outcome evaluation stage for social feedback.

Stimulus preceding negativity (SPN)

Researchers use an event-related potential (ERP) component, stimulus preceding negativity (SPN), to measure individuals' anticipatory motivation.
The classic SPN is a slow negative deflection with frontocentral distribution that is characterized by a gradual increase before the onset of the feedback stimulus (Van der Molen et al., 2014). It is generally considered to be a neural indicator that individuals use to measure the affective or motivational valence before they get the results of their own actions (Pornpattananangkul & Nusslock, 2015). Previous studies have indicated that a more negative SPN reflected a more significant motivation for expected stimuli (Böcker et al., 2001; Brunia et al., 2011; Pornpattananangkul & Nusslock, 2015; Foti & Hajcak, 2012). Specifically, in a slot machine game, if the first two icons are the same, the SPN is higher when people wait for the third icon, compared to the first two icons being different (Donkers, Nieuwenhuis, & van Boxtel, 2005). Additionally, Pornpattananangkul and Nusslock (2015) found that the reward condition increased the SPN compared to the non-reward condition during the anticipatory stage. In addition to non-social reward, social evaluation also affects our mood, motivation, and satisfaction of our needs (Oumeziane et al., 2017). Recently, an EEG study revealed the role of SPN during waiting for the social feedback from others, showing a greater SPN when participants expected the other person to like them than when they expected the other person to dislike them (Van der Molen et al., 2014). Therefore, given the SPN's role in representing anticipatory motivation prior to feedback, it was used to explore the anticipatory motivation of participants before they received social evaluation from different types of their peers in the pursuit of social relationships in my dissertation.

Reward positivity (RewP)

For the outcome evaluation stage (processing of others' feedback), I focused on reward positivity (RewP), which is a positive deflection ERP component that appears at the frontal central areas and peaks around 250–350 ms following feedback (Foti, Weinberg, Dien, & Hajcak, 2011; Holroyd & Coles, 2002; Holroyd & Umemoto, 2016). A series of studies from source localization analysis (Gehring & Willoughby, 2002; Miltner et al., 1997), simultaneous recording of EEG/fMRI studies (Becker et al., 2014; Hauser et al., 2014a), transcranial direct current stimulation study (Reinhart & Woodman, 2014), and intracranial recording with animals (Emeric et al., 2008; Warren et al., 2015), and humans (Smith et al., 2015) have shown that reward positivity is generated in the anterior cingulate cortex (ACC).

The early reinforcement learning theorists proposed that RewP is more sensitive to unfavorable (negative) than favorable (positive) feedback, which is reflected in relative negativity potential when people receive negative feedback (such as an error signal; hence, the original name was feedback-related negativity; FRN) (Holroyd & Coles, 2002). The reinforcement learning theory (Holroyd & Coles, 2002) assumes that the FRN is generated by the dorsal anterior cingulate cortex (dACC) and reflects an inhibition or disinhibition of neurons caused by midbrain dopamine reward prediction error signals. Moreover, an updated reinforcement learning theory proposes that the RewP is relatively more sensitive to positive (such as, reward) than to error feedback (Holroyd et al., 2008; Sambrook & Goslin, 2015). The relatively positive deflection occurs when people receive the positive feedback. This neural response to positive feedback is due to inhibition of ACC activity by the increased dopamine phase (Holroyd et al., 2008). Due to the character of the neural response to positive feedback, such positivity is reduced or absent in the event of a negative outcome (such as loss) and also leads to the relative negativity observed after negative feedback (Sambrook & Goslin, 2015; Peterburs et al., 2016; Holroyd & Umemoto, 2016).

In earlier studies using RewP, researchers focused primarily on monetary outcomes (for example, losing or winning money) and points (Becker et al., 2014; Foti, Weinberg, Dien, & Hajcak, 2011; Holroyd & Coles, 2002; Holroyd, Pakzad-Vaezi, & Krigolson, 2008). However, there is growing interest in assessing the neural basis of social decision-making and social reward processing. Social reward has been widely studied and is considered to be an important reward that has a significant impact on the development of individual behavior (Cooper et al., 2014; Weinberg et al., 2021). Social rewards, such as social reputation and social acceptance, can be considered positive reinforcers, increasing the likelihood that the behavior will be performed in the future (Matyjek et al., 2020). Previous studies have not only used RewP as a neural indicator of monetary reward processing, but RewP also reflects the processing of social reward (Ethridge et al., 2017), in which the larger RewP reflected a higher reward value. In my dissertation, I focus on how individuals process social feedback while pursuing interpersonal relationships, especially when people receive social rejection and social acceptance from others. Therefore, in my dissertation, based on the value processing of social feedback reflected by RewP, I used RewP to explore the changes of social reward under different conditions.

Frontal-midline theta oscillation

Time-frequency analysis was used to examine the modulation of specific frequencies during the outcome evaluation stage (processing of others' feedback). In the analysis of multi-dimensional EEG data, the decomposition of frequency information as an important dimension provides an opportunity to link the EEG data with experimental manipulation, individual behavior, and other neurophysiological processes (Cohen, 2014). The results of time-frequency analysis make it possible to explain the neurophysiological mechanism of neural oscillations (Cohen, 2014; Cohen, 2017). Numerous studies have shown that perceptual, cognitive, motor, and emotional processes are closely linked to specific oscillatory patterns (Cohen, 2017; Cavanagh et al., 2012; Siegel et al., 2012; Yao et al., 2019).

Specifically, a previous study has revealed the important role of the frontal-midline theta oscillation (4-8 Hz) in negative affect, emotion regulation, cognitive control, and pain detection (Cavanagh & Shackman, 2015). In an invasive EEG study, intracranial electrodes revealed the burst of theta oscillation when the participants experienced social exclusion, which suggested that the theta oscillation could be used as the neural signature of social pain (Cristofori et al., 2013). Subsequent studies at the scalp level have shown that activation of frontal-midline theta oscillation can be observed when people experience negative social evaluations (that is, unexpected social rejection) (van der Molen et al., 2017; van der Molen et al., 2018). In addition, van Noordt et al. (2015) found the link between the frontal-midline theta oscillation and the distress feeling during social exclusion situations. Taken together, I used theta oscillations in my dissertation as a neural indicator to capture the social pain caused by social rejection.

1.3 Behavioral indices related to the pursuit of relationships

Because of the basic need for belonging, social acceptance is deeply rewarding for people, while social rejection is deeply threatening (Baumeister & Leary, 1995; DeWall & Bushman, 2011; Leary & Acosta, 2018). Therefore, in the pursuit of important relationships (such as romantic relationships), the conflicting motives of wanting to receive acceptance while avoiding rejection often occur, which also leads to decision-making dilemmas (Joel et al., 2019). For example, sharing an idea or secret with a friend can lead either to a closer relationship (if the friend responds positively) or to estrangement (if the friend responds negatively). By contrast, not sharing this information means passing up opportunities to improve relationships and avoid the risk of rejection. In order to successfully establish and maintain a relationship, people often weigh up and consider the rewards and threats of their behavior (Baker & McNulty, 2013; Gere, MacDonald, Joel, Spielmann, & Impett, 2013; Joel et al., 2019; Spielmann, Maxwell, MacDonald, & Baratta, 2013b).

Previous studies have shown that implicit concept conflicts can be reflected in response time (Greenwald, McGhee, & Schwartz,1998; Stroop, 1935); for example, a slow response reflects the cognitive interference generated by inconsistent constructs, while an accelerated response reflects the facilitation effect generated by paired consistent constructs. In a recent study using a social evaluation task, researchers found that adolescents and adults had different self-views by recording participants' responses time when they predicted whether they were liked or disliked by others (Rodman, Powers, & Somerville, 2017). Therefore, reaction time could be used as a valuable indicator in interpersonal relationships to reveal the conflicting process in which people wish to pursue interpersonal relationships and avoid the harm of rejection.

In previous studies on the pursuit of interpersonal relationships(Cooper et al., 2013; van der Veen et al., 2019), the choice for participants were somewhat limited. Specifically, participants were asked to judge 50 percent of their speed dates as people they liked and 50 percent as people they did not like. The potential differences between the number of two judgments (liking or disliking others) were not examined. In addition, this manipulation affected the ecological validity of the experiment. Thus, in my three experiments, the participants were free to choose and they made judgments based on their preferences. This manipulation can improve the credibility of the experiment and also improve the ecological validity in pursuit of social relationships context. This manipulation also made the number of the judgments meaningful, so I collected the number of judgments and added it to the subsequent analysis to explore the difference in the number of choices between the two types of judgments (like or dislike others).

1.4 Social acceptance and rejection

Although there are different types of relationships, such as family relationships, acquaintanceship, kinship, friendship, and romantic relationships, they all share the desire for constant attention and concern from others (Jackson-Dwyer, 2013; Leary & Acosta, 2018). The motivation to belong drives humans to approach positive social outcomes (such as acceptance and intimacy) while driving people to avoid negative social outcomes (such as rejection and loneliness) (Baumeister & Leary, 1995; Joel et al., 2019; Leary & Acosta, 2018). However, the outcome of human interaction can be positive or negative, and everyone may experience social acceptance and rejection to some extent in their lives.

1.4.1 Social acceptance

Social acceptance is a social signal from others that they would like you to be part of a group and to form a social relationship (Leary, 2010; Pond, Richman, Chester, & DeWall, 2014; Leary & Acosta, 2018). Based on the human desire for social connection, social acceptance seems to have a strong reward value (Baumeister & Leary, 1995; Sherman et al., 2017; Weinberg et al., 2021).

As an important signal in establishing interpersonal relationship, social evaluation (social acceptance, social reputation, etc.) plays an important role in guiding and regulating individuals in the process of social interaction (Izuma et al., 2008; Sherman et al., 2017; Weinberg et al., 2021). An increasing number of studies have focused on the neural basis of individual processing of social feedback (e.g., Guyer et al., 2012; Bhanji & Delgado, 2014; Vrticka et al., 2014; Jarcho et al., 2015; Sherman et al., 2017). The fMRI studies have provided evidence that social interaction activated reward circuitry in the brain, which includes the nucleus accumbens (NAcc), ventromedial prefrontal cortex (vmPFC), and ventral tegmental area (VTA). This occurs, for example, when individuals experience and engage in social interactions and social relationships (Bhanji & Delgado, 2014; Ruff & Fehr, 2014; Sherman et al., 2016); when they see happy faces and attractive faces (Aharon et al., 2001; Cloutier, Heatherton, Whalen & Kelley, 2008; Spreckelmeyer et al., 2013); and when they receive positive social feedback and social approval from others (Cooper, Dunne, Furey, & O'Doherty, 2014; Izuma, Saito & Sadato, 2008; Korn, Prehn, Park, Walter, & Heekeren, 2012). Recent studies have also found that, in social media, when an individual's posted status receives "like" feedback from others, the individual will also activate brain regions including NAcc and vmPFC (Sherman et al., 2016; 2018).

In addition, EEG studies have shown that social acceptance induces reward-related brain ERP components (that is, reward positivity; Ait Oumeziane, Jones, & Foti, 2019; Distefano et al., 2018; Ethridge & Weinberg, 2018; Funkhouser et al., 2019; Weinberg et al., 2021). More specifically, participants showed increased RewP when they received positive first impressions (social acceptance) relative to negative first impressions (social rejection) from others (Ait Oumeziane, Jones, & Foti, 2019; Distefano et al., 2018). In addition, during the island getaway paradigm, participants voted for six characters on the Hawaiian Islands and they also received "keep" (accept) or "kick out" (reject) choices from their peers. The results indicated that the social acceptance induced larger RewP than social rejection feedback (Ethridge & Weinberg, 2018; Funkhouser et al., 2019; Weinberg et al., 2021). Further studies comparing social and non-social rewards have found similar brain responses to monetary and social acceptance (Ethridge et al., 2017; Ethridge & Weinberg, 2018; Izuma et al., 2008; Wake & Izuma, 2017), which may support the idea that the neural mechanisms underlying the motivation for social connection share the same reward system as the pursuit of monetary rewards (Fliessbach et al., 2007; Levy & Glimcher, 2012; Montague & Berns, 2002).

1.4.2 Social rejection

Social rejection is a kind of negative feedback and an apparent social signal of being unwanted, meaning that individuals are actively excluded from interpersonal relationships and social interactions (Williams, 2009; Leary & Acosta, 2018). Our lives contain many scenarios of social rejection, such as being rejected for the desired job or being rejected by one's romantic partner, all of which can be frustrating and painful.

Social pain

Social pain is defined as an unpleasant experience that occurs when an individual perceives potential or actual damage to social relationships or relation values (such as negative social evaluation, social rejection, or loss; Eisenberger, 2012). In our everyday experience, breakups, broken relationships, and the loss of those closest to us are often the most emotionally devastating events. Clinical psychologists believe that social pain events are significantly associated with the onset and persistence of a variety of psychological disorders, including personality disorder, depression and anxiety disorder, and even suicide and homicide (Riva & Eck, 2016). Such disorders, in turn, are likely to affect the formation of social connections in the future, meaning a greater chance of experiencing social rejection again, which creates a vicious cycle (Riva & Eck, 2016). Therefore, it is significant to understand the influence of social pain events on the occurrence and development of mental illness.

Over the past two decades, there has been increasing evidence that the experience of social pain caused by social ostracism, rejection, or social loss shares some of the same neural responses as the distressing feeling caused by physical pain (Eisenberg, 2015b). It seems coincidental that, in many cases, people describe and use physical pain terms to capture their emotional reactions to these negative social experiences as painful events, such as hurt feelings, heartbreak, and emotional scars (MacDonald & Leary 2005). However, this is not a language-specific phenomenon; it seems universal (Eisenberg, 2015b; MacDonald & Leary 2005).

Pharmacological evidence has found that endogenous opioid activity (mu, delta and kappa are three receptors in the opioid system that are activated by endogenous opioids) is altered by social bonding processes in which social bonding increases endogenous opioids and pleasure experiences, while social separation reduces endogenous opioids and produces pain and suffering (Panksepp, 1998; Lutz, Courtet, & Calati, 2020; Merrer et al., 2009; Zöllner & Stein, 2006). The opioid system is known for its role in euphoria and relief of physical pain (Ballantyne & Sullivan, 2017).

For neuroimaging evidence, using fMRI technology, Eisenberg et al. (2003) revealed that individuals exhibit increased anterior cingulate cortex (ACC) and anterior insula (AI) activity when they are in social exclusion condition, relative to the social inclusion condition during cyberball paradigm. Individuals also reported more social distress, which was associated with stronger dorsal ACC activity. Importantly, ACC and AI are important brain regions for the affective component of physical pain perception (Cristofori et al., 2013; Eisenberg, 2015b; Price et al., 1987). Subsequent studies, including receiving negative social evaluations (Eisenberger et al. 2011a, Takahashi et al. 2009, Wager et al., 2009), viewing images associated with rejection (Kross et al., 2007), and reliving romantic rejection (Fisher et al., 2010; Kross et al., 2011), activated the same brain regions involved in the affective component of physical pain. Interestingly, Kross et al. (2011) found that social pain activated not only the affective component, but also the same sensory component of physical pain involved in brain regions (secondary somatosensory cortices; S2 and the posterior insula; PI) when using participants who had recently broken up.

1.5 Social feedback delay

Waiting is a common phenomenon. We do not always get results or achieve our goals directly; instead, we need to wait for some time, which may be minutes, hours, or even days. For example, we may have to wait for the outcome of an interview or to receive a hospital report.

Recent neuroscience studies have provided evidence that the brain regions involved in feedback processing may differ due to variations in feedback timing (Foerde & Shohamy, 2011; Roesch, Calu, & Schoenbaum, 2007). More specifically, in an animal study, a rat showed stronger activation in the reward system (such as ventral striatum) for immediate reward feedback vs. delayed feedback (Roesch, Calu, & Schoenbaum, 2007). In a human fMRI study (Foerde & Shohamy, 2011), participants were asked to learn specific rules between cues and choices, and after they had made a judgment they received feedback on the outcome of their behavior after different waiting times (1s, 4s, 7s). The results indicated that with the increase of waiting time to receive feedback, the striatum activity decreased gradually, and the hippocampus was more involved in the feedback processing. The researchers proposed that the processing of immediate feedback is primarily done by the striatum, but a delay of a few seconds leads to more involvement in the medial temporal lobe (MTL), specifically the hippocampus, which connects the time intervals between events in order to link information together across time (Foerde & Shohamy, 2011).

In addition to the fMRI studies, electroencephalography (EEG) also provided important evidence that waiting time affects the outcome evaluation. Weinberg and colleagues (2012) first explored how the waiting time affects feedback processing by using EEG. They found significant different patterns of reward positivity (RewP) between gain and loss in a long wait and short wait condition. Results showed that the RewP was only observed in the short delayed(1s) feedback condition, but not in the long-delayed (6s) feedback condition. Several following studies have also focused on the effect of waiting time on outcome evaluation by measuring RewP and replicated the vanished difference between negative and positive feedback in long-delayed conditions (Arbel et al., 2017; Peterburs et al., 2016; Zhang et al., 2018; but see Wang et al., 2014). For instance, Peterburs et al. (2016) manipulated three different waiting times (500 ms, 3500 ms and 6500 ms) and found a gradually reduced difference of RewP between negative and positive feedback with the increased waiting time.

The above studies only focus on the effect of waiting time on non-social feedback processing (such as food and money), but the effect of waiting time on social feedback processing remains unclear. The inevitable wait is intertwined with social relationships and interaction. We seek a social relationship and wait for social feedback, such as acceptance and rejection from others. In addition, in the previous monetary studies, the waiting time effect is that the long wait attenuates the valuation of monetary feedback (Arbel et al., 2017; Peterburs et al., 2016; Weinberg et al., 2012; Zhang et al., 2018), but this does not seem to account for the fact that waiting increases our sense of reward. For example, if you get what you desire or are accepted by someone you like, you may feel that all the waiting was worthwhile and that the result is valuable. Therefore, a complete understanding of the neural mechanism underlying the effect of waiting time on outcome evaluation must include the influence of waiting time on social feedback.

1.5.1 Waiting time as the cost

The time cost is subjectively experienced by people as increased effort (Dunn et al., 2019; Inzlicht, Schmeichel, & Macrae, 2014). Previous studies have found that when participants show less motivation to achieve the goal in a task, the prolonged time cost will reduce their task performance, disengage the participants from the task, and devalue the reward (Boksem et al., 2006; Hopstaken et al., 2015; Umemoto et al., 2019). However, when the motivation increases, these negative effects caused by time cost were suppressed by individuals through effort (that is, cognitive control) and the performance of the participants returned to the baseline, where the participants' behavior performance and brain activation became the same as at the beginning of the experiment (Boksem et al., 2006; Hopstaken et al., 2015). In this process, individual invested efforts to adjust their own behaviors through cognitive control enable us to overcome the negative effects caused by delay (such as fatigue), which is a process in which individuals weigh benefits and costs (Umemoto et al., 2019). Additionally, motivation (such as, intrinsic motivation: personal interests; extrinsic motivation: monetary rewards) often determines whether an individual chooses to overcome the cost of time/effort or to relax and have fun (Dunn et al., 2019). Not only does sufficient motivation enable individuals to complete tasks, but previous studies have found that when the motivation is sufficient to drive the task, the reward after time/effort cost feels more valuable (Alessandri et al., 2008; Clement et al., 2000). This suggests that the motivation may modulate the person's subjective reward valuation after the time or effort cost and their subsequent behavior toward a costly goal.

Similarly, in the social interaction context, people generally have a strong motivation to establish and strengthen relationships with people they like, rather than the people they dislike (Fareri et al., 2012; Hughes & Beer, 2012; Hughes, Zaki, & Ambady, 2017). Moreover, the fMRI studies indicated that receiving social evaluations from a liked one is vital for forming social relationships and leads to greater reward-related brain activation than receiving social evaluations from a non-liked one (Cooper et al., 2014; Hughes et al., 2018). Therefore, I speculate that the different motivations caused by individual subjective preference in social interaction context will modulate the participants' subjective reward valuation after time/effort cost. However, in the social interaction context, there is a lack of understanding of the neural mechanisms of how individual preference in social relationships causes a change in the waiting time effect.

1.6 Oxytocin and social bonding

Oxytocin (OT), a neuropeptide composed of nine amino acids, is known for its role in female labor (Leng et al. 2015; Poisbeau, Grinevich, & Charlet, 2017). In recent years, neuroscientists and psychologists have shifted their research interest from oxytocin's role in promoting labor and lactation to its effect on human social behavior, such as social bonding.

1.6.1 The effects of oxytocin on social bonding

Early studies on the effects of oxytocin on the human parent–child relationship have found that the increase of prenatal and postpartum oxytocin levels in pregnant women can increase parent–child attachment and reduce postpartum stress response (Nelson & Panksepp, 1998). Exposure of the infant to the mother's breast when the mother first breastfeeds increases oxytocin levels in the peripheral nervous system and further promotes feeding behavior (Matthiesen, Ransjö Arvidson, Nissen, & UvnäS-Moberg, 2001). Levine et al. (2007) measured the plasma level of oxytocin in pregnant women every three months before delivery and the first month after delivery and found that the level of oxytocin during pregnancy was positively correlated with the degree of attachment. Mothers with higher oxytocin levels were more likely to look at, touch, and love their babies. Gordon, Zagoory-Sharon, Leckman, and Feldman (2010) studied the relationship between plasma oxytocin and social interaction in a family of three and found that the higher the plasma oxytocin levels of fathers and mothers, the higher the quality of the family's intimate interactions. These studies suggest that oxytocin plays an important role in the formation of early parent–child bonds.

Oxytocin not only promotes parent–child bonding, but also affects couples' bonding. For human couples, oxytocin levels have been reported to be positively correlated with the level of attachment between partners (Tops, Van Peer, Korf, Wijers, & Tucker, 2007). Ditzen et al. (2009) found that nasal spray of oxytocin during marital arguments increased positive communication between couples and reduced cortisol levels in saliva. Scheele et al. (2013) found that oxytocin made men more likely to perceive their female partners as more attractive than other women, which undoubtedly helped maintain intimacy. Recent studies have found that oxytocin reduces single men's reactions to the negative evaluations from female partners and also reduces jealousy when participants experience both imagined and actual infidelity from their romantic partner (Zhao et al., 2018; Zheng et al., 2021).

1.6.2 The pain-reducing effects of oxytocin

Based on solid evidence of analgesic effects of oxytocin on physical pain from animal studies, researchers saw the prospect of therapeutic interventions using oxytocin for pain (Boll et al., 2018). In addition to animal studies, human studies have also found that oxytocin decreased physical pain sensitivity; for example, intranasal OT reduced pathologic pain (Yang, 1994) and decreased perceived pain intensity (Paloyelis et al., 2016; Rash & Campbell, 2014; Zunhammer et al., 2016). An earlier study found that higher plasma levels of oxytocin were associated with higher tolerance of pain (Grewen et al., 2008). Although a number of studies have explored the effects of oxytocin on physical pain, how oxytocin regulates social pain remains unclear.

One important clue is the recent physical-social pain overlap theory, in which social pain shares a neural basis to some extent with physical pain (as mentioned in Chapter 1.4.2). In response to physical pain, there are two important components. One is a sensory component (mainly involving the anterior cingulate cortex; anterior insula), which codes the location, intensity, and quality of pain (such as stinging or aching). The other is an affective component (mainly involved secondary somatosensory cortex; posterior insula), which codes unpleasant or painful experiences (Cristofori et al., 2013; Eisenberger, 2015). Neuroimaging evidence has supported not only that social pain activates the affective component of the brain, but also that the sensory component is activated when the pain is sufficiently intense (for example, romantic rejection) (Kross et al., 2011). Therefore, it is reasonable to speculate that oxytocin may also have a pain-reducing effect on social pain, as well as on sensory and affective components.

In two recent behavioral studies using the cyberball paradigm to induce social ostracism, the participants administered oxytocin treatment responded to social ostracism with reduced feelings of social discomfort (Pfundmair & Echterhoff, 2021), a better mood, and feeling accepted more often than the placebo group during the cyberball paradigm (Henningsson et al., 2021). Another EEG study, by Petereit et al. (2019), reported that oxytocin reduced the link between neural response (that is, late positive potential) and self-reported ostracism during cyberball. Although none of these three studies directly measured social pain, their results suggest that oxytocin may reduce negative emotions associated with social rejection.

1.7 Purpose and hypothesis of the research

The overall purpose of this dissertation is to explore the behavior of pursuing relationships and the brain processing mode of receiving social feedback from others during the pursuit of establishing interpersonal relationships. Previous studies have focused on existing social relationships and individual behaviors and brain responses when such social relationships changed (Acevedo et al., 2012; Aron et al., 2005; Fisher et al., 2010, Kross et al., 2011). Therefore, the first goal of the present thesis is to expand the previous research to explore the behavior and brain response in the decision-making stage, anticipatory stage, and feedback processing stage during the pursuit of social relationships. Considering that, in the pursuit of social relationships, getting feedback from others is often not immediate, this thesis tried to explore the impact of waiting time on the brain response to the social evaluation of their future relationships with others. This will help us understand the impact of waiting time on the result of a social relationship in a real social environment. This study will also expand previous research that focused only on the processing of the waiting time effect for monetary reward and help us fully understand the mechanism of waiting effect on outcome evaluation. Finally, according to previous studies, social pain and negative emotional reactions caused by social rejection may be devastating to individuals in social relationships. Exploring the influence and neural mechanism of oxytocin on social pain would help find relief and intervention of social pain in the future. This would help reduce the negative impact of people in the face of negative social evaluation or social relationship breakdown, thereby promoting and maintaining people's psychological and physical health. It is worth noting that, as mentioned in 1.1.2 and 1.5.1, we must examine the influence of individual preferences in order to explain the behavior and neural activity evoked by any social evaluation. Therefore, throughout the dissertation, I adopt a new paradigm that I have developed so that the personal preferences of the participants can be manipulated in our studies.

1.7.1 Study I

The first study assessed the neurophysiological activity of the pursuer's brain while anticipating and experiencing feedback (acceptance vs. rejection) from their various speed dates to fill the gap in the psychological and neural underpinnings of romantic love pursuit. I introduced a novel online speed dating task where participants met and chose potential romantic partners and saw each partner's feedback. This paradigm allowed me to separate several different stages in pursuing a social relationship and capture related brain activities. In addition, our paradigm created two utterly different individual preferences (liked or disliked person) for the participants, with the partners judging their partner as potential romantic partners or as non-potential romantic partners. Since people want to have a romantic relationship with the person they desire, there is a stronger motivation to form a social relationship with a potential romantic partner (Aron et al., 2005). Therefore, I predicted that the SPN would be greater when waiting for feedback from potential romantic partners than when waiting for feedback from non-potential romantic partners. I hypothesized that the RewP and theta power would reveal reward and pain in romantic-related feedback, respectively. Thus, I predicted a larger RewP for social acceptance vs. rejection from a potential romantic partner since the neuroimaging study has revealed that the reward-related brain areas were activated for social approval (Hughes et al., 2018). Additionally, since break-up was an influential social pain event (Kross et al., 2011), I predicted that romantic rejection would induce greater theta power than any other condition. Considering that romantic rejection can have far-reaching consequences for those rejected, even affecting their physical and mental health (Fisher et al., 2010), I further explored the neural sources of theta oscillation in the processing of a romantic expression. Results from both intracranial EEG recordings and cortical level EEG demonstrate that frontal-midline theta oscillation is a neural indicator of social rejection and is involved in the pain matrix (Cristofori et al., 2013; Van der Molen et al., 2017), so I predicted that the greatest theta power (caused by romantic rejection) was source-localized in the brain regions involved in social pain, such as ACC and some frontal areas.

1.7.2 Study II

The first goal of this study was to explore the effect of waiting time on social feedback. The second goal was to examine whether the impact of waiting time on feedback processing would be modulated by individual preference in a social context. My hypotheses focused on RewP, since the social evaluation paradigm can stably induce RewP generated by positive and negative feedback from the peer (Van der Molen et al., 2017, 2018), and previous ERP studies have reported that the RewP was modulated by waiting time (Arbel et al., 2017; Peterburs et al., 2015; Weinberg et al., 2014; Zhang et al., 2018) and subjective preference (Peterburs et al., 2019). Two hypotheses were tested that would reveal whether RewP is modulated explicitly by waiting time in the social context or whether different individual preferences (liked vs. disliked person) contribute to the effect of waiting time on RewP in processing social feedback. First, if the waiting time effect influenced the RewP in the social context, the amplitude of RewP would show difference in short waiting and long waiting conditions. Second, if the RewP only reflects the effect of waiting time in processing social feedback, irrespective of subjective preference, then the RewP amplitude should diminish in long waiting time conditions, as time/effort cost will devalue the subjective reward value (Boksem et al., 2006; Hopstaken et al., 2015; Umemoto et al., 2019). Conversely, if RewP is modulated by subjective preferences, I hypothesized that two different patterns would be revealed: a long waiting adds value to the feedback from the liked person, which may show increased RewP amplitude for long waiting times, whereas long waiting times decrease value from the disliked persons reflected in reduced RewP.

1.7.3 Study III

The third study was designed to investigate the effect of oxytocin on social pain. To successfully induce great social pain and observe the impact of oxytocin on social pain more intuitively, I adopted the novel online speed dating task consistent with Study I. Two important theories of oxytocin were tested. According to social salience theory (Shamay-Tsoory & Abu-Akel, 2016), oxytocin increases attention to social cues (regardless of positive or negative cues) and social rejection as a signal that threatens humans' survival and the need to belong (Baumeister & Leary, 1995). Thus, oxytocin may increase individual responses to social rejection, so the first hypothesis was that oxytocin would increase theta oscillations in response to social pain. Another hypothesis was based on the affiliation-motivation theory, which states that oxytocin induces a motivational state to affiliate, and prosocial behavior depends on the external environment and personal expectations. Previous studies have demonstrated the role of oxytocin in promoting intimacy and interpersonal interactions (Algoe et al., 2017; Ditzen et al., 2009), significantly reducing the response to social exclusion and infidelity (Henningsson et al., 2021; Pfundmair & Echterhoff, 2021; Zhao et al., 2018; Zheng et al., 2021). Therefore, the second hypothesis was that oxytocin reduces theta power, which reflects the social pain occurred in the experiment.

2 METHODS

2.1 Participants

See Table 1 for the recruitment of participants in the three experiments.

TABLE 1 Basic information of the participant. Recruitment of participants in the three experiments, means, standard deviation (SD) and number(n)

	Study I	**Study II**	**Study III**	
			Oxytocin group	Placebo group
Participants (n)	25	29	30	31
Gender (n)				
Female	13	16	14	17
Male	12	13	16	14
Age (mean ± SD)	20.07 ± 1.96	19.90 ± 1.60	20.47 ± 1.91	20.06 ± 1.88

In Study I, 26 participants aged 18–25 from Shenzhen University were recruited through advertisements, posters, and media in university. All of the participants reported having no current or past history of psychosis, were single, and were heterosexual. All participants reported they were right-handed and had normal or corrected normal vision. Previous studies using similar speed-dating tasks (van der Molen et al., 2017; van der Veen et al., 2019) reported effect sizes of 0.33 and 0.38 for the judgment and feedback interaction, respectively, which were lower than large effect sizes (i.e., 0.4). Therefore, we chose a medium effect size (effect size = 0.25, α = 0.05, power = 0.80) to estimate the sample size required for our study. The required sample size per group was 24 by using G-power 3.1 (Faul et al., 2009). I excluded one participant because of excessive EEG artifacts in the experiment. After the experiment, each participant was rewarded with 80 yuan.

In Study II, we used a similar method to Experiment 1 to determine the sample size until the recruitment deadline, a total of 33 healthy participants aged 18–25 were recruited from Shenzhen University. All of the participants reported having no current or past history of psychosis and all participants reported they were right-handed and had normal or corrected normal vision. I excluded four participants because of excessive EEG artifacts in the experiment.

The participants in Study III came from Shenzhen University. The exclusion criteria were: (1) diagnosed with a mental disorder, (2) non-single, (3) nasal disease or nasal congestion, (4) being on medication, and (5) homosexual or bisexual. To the best of our knowledge, there are no comparable studies reporting effect sizes for reference. Therefore, we recruited no less than 24 participants per group on the basis of the sample size calculated by G power in the previous two studies. To avoid losing participants who do not fully believe in online speed dating events and drop out of the experiment halfway, we increased the sample size when we recruited participants. Sixty-five participants met the inclusion criteria and 63 participants completed full experiment stages. In addition, I excluded two participants from subsequent data analysis due to their excessive artifact in EEG experiments. Therefore, the final retained sample size is the data of 61 participants, including 30 participants in the oxytocin group (16 men and 14 women) and 31 participants in the placebo group (14 men and 17 women). Two of the participants were left-handed and the rest were right-handed. All female participants reported not using oral contraceptives and not being pregnant. After completing the two stages of the experiments, all participants were compensated with 120 yuan. To control the impact of personality traits on the effect of oxytocin (Bartz et al., 2011), I conducted a questionnaire survey of demographic variables for all participants, and the results are shown in Table 2. All participants in the three studies signed informed consent before inclusion, and the study protocol was approved by the Ethics Committee of Shenzhen University School of Medicine.

TABLE 2 Participant demographic and trait information in Study III. Participant demographic and trait information, means, standard errors (SE) and number(n)

Measurements	**Oxytocin**	**Placebo**		***p* value**
Number of relationships (*mean* ± SE)	1.37 ± 1.91	1.35 ± 1.05	$t(59) = .04$	.972
Rejection Sensitivity Questionnaire (SE)	10.11 ± .43	10.54 ± .52	$t(59) = -.64$	.525
Rosenberg Self-Esteem Scale (*mean* ± SE)	31.73 ± .75	30.68 ± .99	$t(59) = .85$	.399
BDI-II Depression (*mean* ± SE)	9.17 ± 1.32	8.26 ± 1.28	$t(59) = .49$	.624
Fear of Negative Evaluation Scale (*mean* ± SE)	37.53 ± 2.01	39.77 ± 1.75	$t(59) = -.84$	.402
Liebowitz Social Anxiety Scale (*mean* ± SE)	40.77 ± 3.21	38.97 ± 3.25	$t(59) = .39$	.695

2.2 Experimental design

I created a novel online speed dating task that combined the social evaluation task and the speed dating task in previous studies (Cristofori et al., 2013; Somerville et al., 2006). This paradigm simulates real social interactions context, helps me manipulate subjective preferences in social interactions, and separates different stages during the pursuit of social relationships. The three studies in the dissertation used a similar paradigm, and the only difference is the cover story of Study II, which is detailed below.

2.2.1 Cover story

In Studies I and III, the participants were told that they were participating in a multi-university speed dating study. In this event, all participants were shown pictures of each other and were able to choose their potential romantic partners based on the first impressions. Therefore, each participant needed to send a digital photo of themselves to us. If the participants marked each other as potential partners, they would have access to each other's information and further contact.

In Study II, I did not emphasize that it was a speed dating event, but did state that this was a multi-university study about first impressions and making friends, and that each person needed to make a judgment on their peers based on their first impressions.

2.2.2 Stimuli

On the day the participants submitted their photos, their photos were normalized (guaranteed to have the same size and background color as the photos of the fictional partners in the experiment), and the normalized photos were re-sent to the participants for confirmation in order to ensure they were satisfied with the final photo used for the online speed dating. In addition, the participants were allowed to replace their photos until they agreed to use the standardized photos. According to a previous study (Gunther Moor et al., 2010), photos of fictional partners used in the experiment were all neutral faces, and all the photos were rated (Self-Assessment Manikin; Bradley & Lang, 1994) by another group of a total of 24 participants before used in the speed dating task. Finally, 340 portrait photos taken at different universities were used as fictional partners in the experiment, including 170 male photos and 170 female photos. Normalized photos are 185 × 240 pixels, with background colors R: 44, G: 44, B: 44.

In Study II, I did not need to present the opposite-sex partners to the participants, so I randomly selected 130 photos from the above male and female photos – a total of 260 photos as experimental materials. The stimulus parameters presented in the three experiments are summarized in Table 3.

TABLE 3 The parameters of the stimulus presented in the experiment

	Study I	Study II	Study III
Gender of peer	opposite sex	Opposite sex and same sex	opposite sex
The number of peer photos Male photos Female photos	340 170 170	260 130 130	340 170 170
Photo size	185 × 240 pixels	185 × 240 pixels	185 × 240 pixels
The background color of the photo	R: 44, G: 44, B: 44	R: 44, G: 44, B: 44	R: 44, G: 44, B: 44
The size of the social feedback stimulus	210 × 210 pixels	210 × 210 pixels	210 × 210 pixels

2.2.3 Procedure

For Study I, the experiment consists of three sessions in total (1) pre-task session: rating their partners' likeability; (2) online speed dating task (3) post-task session: rating their partners' likeability again. In the pre-task session, participants were invited to the laboratory; they first completed a personal information questionnaire that including information such as name, birth, and email address. The purpose of this operation was to make the participants trust the speed dating event. Next, photos of opposite-sex speed dates were presented to the participants, and they were asked to rate the likeability of their partners on a seven-point scale, with 1 corresponding to "not at all" and 7 corresponding to "very much" (Figure 1A). Participants were also told that their speed dates would also rate them based on first impressions and that they would see each other's ratings during the next EEG task. It should be noted that there are no real speed dates to evaluate the participants, and all evaluations are controlled by the experimenter. In addition, the personal information of the participants collected in this session was deleted directly after the experiment ended without any backup.

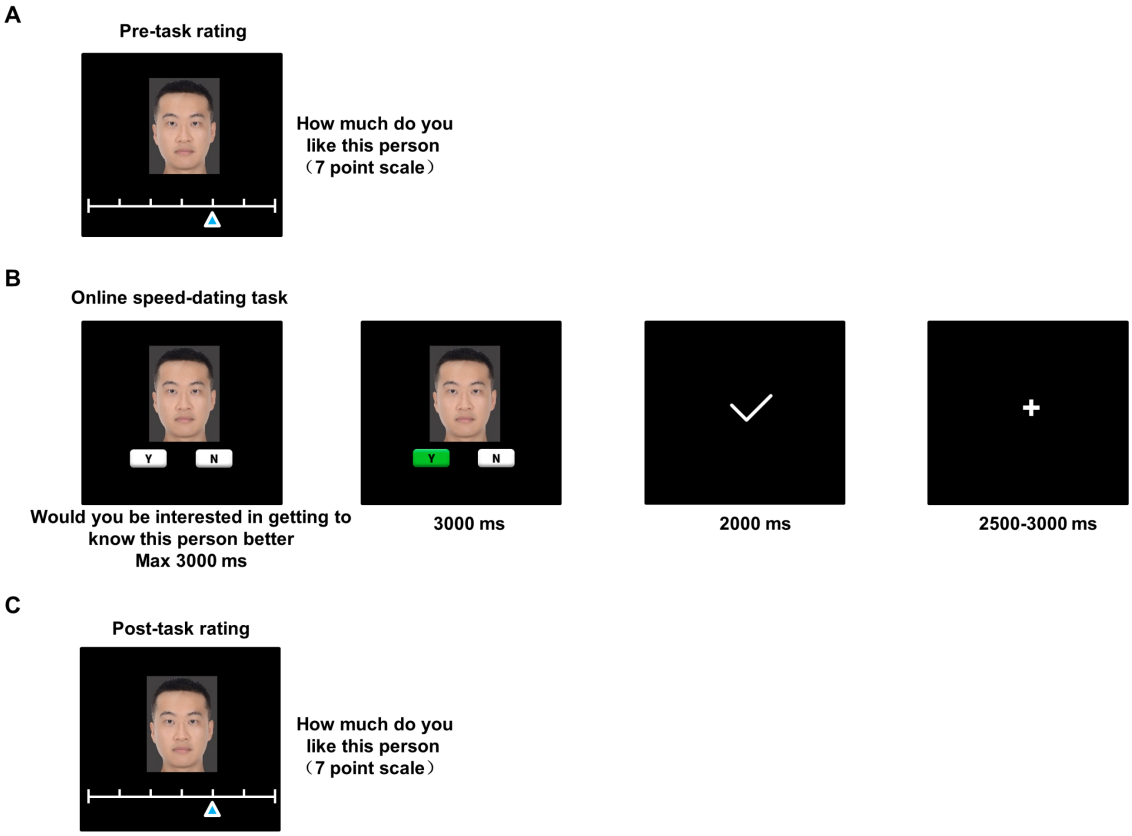

FIGURE 1 Schematic representation of the novel online speed dating task. (A) In the pre-task, the participants were asked to rate the likability of their speed dates. (B) In the EEG session, participants needed to make a judgment first within a 3000 ms time window. The button they chose would be highlighted (turn green) for 3000 ms. After that, the participants would see their speed dates feedback, and it remained on the screen for 2000 ms. (C) In the pre-task, the participants were asked to rate the likability of their speed dates again.

Approximately one or two weeks after finishing the pre-task, participants were invited to the lab to complete the EEG session. The participants were shown pictures of speed dates on the screen, and when they saw their speed dates, they were asked to answer, "Would you be interested in getting to know this person better?" After they made a judgment, their speed date feedback was presented. The experiment yielded four different outcomes: the Match outcome (both the participants and their speed dates chose "yes"), the Rejection outcome (the participants chose "yes" and their speed dates chose "no"), the Disinterest outcome (both the participants and their speed dates chose "no"), and the Unrequited outcome (the participants chose "no" and their speed dates chose "yes"). The participants were informed that if they were "Matched" with their speed dates, they would have the opportunity to get each other's contact information.

An important difference between our manipulation during the EEG session and previous studies is that, in our experiment the participants are free to choose, they are not subject to any restrictions, and they make judgments based on their preferences. This is in contrast to previous studies, where the participants were asked to make "yes" choices to at least 50 percent of the options presented (Cooper et al., 2013; van der Veen et al., 2019). This manipulation can improve the credibility of the participants and also improve the ecological validity in pursuit of social relationships context.

The schematic of the EEG session is shown in Figure 1B. Participants were required to make a judgment to their partner by pressing various keys on the keyboard. The "Y" button on the screen represented "yes"; that is, the participants were interested in getting to know their speed dates better. The "N" button represented "No"; that is, the participants were not interested in getting to know their speed dates better. The "F" and "J" keys corresponded to the "Y" and "N" buttons on the screen, and these two buttons were counterbalanced between participants. The "N" and "Y" buttons were 100 x 50 pixels on the screen. Participants were asked to make a judgment within a limited time window (3000 ms) after the photo of the speed dates appeared. If the participants failed to respond within this limited time window, this trial would end with a "response too slow" on the screen, and they would not find out that speed date's evaluation. If a judgment was made within the time limit, the button on the screen corresponding to the judgment would turn green for 3000 ms. Next, the participant would see their speed date's evaluation, and the feedback stimulus would be presented for 2000 ms, where "√" indicates the acceptance feedback from their partner and "X" indicates the rejection feedback from their partner (210 × 210 pixels). The social evaluation types of the speed dates were randomly generated and participants had a 50 percent probability of receiving both romantic interest and romantic rejection feedback. Before the formal experiment, participants had 10 practice trials.

In the post-task after the EEG session, the participants were asked to rate the likeability of their speed dates again (Figure 1C), because I wanted to examine whether the feedback from others during the EEG session would affect the participants' post-task ratings. In addition, participants were asked to complete a seven-point Likert scale about how motivated they want to know their speed dates evaluation, with 1 representing "not at all" and 7 representing "very much", and how much pleasantness they felt when they received four different outcomes, with 1 representing "very unhappy" and 7 representing "very happy." In order to measure the change of anxiety states and current mood, the participants were asked to complete State-Trait Anxiety Inventory (STAI; Spielberger, 1983) and the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988) before and after the EEG task. After the last participant completed the experiment, I explained the manipulation and purpose of the experiment to all the participants, and no participants reported suspicion about the manipulation in the experiment.

For Study II, the differences between Studies I and II were as follows: (a) participants will not only see photos of their peers of the opposite sex, but also pictures of their peers of the same sex; (b) the question used was "Do you like this person?" during the EEG task; (c) the participants did not need to rate the likeability before and after the EEG task; (d) a waiting time interval was added before the evaluation of others was presented (short wait: 800–1200 ms; long wait: 5000–6000 ms); (e) a self-reported worthiness questionnaire (what they thought of the waiting time, 1 = ''Not worth it''; 7 = ''very worth it'') was added after the EEG task. Other than that, the rest of the procedure is the same as in Study I. The schematic of Study II in the EEG session was presented in Figure 2.

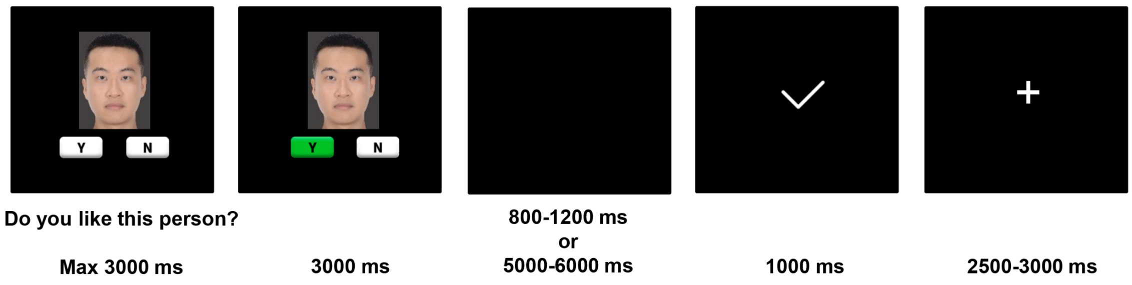

FIGURE 2 Schematic representation of Study II. Participants were asked to make a judgment within 3000 ms. Upon keyboard press, the selected button was highlighted and turned green for 1000ms. Subsequently, the photographs and buttons disappeared, and a blank screen was presented in a random interval (short delay for 800–1200ms and long delay for 5000–6000 ms). After waiting time, the feedback was presented for 2000 ms. The task comprised 10 practice trials and 240 formal trials.

The procedure of Study III was mostly the same as Study I. The only difference was that before the EEG task, the participants needed to complete the nasal spray of oxytocin. A double-blind, placebo (PLC)-controlled study with a between-subject design was performed, in which participants randomly received either OT or PLC treatments. Participants were administered 24 IU of OT (OT spray; three puffs of 4 IU per nostril, with intervals of 45–60 s for each spray, until the participants felt no fluid flowing) or PLC (the same components as the OT spray except OT). The OT spray was formulated using a powdered version of the drug (ProSpec company, Israel). The solution was prepared by combining 5 mg of OT (2400 IU) with 6 ml of 0.9% sodium chloride solution. The mother liquor was stored in separate vials (1 ml per vial) at minus 80 ◦C. The vials were then thawed and refrigerated (4 ◦C) on the day of the study. A trained research assistant prepared the nasal spray by transferring OT or placebo from the vial to the sprayer. Participants used the nasal spray on their own under the supervision of trained and experienced experimenters. Administration followed the standard intranasal OT protocol (Guastella et al., 2013) based on the pharmacology of human intranasal OT (Spengler et al., 2017), approximately 45 min before the EEG task. In post-experiment interviews, participants were unable to correctly judge which treatment they had received ($\chi 2$ = 0.81, p = 0.367). After that, participants only needed to complete an EEG session; that is, an online speed dating task in Figure 1b.

2.3 EEG data acquisition and processing

The 64 electrodes (Ag/AgCl actiCAP; 10–20 system; Brain Products, Germany) with a sample rate of 1000 Hz were used to record EEG data. In order to capture the eye blinks and ocular movements, I used a surface electrode, which was placed below the right eye, to record these Electro-oculographic (EOG) signals. I kept the impedance of all electrodes no more than 10kΩ. The analysis of EEG data was performed on BVA 2.1 (Brain Vision Analyzer; Brain Products, Germany).

EEG data were processed off-line and re-referenced was performed to the average of bilateral mastoid electrodes. After applying the band-pass filter (0.1–30 Hz) and notch filter (50 Hz), the continuous EEG data were epoched from -3500 ms to 3000 ms based on the onset of the feedback of the speed dates. Next, in order to remove artifacts of eye blinks, the independent component analysis was applied to detect the typical ocular movement components (Lee, Girolami, & Sejnowski, 1999). Due to the different baseline correction settings of SPN and RewP (see below), I did it separately. Then I implemented an automatic artifacts detection, in which the trials over ±80 μV were targeted and discarded. I presented the artifact-free trials in Tables 5, 6 and 7 for Studies I, II, and III, respectively. The mean rejection rates were 0.5% in study I, 2.1% in study II, and 2.2% in study III.

2.4 EEG data analyses

2.4.1 Event-related brain potential analyses

The artifact-free epochs from -3300 ms to 200 ms surrounding the onset of social evaluation from the speed dates were used to measure the SPN. Here, I used the -2400 to -2000 ms pre-feedback interval for baseline correction. Epochs were visually inspected for residual motor activity, consistent with previous studies (Van der Molen et al., 2014). After two conditions (that is, the participants chose "yes" and chose "no") were collapsed, a gradually increased SPN was observed around 200 ms before the social feedback onset and maximum at Cz electrode.[1] Thus, the mean amplitude from -200 to 0 at Cz was used for SPN analysis.

In addition, the artifact-free epochs from -200 ms to 1000 ms surrounding the onset of social evaluation from the speed dates were used to measure the RewP. I used the -200 to 0 ms pre-feedback interval for baseline correction. After all the conditions were collapsed in Studies I and II, respectively, the largest RewP was observed in 255–355 ms and 280–380 ms after the onset of social feedback at the Cz and Fz. Thus, the mean amplitudes from 255–355 ms at Cz

[1] The previous study recommended the grand-grand average method to determine the electrode point and time window of interest (Kappenman & Luck, 2015), and this method is consistent with previous studies on SPN and RewP (van der Molen et al., 2014, 2017).

and 280–380 ms at Fz were used for RewP analysis for Studies I and II, respectively.

For the first study in my dissertation, I wanted to obtain stable results and use the results as a basis for subsequent studies. Principal component analysis (PCA) was used to provide further supplementary analysis and to prove the most common method (original waveform) of measuring RewP in my research. The PCA is an effective method to solve the problem of EEG component overlap, which helps us resolve the debate on the influence of other components (P2 and P3) in RewP calculation. Therefore, PCA was used to substantiate the interpretation of the RewP. PCA was performed using the ERP_ERO toolkit (Zhang et al., 2020) for PCA analysis, a free toolkit in Matlab. The temporal and spatial components of interest were simultaneously extracted by temporal PCA and Promax rotation (Dien et al., 2005) and projected to the electrode field to correct variance and polarity indeterminacy. I then calculated the amplitude of the back-projected component on the typical electrodes (Zhang et al., 2020). The PCA was performed based on covariance between variables. Finally, 38 components remained that together explained >95 percent of the variance. According to the temporal and spatial properties of RewP, I found that the first component (peak at 324 ms) and the 10th component (peak at 306 ms) were typical for RewP, and they explained 41.88 percent and 1 percent variance, respectively (the two components are spatially correlated with high Pearson correlation, r = 0.92). Thus, I used the first and 10th components as the extracted RewP for further analysis.

2.4.2 Time-frequency power analyses

Time-frequency power analyses were applied at the single-trial level with complex Morlet wavelets. The EEG data were epoched from -2000 to 2000 ms surrounding the feedback onset. The 30 logarithmically spaced steps (from 1 to 30 Hz range) were used at each epoch. The complex Morlet wavelets parameters were set with 1 Hz as the central frequency, and 5 s was set as the time resolution (FWHM). The baseline-corrected spectrogram was applied with a subtraction approach at each frequency, in which the -500 to -200 ms time window was used as a reference interval (Hu et al., 2014). Furthermore, I collapsed all the conditions to detect the greater theta oscillation. I observed the same time window (200–400 ms) and the same maximum electrode at Fz in Study I and III. Thus, I calculated the averaged theta power (4–8 Hz) at Fz during the 200–400 ms time interval after social evaluation appeared.

2.4.3 Source localization analyses

Theta source activity was calculated by using Brainstorm (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011), a free toolkit in MATLAB. All participants were implemented using a standard ICBM152 anatomy template with the Montreal Neurological Institute to fit the cortical mesh surface. The symmetric boundary element model was used for EEG forward model calculation by using

OpenMEEG (Gramfort et al., 2010). Three realistic layers were used in the EEG forward model; the parameters of the scalp were 1922 vertices, relative scalp conductivity = 1; the skull parameters were set as 1922 vertices, relative skull conductivity = .0125, and the brain parameters were set as 1922 vertices, relative brain conductivity = 1 (Ambrosini & Vallesi, 2016; van der Molen et., 2017). The noise covariance matrix of the electrodes was measured by using the -500 to -200 ms time window (before the onset of feedback from the speed dates) to estimate the noise level. Next, at a single trial level, I used the depth-weighted minimum norm estimation (wMNE) approach to calculate unconstrained cortical source (Baillet et al., 2001) with default parameter settings. The advantage of this approach was that it provided a fair spatial resolution, even with the relatively noisy EEG data, and the source localization results were reliable even without the MRI data of individual anatomy (Baillet et al., 2001). Finally, to obtain the source current strength, of which the cortex surface comprised 3 x 5005 vertices, the EEG signal was multiplied by the wMNE inverse operator on the time series for each electrode. Considering that the calculation is a linear transformation, I performed the time-frequency analysis on the source space, which still retains the spectral characteristics of the underlying source (Ambrosini & Vallesi, 2016; Billeke, Zamorano, Cosmelli, & Aboitiz, 2013). The complex Morlet wavelets were used on the source space, as outlined before. For each condition, I averaged all trials and then did the z-score normalization to the theta source data, in which the -500 to -200 ms pre-feedback time interval was selected as the baseline. I rectified the z-scores normalized source data in the specific frequency band (4-8 Hz) and time window (200–400 ms) for further statistical analyses. The parameters of event-related potentials, time-frequency analysis, and source localization analyses for EEG data are summarized in Table 4.

TABLE 4 Summary of parameters for event-related potentials, time-frequency analysis, and source localization analyses in EEG data

	Stimulus preceding negativity (SPN)	**Reward positivity (RewP)**		**Theta oscillation (4-8 Hz)**		**Source-localization analyses (4-8 Hz)**	
	study I	study I	study II	study I	study III	study I	study III
Epoch	-3300 to 200 ms	-200 to 1000 ms	-200 to 1000 ms	-2000 to 2000 ms	-2000 to 2000 ms	-2000 to 2000 ms	-2000 to 2000 ms
Baseline correction	-2400 to -2000 ms	-200 to 0 ms	-200 to 0 ms	-500 to -200 ms	-500 to -200 ms	-500 to -200 ms	-500 to -200 ms
Noise covariance matrix	N/A	N/A	N/A	N/A	N/A	-500 to -200 ms	-500 to -200 ms
Electrode	Cz	Cz	Fz	Fz	Fz	N/A	N/A
Measurement	averaged time window	averaged time window	averaged time window	averaged time window	averaged time window	averaged time window	averaged time window
Time window	-200 to 0 ms	255 to 355 ms	280 to 380 ms	200 to 400 ms	200 to 400 ms	200 to 400 ms	200 to 400 ms

2.5 Statistical analysis

2.5.1 Study I

For behavioral data, I submitted the reaction time (RT) of individual preference (yes or no), the number of participants' judgment of individual preference, STAI, and PANAS scores (phase: pre and post) into *t*-tests. In order to measure the change of likability of the speed dates, four different conditions were created (Match, Rejection, Unrequited, Disinterested), which were calculated in difference scores between the ratings of post-task and pre-task. I then used repeated-measures ANOVA to compare the change of likeability with individual preference (yes or no) by speed date feedback (acceptance (yes) or rejection(no))[2]. The paired t-test was used to compare self-reported motivation ratings in individual preference (yes or no). A two-way repeated ANOVA was used to compare self-reported pleasantness ratings in individual preference (yes or no) by speed date feedback (acceptance or rejection).

For EEG data, I submitted the SPN of individual preference (yes or no) into a paired t-test to compare the two different judgments of the participants. In addition, a two-way repeated-measures ANOVA was used to compare the RewP and theta power in individual preference (yes or no) by speed date feedback (acceptance or rejection) separately. Greenhouse-Geisser correction provided an appropriate way to solve the condition when sphericity was violated.

For statistical analysis of theta source localization result, I used nonparametric cluster-based permutation to test the significant difference in source space between different conditions (Maris & Oostenveld, 2007), by using the function of ft_sourcestatistics in Brainstorm (Oostenveld, Fries, Maris, & Schoffelen, 2011). Because I averaged theta frequency band (4–8 Hz) in a 200–400 ms time window, the test statistic of theta source results was only needed to consider the spatial dimension. First, the alpha level of 0.05 threshold was set to seek the significant vertices for every sample between two conditions. Samples that exceeded the critical *t*-values were then clustered and summed over t-values, which were based on spatial adjacency. Next, for the summed clusters, the cluster-level statistic was used to test significant differences between conditions at each cluster. The statistical significance testing with paired t-tests was implemented by using the Monte Carlo method. The nonparametric cluster-level statistics was performed by calculating a *p*-value under 1000 random permutation distribution of the source data. The cluster-corrected alpha level of 0.05 was set for multiple comparisons. The artifact-free trials are shown in Table 5 for Study I.

[2] Individual preference (yes or no): the participants judged the speed date as a potential romantic partner (yes), and the participants judged the speed date as a potential romantic partner (no); feedback type (acceptance (yes) or rejection (no)): the speed date judged the participant as a potential romantic partner (yes), and the speed date judged participant as non-potential romantic partner (no). In order to distinguish individual preferences and feedback types in the statistical analysis section, we correspond to the feedback type ”yes” as the acceptance feedback comes from the speed date, and ”no” corresponds to the rejection feedback from the speed date.
Therefore, the Match outcome means that both the participants and their speed dates chose “yes”; the Rejection outcome means that the participants chose “yes” and their speed dates chose “no”; the Disinterest outcome means that both the participants and their speed dates chose “no”; and the Unrequited outcome means that the participants chose “no” and their speed dates chose “yes”.

TABLE 5 Average response time for making judgments and the number of trials for each possible outcome for Study I

Participant choice	Response time (*mean* ± SE)	Peer feedback number of trials (*mean* ± SE)	
		Acceptance	Rejection
Yes	1380.87 ± 65.34	28.80 ± 2.02	29.92 ± 1.64
No	1182.79 ± 50.51	50.16 ± 2.00	48.96 ± 1.54

2.5.2 Study II

In Study II, for behavior data, I submitted the reaction time (RT) of individual preference (yes or no), the number of participants' judgment of individual preference (yes or no), STAI, and PANAS scores (phase: pre and post) into *t*-tests. I submitted the self-reported motivation into a *t*-test with individual preference (yes or no). I also submitted the self-reported pleasantness and worthiness ratings into a three-way repeated measure ANOVA with individual preference (yes or no) by waiting time (long or short) by peer feedback (acceptance or rejection).

TABLE 6 Average response time for making judgments and the number of trials for each possible outcome for Study II

Participant choice	Response time (mean ± SE)	Waiting time	Peer feedback number of trials (mean ± SE)	
			Acceptance	Rejection
Yes	1251.18 ± 45.28	Short	27.14 ± 1.73	25.79 ± 1.34
		Long	27.72 ± 1.78	26.93 ± 1.76
No	1189.71 ± 38.55	Short	31.59 ± 1.77	32.31 ± 1.45
		Long	30.90 ± 1.79	32.59 ± 1.59

The difference wave approach was used to isolate the RewP from other confounding ERP components such as P300 (Holroyd & Krigolson, 2007; Sambrook & Goslin, 2015); the difference wave was created for each participant by subtracting the ERP to negative feedback (rejection) from the ERP to positive feedback (acceptance). A two-way repeated measure ANOVA was used to test the RewP with individual preference (yes or no) by waiting time (long or short). Greenhouse-Geisser correction provided an appropriate way to solve the condition when sphericity was violated. The artifact-free trials in Table 6 for Study II.

2.5.3 Study III

For behavioral data, I submitted the reaction time (RT) of individual preference (yes or no), and the number of participants' judgment into a two-way ANOVA with individual preference (yes or no) by treatment (oxytocin or placebo). A three-way ANOVA was used to test self-reported pleasantness ratings with treatment (oxytocin or placebo) by individual preference (yes or no) by speed date feedback (acceptance or rejection). In addition, the STAI and PANAS scores were submitted into a two-way ANOVA with treatment (oxytocin or placebo) by phase (pre or post). Note that the treatment (oxytocin or placebo) was the between-subjects factor, and other factors were within-subjects factors.

For the EEG data, I submitted the theta power into a three-way ANOVA with treatment (oxytocin or placebo) by individual preference (yes or no) by speed date feedback (acceptance or rejection). The post-hoc comparisons would be applied when the interactions were significant. Greenhouse-Geisser correction provided an appropriate way to solve the condition when sphericity was violated. I also calculated the correlation analysis to investigate the relationship between theta oscillation and self-reported pleasantness ratings. Pearson's linear correlation was implemented in the nonparametric permutation test (Groppe, Urbach, & Kutas, 2011). The 10,000 random permutations were used to draw the possible permutation distributions with the 0.05 alpha level. I used the cocor r statistic tool (Diedenhofen & Musch, 2015) to further verify the difference of the correlation results between the two treatment groups, only if the correlation reached significance. The artifact-free trials for Study III are shown in Table 7.

I used theta source localization data in the same way as in Study I. For more details, please see section 2.5.1.

TABLE 7 Average response time for making judgments and the number of trials for each possible outcome for study III

Participant choice	**Response time (mean ± SE)**		**Peer feedback**	**Number of trials (mean ± SE)**	
	Oxytocin	**Placebo**		**OT**	**PLC**
Yes	1354.27 ± 49.84	1378.03 ± 49.03	Yes	29.43 ± 2.00	26.45 ± 1.97
			No	29.47 ± 1.77	27.97 ± 1.75
No	1190.84 ± 45.88	1163.08 ± 45.14	Yes	48.73 ± 2.06	51.58 ± 2.03
			No	48.97 ± 1.80	50.19 ± 1.77

3 SUMMARY OF THE RESULTS

3.1 Study I

3.1.1 Behavioral results

The results showed that the reaction time (RT) of making a "yes" judgment was significantly longer than making a "no" judgment ($t(1,24) = 5.43$, $p < 0.001$, Cohen's $d = 1.09$), revealing that the participants took longer to show their romantic interest to their speed date (1380.87 ± 65.34 ms) than to show disinterest (mean = 1182.79, SE = 50.51 ms; Figure. 2A). Additionally, I found that the participants more often made "No" judgments (100.00 ± 3.27) than "Yes" judgments (59.20 ± 3.30; $t(1,24) = 6.22$, $p < 0.001$, Cohen's $d = 1.24$). Furthermore, the main effect of the individual preference in the change of the likeability rating was significant ($F(1, 24) = 11.21$; $p = 0.003$; $\eta_p^2 = 0.32$), which suggested that the participants increase their likeability of the speed dates if they judged them as potential romantic partners rather than non-potential romantic partners.

3.1.2 Questionnaire results

Further, the participants reported a stronger motivation for potential romantic partners (5.32 ± .15) to know their choices than for non-potential romantic partners (4.10 ± .15; t (1, 24) = 5.80, $p < 0.001$, Cohen's $d = 1.16$; Fig. 2B). As depicted in Figure 2C, I found a significant main effect of speed date feedback in self-reported pleasantness ratings, $F(1, 24) = 42.69$; $p < 0.001$; $\eta_p^2 = 0.64$. More importantly, the interaction between individual preference and speed date feedback was significant ($F(1,24)=33.65$, $p < 0.001$, $\eta_p^2 = 0.58$), which participants reported more pleasantness when they received acceptance from their potential romantic partner (Match condition: both the participants and their speed dates chose "yes"; mean = 5.72, SD = 0.19) than when they received rejection from their potential romantic partner (Rejection condition: the participants chose "yes" and their speed dates chose "no"; mean = 3.08; SD = 0.16; p < 0.001). However, there was no significant difference between when the participants received acceptance from their non-potential romantic partner (Unrequited outcomes: the participants chose "no" and their speed dates chose "yes"; mean = 4.20, SD =0.20) and when the participants received rejection from their non-potential romantic partner (Disinterest outcomes: both the participants and their speed dates chose "no"; mean = 4.00, SD = 0.21; p = 0.519). No significant effects were found for the STAI-S and PANAS scales (all p values > .12).

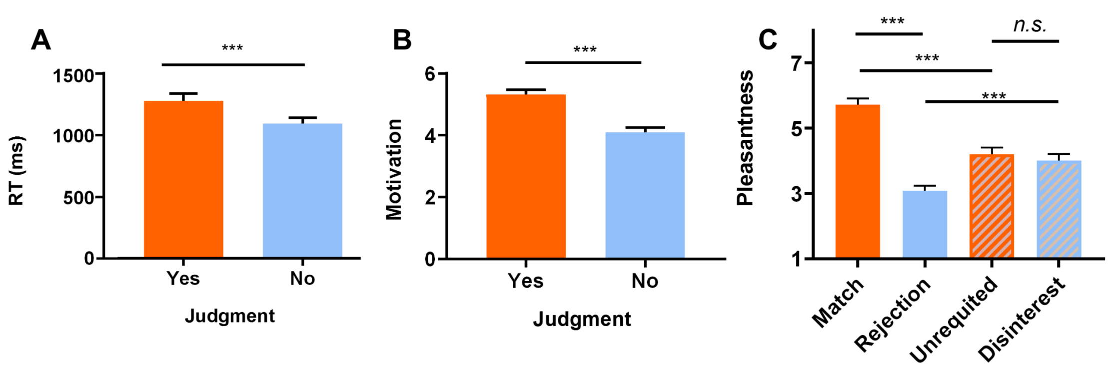

FIGURE 3 Behavioral data and Self-reported questionnaires in Study I. (A) The reaction time (RT) of the participants made the judgment. (B) The self-reported motivation under two different preferences. (C) The self-reported pleasantness in four possible outcomes. Yes on the judgment scale refers to cases when the participant indicated liking the other person and No to cases when indicating a dislike for the other person. The Match outcome (both the participants and their speed dates chose "yes"), the Rejection outcome (the participants chose "yes" and their speed dates chose "no"), the Disinterest outcome (both the participants and their speed dates chose "no"), and the Unrequited outcome (the participants chose "no" and their speed dates chose "yes"). Error bars represent standard errors. *n.s* indicates no significance. *** p < .001.

3.1.3 EEG results

Stimulus preceding negativity (SPN)

As shown in Figure 4, I found a more negative SPN when the participants were waiting for the feedback from potential romantic partner (mean = -4.51, SD = 0.75) relative to when the participants were waiting for the feedback from non-potential romantic partner (mean = -2.74, SD = 0.57) in their speed date ($t(1,24)$ = -3.49, p = 0.002, Cohen's d =0.68).

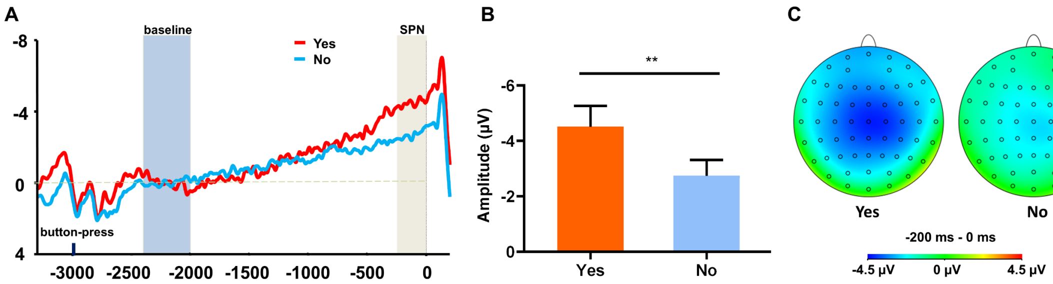

FIGURE 4 Stimulus preceding negativity (SPN) in Study I. (A) Feedback-locked grand-averaged ERP waveforms at Cz for two participants' judgments. (B) Average SPN amplitude for two participants' judgments. (C) Scalp distribution represented by the average amplitude in a -200 to 0 ms time window. The Blue -shaded area indicates the baseline time window (-2400 to 2000 ms), and the Gray-shaded area indicates the quantified time window (-200 to 0 ms). Yes on the judgment scale refers to cases when the participant indicated liking the other person and No refers to cases when the participant indicated disliking the other person. Error bars represent standard errors. ** p < .01.

Reward positivity (RewP)

Grand-averaged ERPs at Cz are depicted in Figure 5A. I found a significant main effect of individual preference ($F(1,24) = 13.91$, $p = 0.001$, $\eta_p^2 = 0.37$) and a significant main effect of speed date feedback ($F(1,24) = 24.13$, $p < 0.001$, $\eta_p^2 = 0.50$), which were included in a significant interaction between individual preference and speed date feedback ($F(1,24) = 4.46$, $p = 0.045$, $\eta_p^2 = .16$). Follow-up paired samples t-test revealed that the RewP to the speed date's feedback (8.04 ± 1.51μV) was significantly larger for Match outcomes relative to all other conditions (all ps < 0.001).

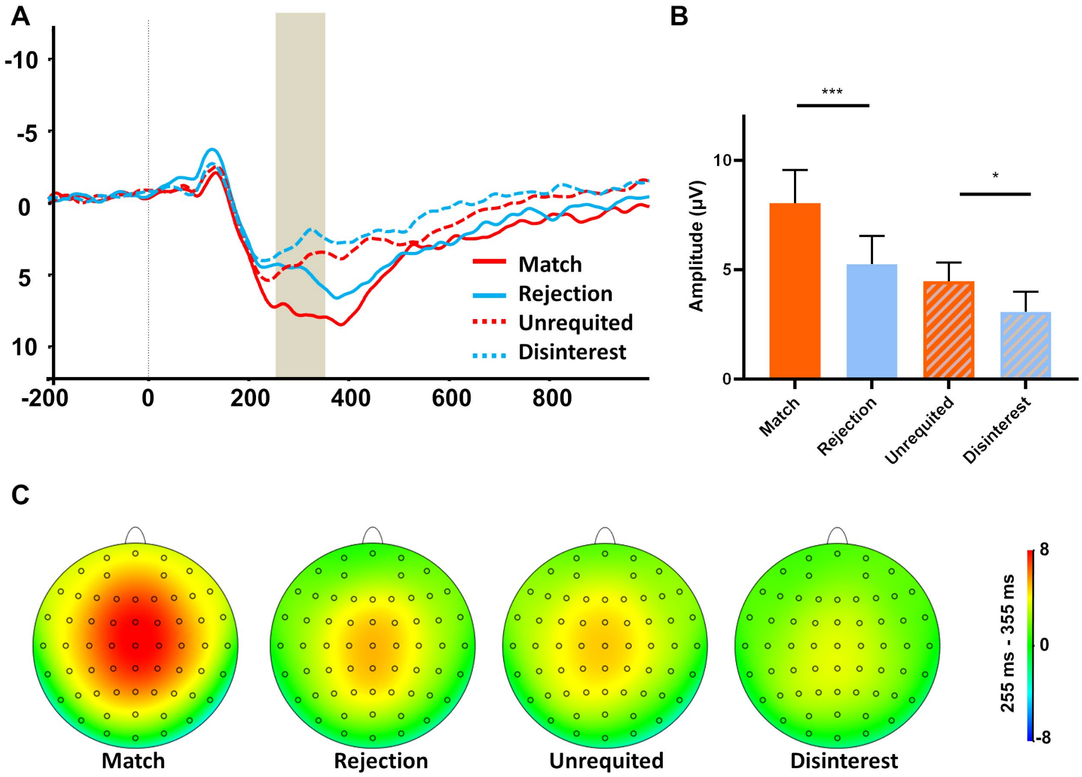

FIGURE 5 Reward positivity (RewP) in Study I. (A) Feedback-locked grand-averaged ERP waveforms at Cz in four outcomes. (B) Average RewP amplitude per outcome (C) Scalp distribution in four outcomes represented by the average amplitude in a 255–355 ms time window. The Match outcome (both the participants and their speed dates chose "yes"), the Rejection outcome (the participants chose "yes" and their speed dates chose "no"), the Disinterest outcome (both the participants and their speed dates chose "no"), and the Unrequited outcome (the participants chose "no" and their speed dates chose "yes"). *** $p < 0.001$, * $p < 0.05$

Figure 6 depicts the projected waveform of PCA-RewP and the topographic distribution in the time domain. Two-way ANOVA conducted at the peak of PCA-RewP revealed a similar result with the original RewP method. I found a significant main effect of individual preferences, $F(1,24) = 15.52$, $p = 0.001$, $\eta_p{}^2 = 0.39$, and a significant main effect of speed date feedback, $F(1,24) = 22.64$, $p < 0.001$, $\eta_p{}^2 = 0.49$. Also, the interaction between individual preference and speed date feedback was significant, $F(1,24) = 7.57$, $p = 0.011$, $\eta_p{}^2 = 0.24$. Further analyses showed that the PCA-RewP was significantly larger for Match outcomes (6.84 ± 1.85 μV) relative to the other conditions (all other ps < 0.001).

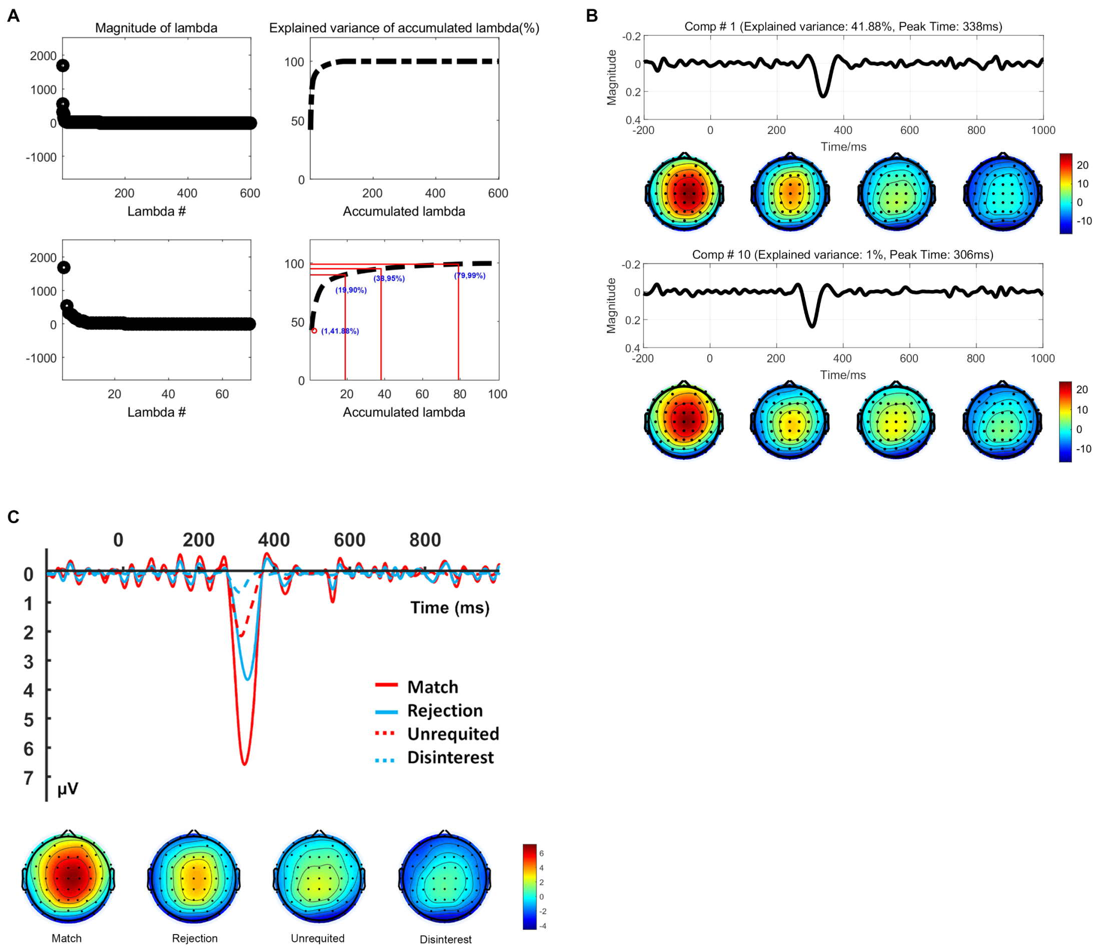

FIGURE 6 Results of PCA to extract RewP in Study I. t-PCA and Promax rotation were used to extract the RewP. (A) The number of components extracted explains the variation. (B) The temporal (loadings) and spatial (scores) subcomponents for first and 10th extracted components. Note that the spatial subcomponents are averaged over all participants. (C) The grand-averaged PCA-RewP waveforms at Cz and corresponding scalp distribution in four outcomes. The four outcomes are Match (both the participants and their speed dates chose "yes"), the Rejection (the participants chose "yes" and their speed dates chose "no"), the Disinterest (both the participants and their speed dates chose "yes"), and the Unrequited (the participants chose "no" and their speed dates chose "yes").

Theta oscillation

As depicted in Figure 7, the theta power yielded a significant main effect of individual preference ($F(1,24)$ =14.02, p = 0.001, η_p^2 = 0.37), and a main effect of speed dates feedback (F(1,24) = 12.08, p = 0.002, η_p^2 = 0.34), which were included in a significant interaction between individual preference and speed date feedback (F(1,24) =6.92, p = 0.015, η_p^2 = 0.22). Follow-up paired samples t-test indicated that theta power was significantly highest in the Rejection condition (the participants chose "yes", the speed dates chose "no") relative to all other conditions (p values < 0.001). All other contrasts were not significant (p values > 0.54).

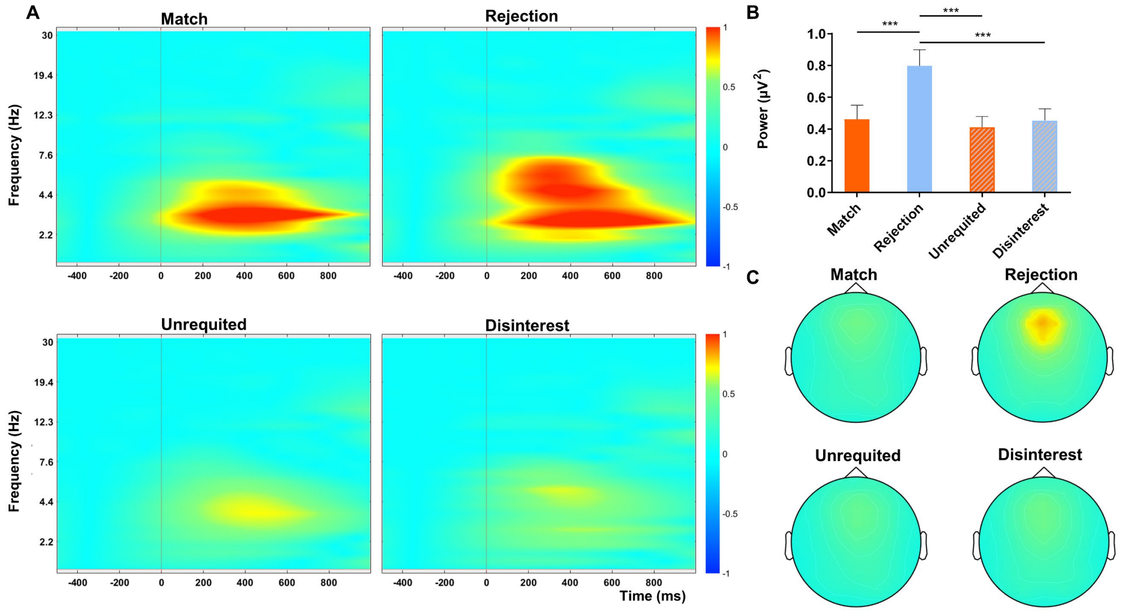

FIGURE 7 Time-frequency theta oscillation in Study I. Time-frequency theta power at Fz during the 200-400 ms post-feedback interval. (A) Time-frequency plots for the four conditions. (B) Average theta power per outcome. (C) Scalp distribution of theta power. The four outcomes are Match (both the participants and their speed dates chose "yes"), the Rejection (the participants chose "yes" and their speed dates chose "no"), the Disinterest (both the participants and their speed dates chose "yes"), and the Unrequited (the participants chose "no" and their speed dates chose "yes"). Error bars represent standard errors. *** p < 0.001.

Source localization

The four source maps of feedback-related theta oscillation are presented in Figure 8. An obviously increased theta power localized over mid-frontal regions occurred when the participants received rejection from a potential romantic partner (Rejection condition) compared with other conditions. Furthermore, non-parametric permutation testing suggested that the significant differences of theta power between rejection conditions and other conditions were mainly located in the anterior cingulate cortex (ACC) and frontal pole. The results of the source maps are displayed in Figure 9. The three contrasts between Rejection and Match, Disinterest, and Unrequited showed the increased theta oscillation of the Rejection condition compared to other conditions. More specifically, the significant clusters of Rejection condition relative to Match condition involved cluster 1: size = 214, p = 0.024 and cluster 2: size = 155, p = 0.045; the Rejection condition relative to Disinterest condition involved cluster 1: size = 181, p = 0.042, cluster 2: size = 175, p = 0.045; and the Rejection condition relative to Unrequited condition involved in one cluster: size = 174, p = 0.04. Although the non-parametric permutation tests of the space source cannot give a high spatial precision of these differences (Maris & Oostenveld, 2007; Sassenhagen & Draschkow, 2019), the more clear differences were occurred during 200–400 ms time window and located in the prefrontal region and cingulate cortex.

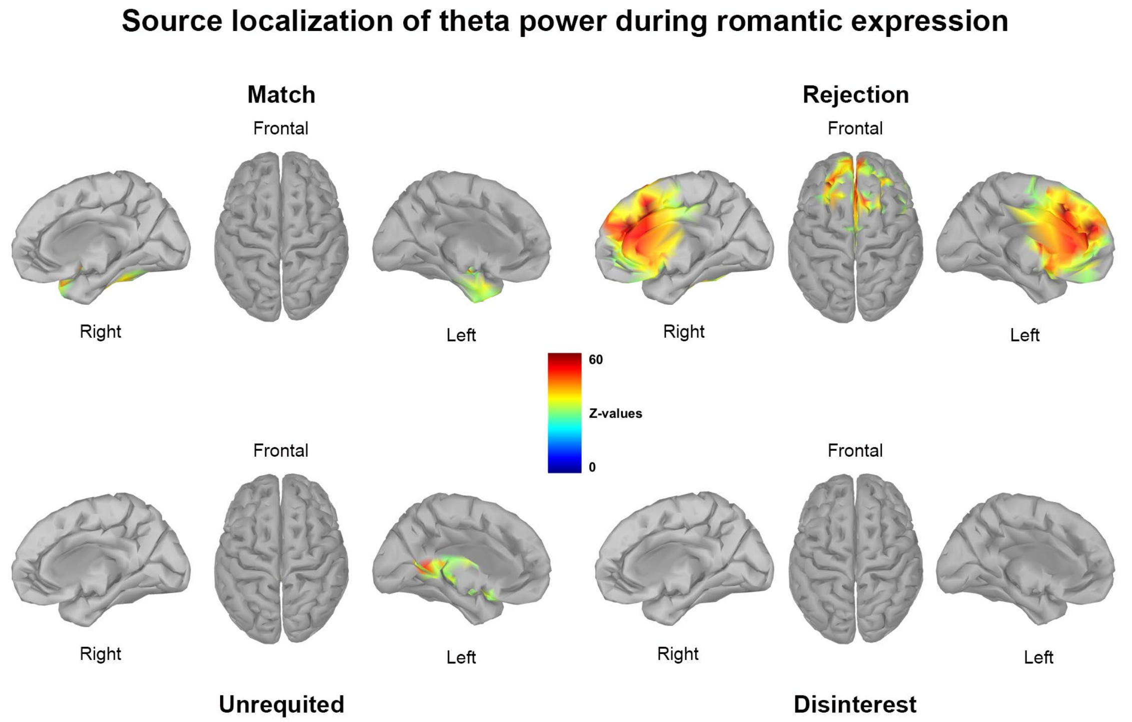

FIGURE 8 Source maps of theta oscillation in Study I. The source maps of theta oscillation for four outcomes (averaged 200–400 ms post-feedback interval). Rejection condition means the participants chose "yes" and the speed dates chose "no". Match condition means the participants chose "yes" and the speed dates chose "yes". Disinterest condition means the participants chose "no" and the speed dates chose "no". Unrequited condition means the participants chose "no" and the speed dates chose "yes."

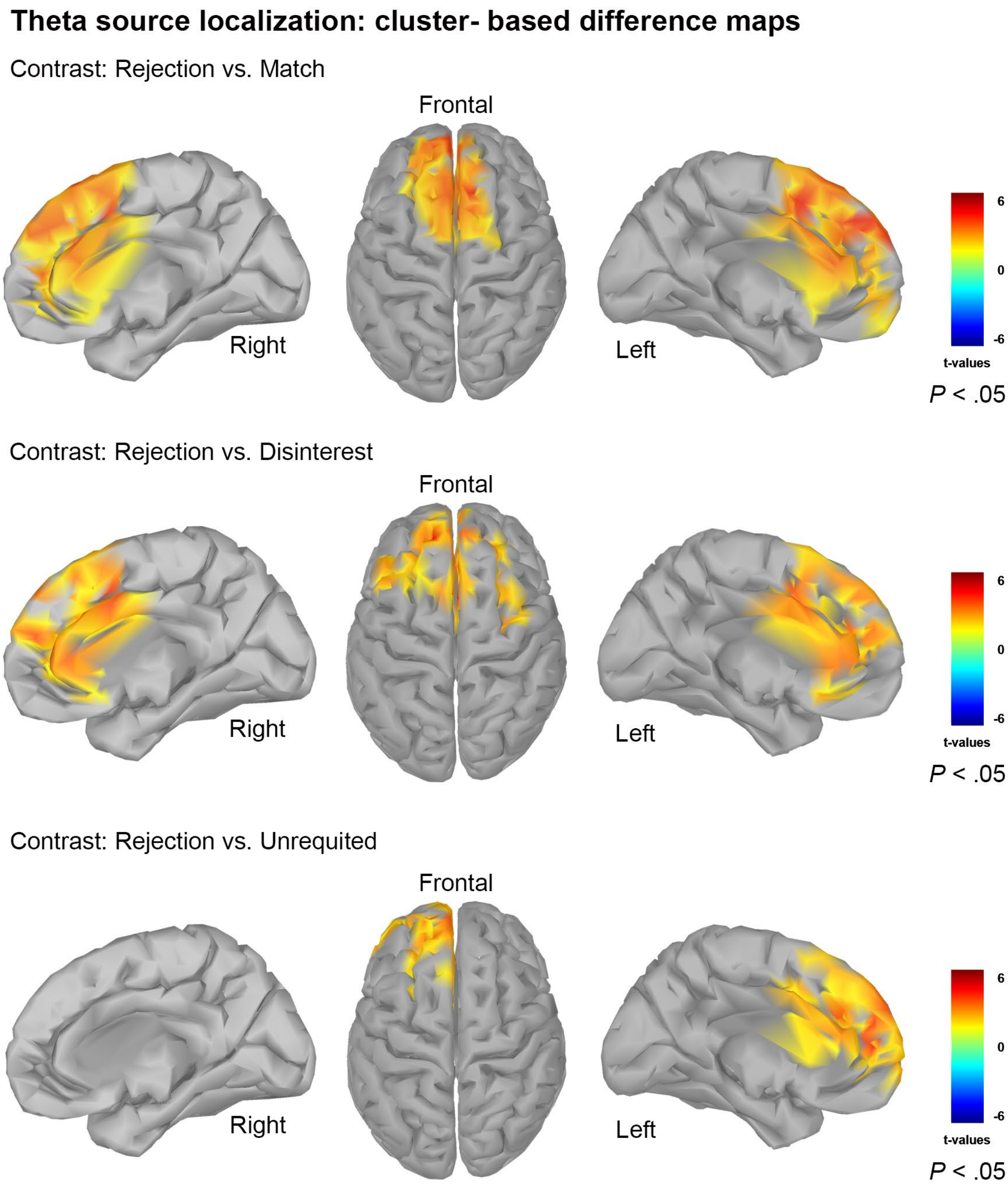

FIGURE 9 Statistical differences of theta source activity in Study I. The statistical differences of theta source activity between Rejection and the Match, Disinterest, and Unrequited conditions. The Rejection condition means the participants chose "yes" and the speed dates chose "no". Match condition means the participants chose "yes" and the speed dates chose "yes". The Disinterest condition means the participants chose "no" and the speed dates chose "no". The Unrequited condition means the participants choose "no" and the speed dates chose "yes."

3.2 Study II

3.2.1 Behavioral results

As depicted in Figure 10a, there was a significant main effect of individual preference on RTs ($t(1,28) = 2.96$, $p = 0.006$, Cohen's $d = 0.55$), indicating that the participants made a choice more quickly when they judged others as disliked (1189.71 ± 38.55) than when they judged others as liked (1251.18 ± 48.28). I also found that the participants more often made "No" judgments (142.48 ± 7.00) than "Yes" judgments (97.52 ± 7.00; $t(1,28) = 3.21$, $p = 0.003$, Cohen's $d = 0.60$).

3.2.2 Questionnaire results

In the self-reported motivation scale (Figure 10b), participants showed a stronger motivation to know the feedback from liked peers (4.52 ± .12) than to know the feedback from disliked peers (3.76 ± .18), $t(1,28) = 4.14$, $p < 0.001$, Cohen's d = 0.77.

In a self-report questionnaire about pleasantness (Figure 10c), I found the significant main effect of peer feedback ($F(1,28) = 37.19$, $p < 0.001$, $\eta_p^2 = 0.57$), indicating that participants felt more pleasantness when they received acceptance feedback from others compared to rejection feedback. I found a significant interaction between individual preferences and peer feedback; $F(1,28) = 59.44$, $p < 0.001$, $\eta_p^2 = 0.68$. Further analysis indicated that participants felt more pleasantness when they received acceptance feedback from the peers they liked than when they received rejection feedback ($F(1,28) = 146.03$, $p < 0.001$, $\eta p2 = 0.84$) but the feeling was not different between acceptance and rejection feedback from disliked peers, $p = .957$. I found a significant interaction between waiting time and peer feedback; $F(1,28) = 6.31$, $p = 0.018$, $\eta_p^2 = 0.18$. Further analysis indicated that, in both short and long wait conditions, the participants felt more pleasant when they received acceptance feedback than rejection feedback (all ps < 0.001). We also compared differences in self pleasantness ratings when participants received positive feedback after long and short waits, and when participants received negative feedback after long and short waits, but neither difference was significant (positive feedback, $p = 0.065$; negative feedback $p = 0.089$). No other results reached significance (all ps > 0.07).

In addition, regarding the self-report worthiness (Figure 10d), I found the main effect of subjective preference ($F(1,28) = 58.68$, $p < 0.001$, $\eta_p^2 = 0.68$) and the main effect of peer feedback ($F(1,28) = 25.30$, $p < 0.001$, $\eta_p^2 = 0.48$) were significant. In addition, the interaction between subjective preference and waiting time ($F(1,28) = 17.27$, $p < 0.001$, $\eta_p^2 = 0.38$), the interaction between subjective preference and peer feedback ($F(1,28) = 58.13$, $p < 0.001$, $\eta_p^2 = 0.68$) and the interaction between waiting time and peer feedback ($F(1,28) = 6.90$, $p = 0.014$, $\eta_p^2 = .20$) were significant. Importantly, I found a significant interaction among subjective preference, waiting time, and peer feedback; $F(1,28) = 6.63$, $p = 0.016$, $\eta_p^2 = 0.19$. Further analysis showed that when the participants meet their liked peers, the long wait for acceptance is more worthwhile than the short wait (t(1,28)

= 3.29; p = 0.003; Cohen's d = 0.61), not in rejection feedback (p = 0.46). However, when the participants were faced with disliked peers, the overall trend was that the long wait was less worthwhile, regardless of whether the wait was for acceptance (t(1,28) = 3.79; $p < 0.001$; Cohen's d = 0.71) or rejection feedback (t(1,28) = 3.18; p = 0.004; Cohen's d = 0.59).

The STAI-state and PANAS were not different between pre and post-tasks (all p values > 0.19).

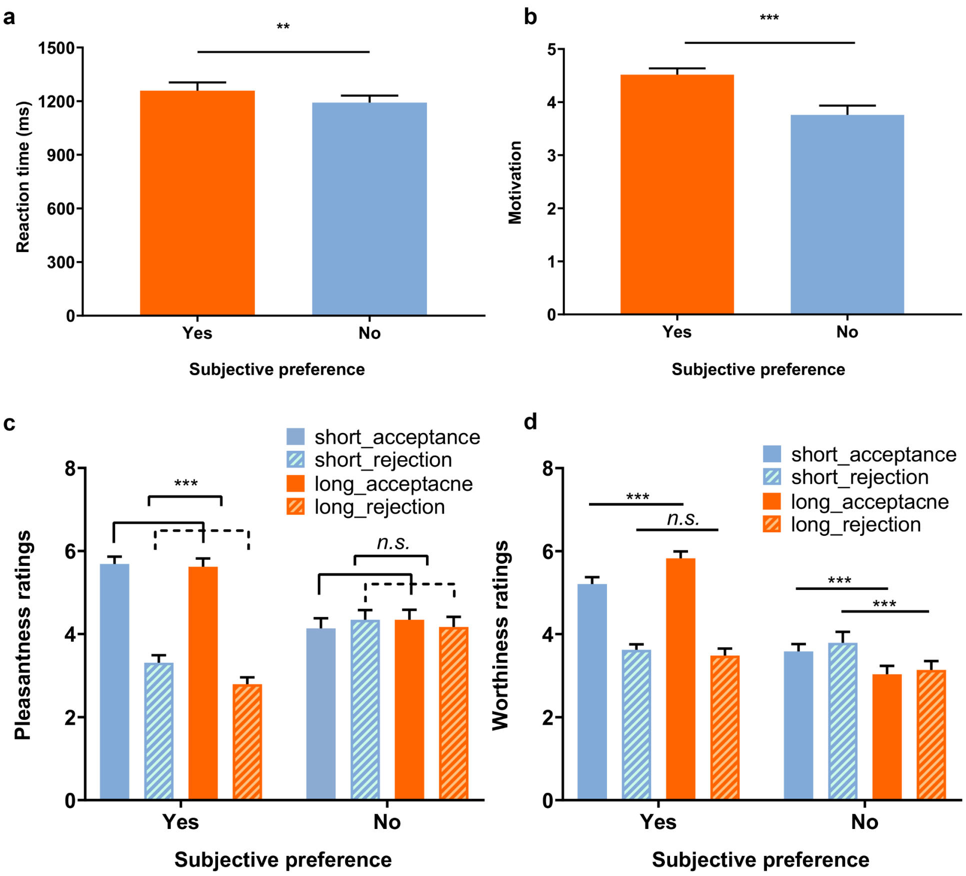

FIGURE 10 Behavior and self-reported ratings in Study II. (a) The reaction time of the participants made the judgment. (b) The self-reported motivation under two different preferences. (c) The self-report pleasantness. (d) The self-reported worthiness. Yes on the subjective preference scale refers to cases when the participant indicated liking the other person and No refers to cases indicating a dislike for the other person. Short_acceptance = receiving social acceptance feedback after a short waiting time; short_rejection = receiving social rejection feedback after a short waiting time; long_acceptance = receiving social acceptance feedback after a long waiting time; long_rejection = receiving social rejection feedback after a long waiting time. Error bars represent standard errors. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, *n.s.* indicates no significance.

3.2.3 EEG results

Reward positivity (RewP)

Grand-averaged ERPs at Fz are depicted in Figure 10. The difference wave was created by subtracting the ERP to negative feedback (rejection) from the ERP to positive feedback (acceptance) in two different subjective preference conditions for each participants.. The main effect of subjective preference was significant; F(1,28) = 6.94, $p = 0.014$, $\eta_p^2 = 0.20$. A larger RewP was observed when participants faced their liked peers compared to disliked peers. The main effect of waiting time was not significant ($p = 0.42$). Importantly, I found the significant interaction between subjective preference and waiting time, F(1,28) = 16.40, $p < 0.001$, $\eta_p^2 =$ 0.37. Further analyses were conducted for each subjective preference separately. Compared with the short waiting time condition, I found a reduced RewP after a long waiting time in the "dislike" condition (t(1,28) = 2 .18; $p = 0.038$; Cohen's d =.41); this result is consistent with previous studies, reflecting that the increased waiting time reduced RewP amplitude. However, compared with the short waiting time condition, an increased RewP was observed after the long waiting time in the "like" condition (t(1,28) = -2.55; $p = 0.017$; Cohen's d = -0.471).

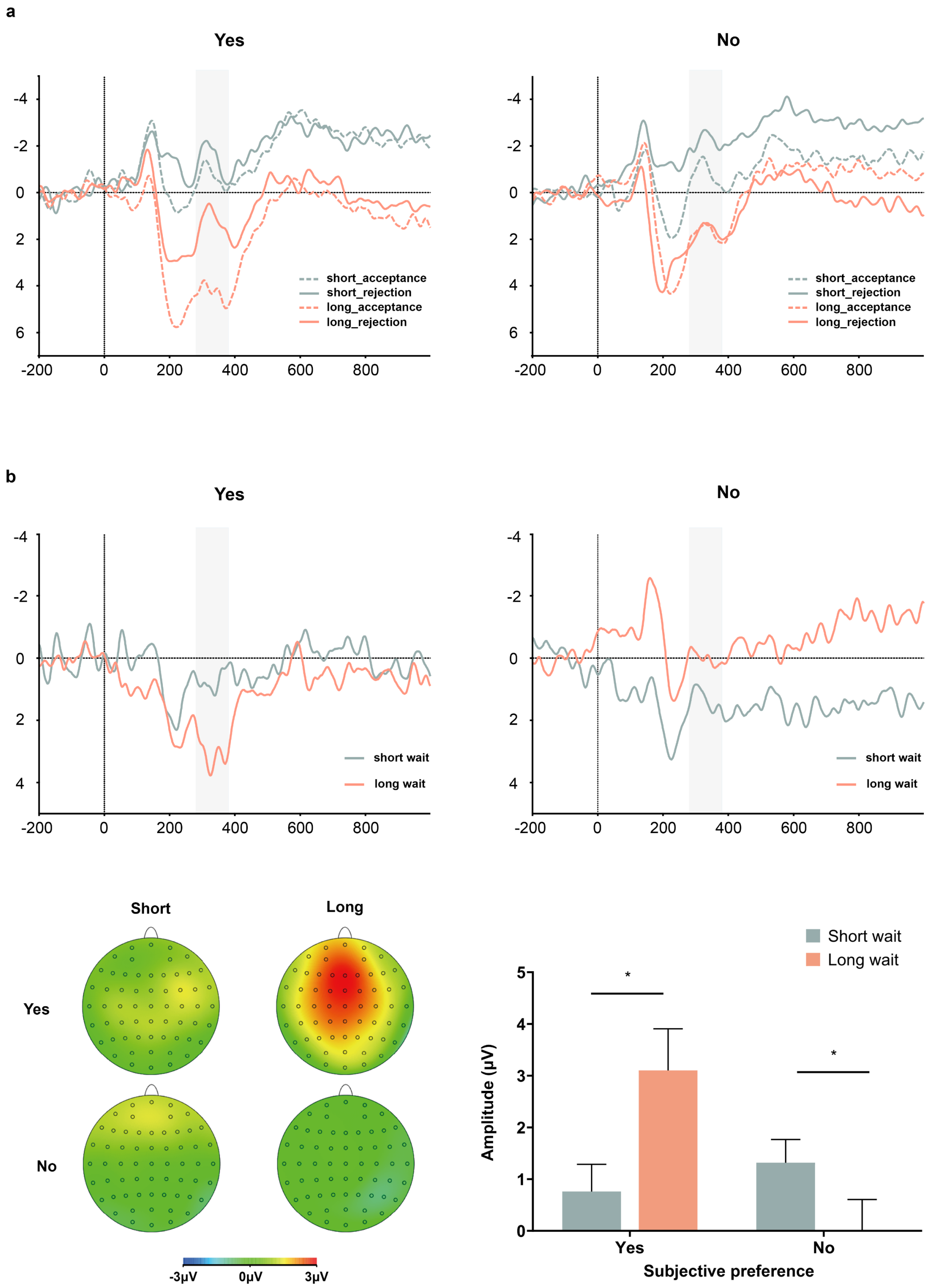

FIGURE 11 Results of reward positivity (RewP) in Study II. (a) Feedback-locked grand-averaged ERP waveforms at Fz in four conditions for the liked person (left panel) and disliked person (right panel). (b) The difference wave between the responses for acceptance and rejection feedback (RewP) at Fz in the four conditions for the liked person (left panel) and disliked person (right panel) and corresponding scalp distribution and average RewP amplitude. Yes on the subjective preference scale refers to cases where the participant indicated

liking the other person and No refers to cases where the participant indicated a dislike for the other person. Short_acceptance = receiving social acceptance feedback after a short waiting time; short_rejection = receiving social rejection feedback after a short waiting time; long_acceptance = receiving social acceptance feedback after a long waiting time; long_rejection = receiving social rejection feedback after a long waiting time. Gray-shaded area indicates the 280–380 ms analysis window is quantified. Error bars represent standard errors. * $p < 0.05$.

3.3 Study III

3.3.1 Behavioral results

The result showed that the reaction time (RT) of making a ″yes″ judgment was significantly longer than making a ″no″ judgment (F(1,59) =70.03, $p < 0.001$, $\eta_p^2 = 0.54$), revealing that the participants took longer to show their romantic interest to their speed date (1366.34 ± 34.69 ms) than to show disinterest in their speed dates (mean = 1176.73, SE = 31.96 ms). I also found that the participants more often made "No" judgments (99.77 ± 2.55) than "Yes" judgments (56.62 ± 2.49; F(1,59) =75.47, $p < 0.001$, $\eta_p^2 = 0.56$).

3.3.2 Questionnaire results

As presented in Figure 12, I found a significant main effect of individual preference in self-reported pleasantness ratings (F (1, 59) = 6.32, $p = 0.015$, $\eta_p^2 = 0.10$), and main effect of speed date feedback (F (1, 59) = 66.76, $p < 0.001$, $\eta_p^2 = 0.53$). There was also a significant interaction between individual preference and speed date feedback (F (1, 59) = 145.20, $p < 0.001$, $\eta_p^2 = 0.71$), with participants reporting more unpleasantness when they received rejection from their potential romantic partner (Rejection condition; $p < 0.001$), but not when the participants received acceptance from the non-potential romantic partner (Unrequited condition; $p = 0.059$). In addition, the significant main effect of treatment was observed (F (1, 59) =14.77, $p < 0.001$, $\eta_p^2 = 0.20$); compared with the placebo group, the oxytocin group reported more pleasantness. More importantly, I found a significant interaction among treatment, individual preference, and speed date feedback (F (1, 59) = 12.43, $p = 0.001$, $\eta_p^2 = 0.17$). Further analysis indicated that the participants in the placebo group showed lower pleasantness when they received a rejection from a potential romantic partner (Rejection condition) than when they received acceptance from a potential romantic partner (Match condition; $p < 0.001$), but there was no difference between the Unrequited (the participants chose ″no,″ the speed dates chose ″yes″) and Disinterest conditions (the participants chose ″no,″ the speed dates chose ″no″; $p = 0.309$). However, in the oxytocin group, the participants reported lower pleasantness when they received a rejection from a potential romantic partner (Rejection condition) than when they received acceptance from a non-potential romantic partner (Match condition $p < 0.001$), On the other hand, the participants reported more pleasantness when they received a rejection from non-potential romantic partner (Disinterest condition) than when they received acceptance from non-potential romantic partner (Unrequited condition; $p < 0.001$).

Furthermore, in order to directly reflect the change in pleasantness reported by the participants, we conducted paired sample *t*-tests on the self-rated pleasantness and anchor points (score 4) of the two groups under the four conditions. In the placebo group, compared with anchor points, the results found an increased pleasantness rating when the participants received acceptance from the potential romantic partner (Match condition) and a decreased pleasantness when they received a rejection from the potential romantic partner (Rejection condition; both p values < 0.001). In addition, the self-reported pleasantness ratings in the Unrequited and Disinterest conditions were not different from the anchor point (both p values > 0.15). In the oxytocin group, compared with anchor points, the results found an increased pleasantness rating in the Match condition and a decreased pleasantness rating in the Rejection condition (both p values < 0.003). Compared to the anchor point, the participants showed an increased pleasantness rating in the Disinterest condition ($p < 0.001$), which was different from the placebo group. In addition, a similar result with the placebo group was found in the Unrequited condition, in which the self-reported pleasantness rating was not different from the anchor point ($p = 1.00$). Moreover, the STAI and PANAS scores before and after were not different (all p values > 0.08).

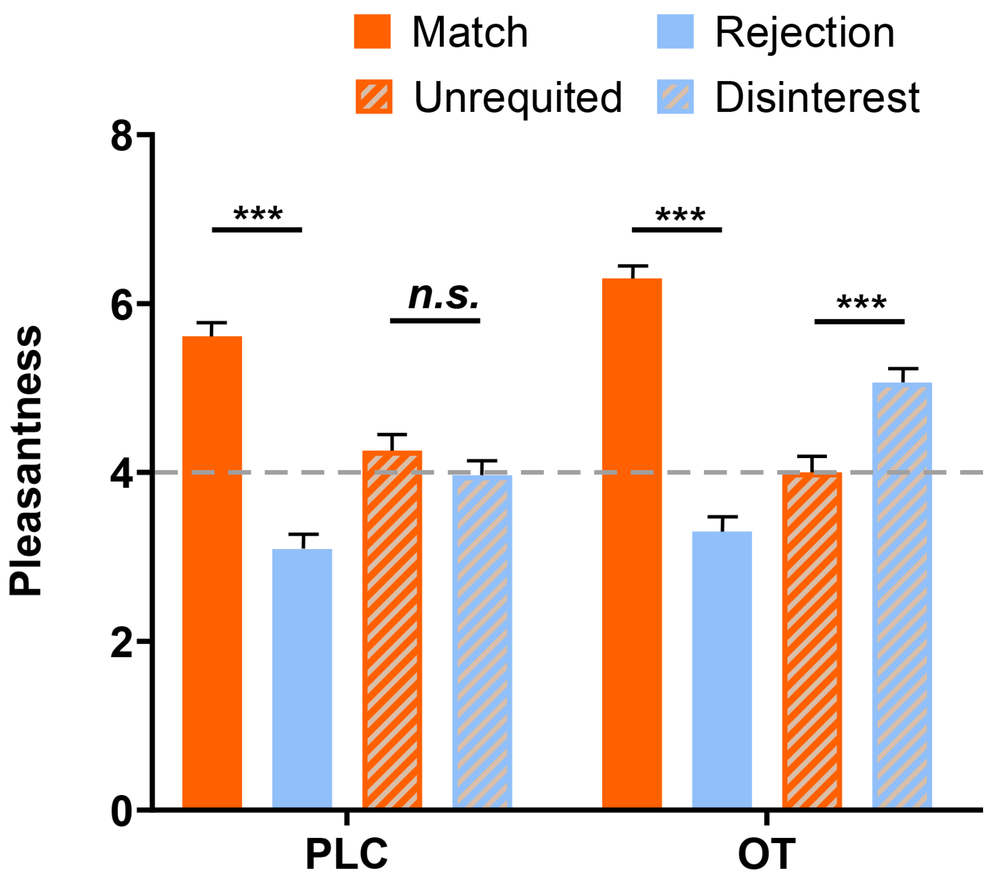

FIGURE 12 The participants reported pleasantness scores in four conditions for each group. PLC means placebo group, and OT means oxytocin group. The four outcomes are Match (both the participants and their speed dates chose ”yes”), the Rejection (the participants chose “yes” and their speed dates chose “no”), the Disinterest (the participants and their speed dates both chose “yes”), and the Unrequited (the participants chose “no” and their speed dates chose “yes”). Error bars represent standard errors. *n.s.* indicates no difference. *** $p < 0.001$.

3.3.3 EEG results

Theta oscillation

As shown in Figure 13, the theta power yielded a significant main effect of individual preference ($F(1, 59) = 17.90$, $p < 0.001$, $\eta_p^2 = 0.23$), and a main effect of speed date feedback ($F(1, 59) = 12.83$, $p = 0.001$, $\eta_p^2 = 0.18$). There was a significant interaction between individual preference and speed date feedback ($F(1, 59) = 15.20$, $p < 0.001$, $\eta_p^2 = 0.21$). In addition, the main effect of treatment reached significance ($F(1, 59) = 5.00$, $p = 0.029$, $\eta_p^2 = 0.08$), which showed an increased theta power from placebo vs. oxytocin group. Furthermore, the interaction among treatment, individual preference, and speed date feedback was significant ($F(1, 59) = 6.43$, $p = 0.014$, $\eta_p^2 = 0.10$). Further analysis showed that when the participants received rejection from the potential romantic partner (Rejection condition), there would be a larger theta power in placebo group than in oxytocin group (p = 0.002); no other differences were found in other conditions between placebo and oxytocin group (p values > 0.080).

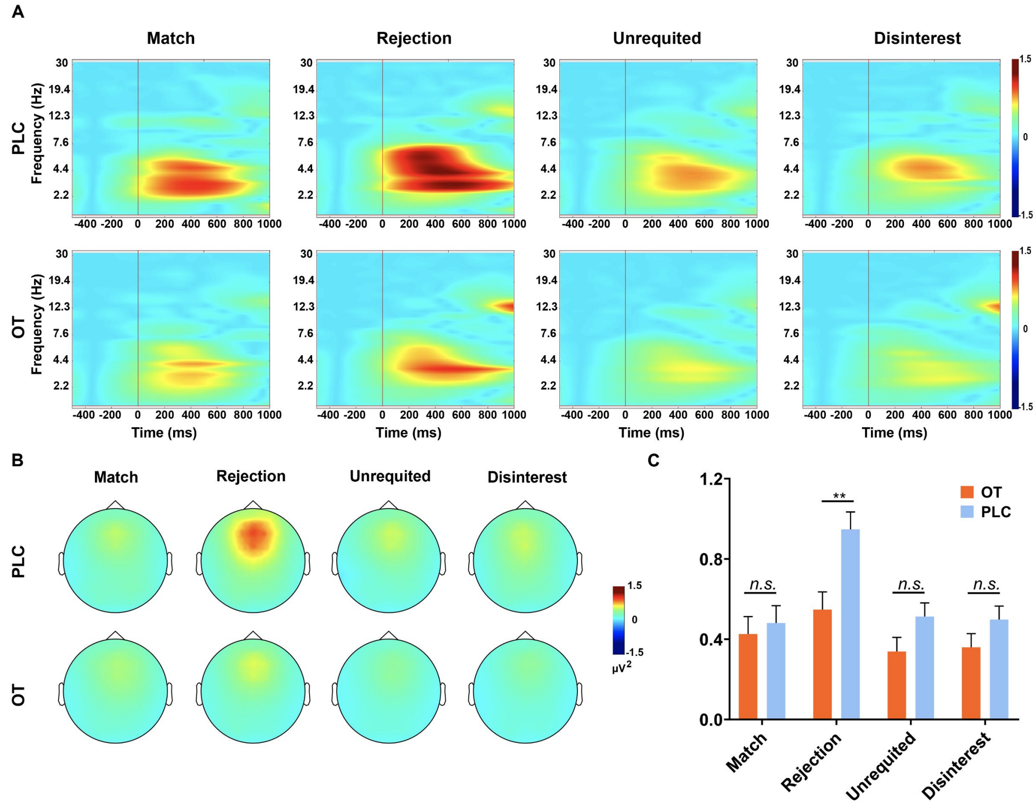

FIGURE 13 Time-frequency theta oscillation in Study III. The averaged 200–400 ms time window at Fz was used to calculate the theta power. (A) Time-frequency plots for placebo and oxytocin groups. (B) The scalp distribution of theta oscillation. (C) The statistical results of the theta power in bar plots. PLC means placebo group, and OT means oxytocin group. The four outcomes are Match (both the participants and their speed dates chose "yes"), the Rejection (the participants chose "yes" and their speed dates chose "no"), the Disinterest (both the participants and their speed dates chose "yes"), and the Unrequited (the participants chose "no" and their speed dates chose "yes"). Error bars represent standard errors. ** $p < 0.01$. *n.s.* indicates no difference.

Source localization

Based on time-frequency analysis, I further compared the neural sources in the Rejection condition (the participants chose ”yes,” the speed dates chose ”no”) between the placebo and oxytocin group. As displayed in Figure 14, there was a different pattern of theta source activity in the mid-frontal regions between the placebo and oxytocin group in the Rejection condition. Furthermore, non-parametric permutation testing suggested that the significant differences of the theta power between placebo and oxytocin group in the Rejection condition were mainly located in the cingulate cortex (ACC; BA 24, 25, and 32), the frontal pole (BA 9 and BA10), the supplementary motor area (BA6), and the somatosensory motor cortex (left BA2, left and right BA3), with the cluster 1: size = 478, $p = 0.005$; cluster 2: size = 343, $p = 0.015$. Although the non-parametric permutation tests of the space source cannot give a high spatial precision of these differences (Maris & Oostenveld, 2007; Sassenhagen & Draschkow, 2019), clearer differences occurred during the 200–400 ms time window and were located in the mid-frontal region and cingulate cortex.

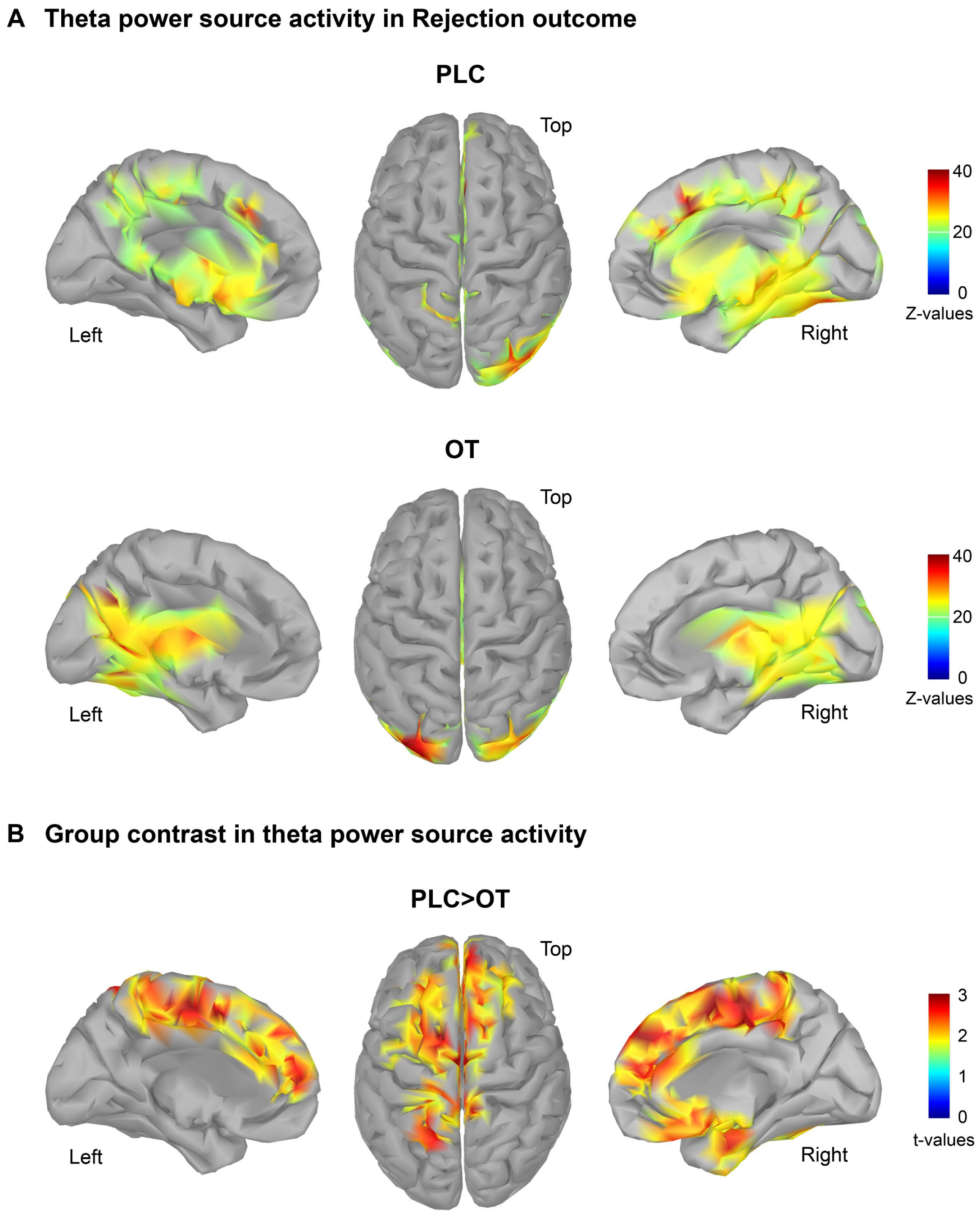

FIGURE 14 Source maps of theta oscillation in Study III. (A) The source maps of theta oscillation for Rejection outcome in the oxytocin group (OT) and placebo group (PLC). (B) The statistical differences of theta source activity between the placebo and oxytocin groups in the Rejection outcome. Rejection outcome means the participants chose “yes” and the speed dates chose “no”.

I also calculated the correlations between theta power and distress experience in four conditions for each group. The results showed a significant negative correlation between theta power and self-reported pleasantness for the Rejection outcome in the placebo group (r = -0.56, p < 0.001; Figure 15), but no such correlation was found in the oxytocin group (r = -0.10, p = 0.31). In order to verify this difference between the placebo and oxytocin groups, I used the cocor r toolkit (Diedenhofen & Musch, 2015) to calculate these correlations. Importantly, the difference in the correlation between the two groups existed (z = -1.97, p = 0.048, two-tailed). No other correlations reached significance (all p values > 0.10).

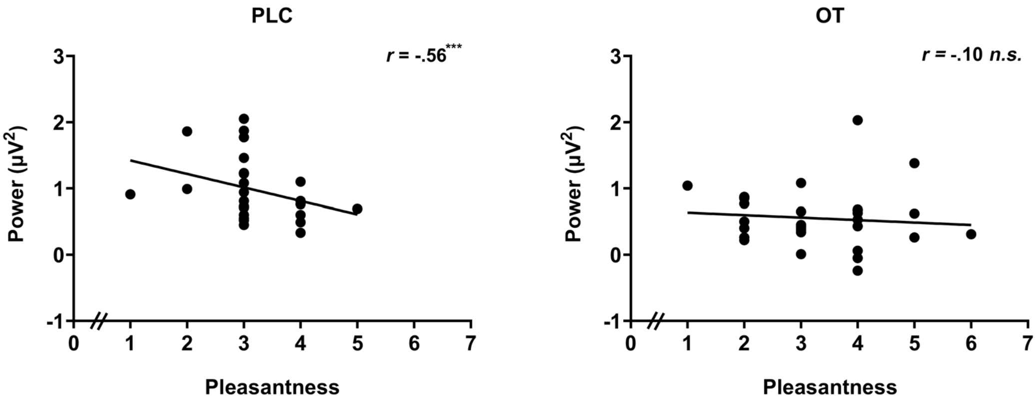

FIGURE 15 The statistical results of correlation analysis for the Pearson correlation between self-reported pleasantness and theta power in the Rejection condition for the placebo (PLC) and oxytocin (OT) groups. *** p < .001. *n.s.* indicates no difference.

TABLE 8 Summary of behavioral results from Study I, II and III

		Effect[a]		*p* value		Main results
Reaction time (RT)	**Study I**	Individual preference	$t(1,24) = 5.43$	< 0.001	Cohen's d = 1.09	RT_Yes > RT_No
	Study II	Individual preference	$t(1,28) = 2.96$	0.006	Cohen's d = 0.55	RT_Yes > RT_No
	Study III	Individual Preference	$F(1,59) = 70.03$	< .001	$\eta_p^2 = 0.54$	RT_Yes > RT_No
The number of the judgments (Yes or No)	**Study I**	Individual Preference	$t(1,24) = 6.22$	< 0.001	Cohen's d = 1.24	Number of Yes < Number of No
	Study II	Individual Preference	$t(1,28) = 3.21$	0.003	Cohen's d = 0.60	Number of Yes < Number of No
	Study III	Individual Preference	$F(1,59) = 75.47$	< 0.001	$\eta_p^2 = 0.56$	Number of Yes < Number of No

a. Only significant or marginally significant effects are reported

Note. Factors used in the experiments: individual preference (like or dislike; participants judge whether they like or dislike other people)

RT_Yes: the reaction time of making the "yes" judgment

RT_No: the reaction time of making the "no" judgment

Number of Yes: the number of the "yes" judgments made by the participants

Number of No: the number of the "no" judgments made by the participants

TABLE 9 Summary of questionnaire results from Study I, II and III

		Effect[a]		p value		Main results
Self-reported pleasantness	Study I	Feedback type	F (1, 24) = 42.69	< 0.001	η_p^2 = 0.64	Acceptance > rejection
		individual preference × feedback type	F(1,24)=33.65	< 0.001	η_p^2 = 0.58	Feedback from liked people: Acceptance > rejection; Feedback from disliked people: no difference between Acceptance and rejection
	Study II	Feedback type	F(1,28) = 37.19	< 0.001	η_p^2 = 0.57	Acceptance > rejection
		Individual preference × feedback type	F(1,28) = 146.03	< 0.001	η_p^2 = 0.84	Feedback from liked people: Acceptance > rejection; Feedback from disliked people: no difference between Acceptance and rejection
		Waiting time ×Feedback type	F(1,28) = 6.31	0.018	η_p^2 = 0.18	In both short and long wait conditions: acceptance > rejection
	Study III	Individual preference	*F* (1, 59) = 6.32	0.015	η_p^2 = 0.10	Liked people > disliked people
		Feedback type	*F* (1, 59) = 66.76	< 0.001	η_p^2 = 0.53	Acceptance > rejection
		Individual preference × feedback type	*F* (1, 59) = 145.20	< 0.001	η_p^2 = 0.71	Feedback from liked people: Acceptance > rejection;

		Effect[a]		***p* value**		Main results
						Feedback from disliked people: no difference between Acceptance and rejection
		Treatment	*F* (1, 59) =14.77	< .001	η_p^2 = 0.20	Oxytocin group > placebo group
		Treatment ×Individual preference ×Feedback type	*F* (1, 59) = 12.43	0.001	η_p^2 = 0.17	Placebo group: Match > Rejection, no difference between Unrequited and Disinterest; Oxytocin group: Match > Rejection, Disinterest > Unrequited
Self-reported motivation	**Study I**	Individual preference	*t* (1, 24) = 5.80	< 0.001	Cohen's *d* = 1.16,	Liked people > disliked poeple
	Study II	Individual preference	t(1,28) = 4.14	< 0.001	Cohen's *d* = 0.77	Liked people > disliked poeple
Self-reported worthiness	**Study II**	Individual preference	*F*(1,28) = 58.68	< .001	η_p^2 = 0.68	Liked people > disliked poeple
		Feedback type	*F*(1,28) = 25.30	< .001	η_p^2 = 0.48	Yes > No
		Individual preference × Waiting time	*F*(1,28) = 17.27	< .001	η_p^2 = 0.38	In both short and long wait condition: liked people > disliked people

Effect[a]		*p* value		Main results
Individual preference × Feedback type	$F(1,28) = 58.13$	< .001	$\eta_p^2 = 0.68$	For the liked people: acceptance > rejection; For the disliked people: no difference
Waiting time ×Feedback type	$F(1,28) = 6.90$	$p = .014$	$\eta_p^2 = 0.20$	For the acceptance feedback: short wait < long wait; For the rejection feedback: short wait > long wait
Individual preference ×Waiting time ×Feedback type	$F(1,28) = 6.63$	$p = .016$	$\eta_p^2 = 0.19$	For the liked peers: the long wait for acceptance > short wait for acceptance; for the disliked peers: the long wait < short wait, regardless of feedback types

a. Only significant or marginally significant effects are reported

Note. Factors used in the experiments: treatment (oxytocin or placebo), individual preference (like or dislike; participants judge whether they like or dislike other people), feedback type (acceptance or rejection), waiting time (short or long).

TABLE 10 Summary of EEG results from Study I, II and III

		Effect[a]		*p* value		Main results
Stimulus preceding negativity (SPN)	**Study I**	individual preference	$t(1,24) = -3.49$	0.002	Cohen's $d = 0.68$	Liked people> Disliked people
Reward positivity (RewP)	**Study I**	Individual preference	$F(1,24) = 13.91$	0.001	$\eta_p^2 = 0.37$	Liked people > Disliked people
		Feedback type	$F(1,24) = 24.13$	< 0.001	$\eta_p^2 = 0.50$	acceptance > rejection
		Individual preference × feedback type	F(1,24) = 4.46	0.045	$\eta_p^2 = 0.16$	Match > Rejection; Match > Unrequited; Match > Disinterest
	Study II	Individual preference	F(1,28) = 6.94	0.014	$\eta_p^2 = 0.20$	Liked people> disliked people
		Individual preference × Waiting time	F(1,28) = 16.40	< 0.001	$\eta_p^2 = 0.37$	For the liked people: long wait > short wait; for the disliked people: long wait < short wait
Theta oscillation	**Study I**	Individual preference	$F(1,24) = 14.02$	0.001	$\eta_p^2 = 0.37$	Liked people > Disliked people
		Feedback type	F(1,24) = 12.08	0.002	$\eta_p^2 = 0.34$	rejction > acceptance
		Individual preference × feedback type	F(1,24) =6.92	0.015	$\eta_p^2 = 0.22$	Rejection > Match; Rejection > Unrequited; Rejection > Disinterest
	Study III	Individual preference	$F(1, 59) = 17.90$	< 0.001	$\eta_p^2 = 0.23$	Liked people > Disliked people
		Feedback type	F(1, 59) = 12.83	0.001	$\eta_p^2 = 0.18$	rejction > acceptance
		Individual preference × feedback type	F(1, 59) = 15.20	<0.001	$\eta_p^2 = 0.21$	Rejection > Match; Rejection > Unrequited; Rejection > Disinterest
		Treatment	F(1, 59) = 5.00	0.029	$\eta_p^2 = 0.08$	Placebo > Oxytocin

	Effect[a]		*p* value		Main results
	Treatment ×Individual preference ×Feedback type	F(1, 59) =6.43	0.014	η_p^2 = 0.10	In rejection condition: Placebo group > oxytocin group

a. Only significant or marginally significant effects are reported

Note. Factors used in the experiments: treatment (oxytocin or placebo), individual preference (like or dislike; participants judge whether they like or dislike other people), feedback type (acceptance or rejection), waiting time (short or long).

Match: both the participants and their speed dates chose "yes"

Rejection: the participants chose "yes" and their speed dates chose "no"

Disinterest: both the participants and their speed dates chose "no"

Unrequited: the participants chose "no" and their speed dates chose "yes"

4 DISCUSSION

This dissertation explored individual behavior patterns in the pursuit of interpersonal relationships, as well as the emotional experience and brain response to the social evaluation from potentially important others and unimportant others, and the alleviation of social pain caused by social rejection. These include decision-making behavior in pursuit of a romantic relationship (Studies I and III) and friendship (Study II), brain activity (that is, stimulus preceding negativity; SPN) and emotional experience (self-reported worthiness and motivation questionnaires) while waiting for feedback from others (Studies I and II), emotional experience (self-reported pleasantness questionnaire) and brain response (that is, reward positivity; RewP and theta oscillation) to social evaluations when participants received social rejection and acceptance from others (Studies I, II, and III), and the pain-reducing effects of oxytocin on powerful romantic rejection-induced social pain (Study III).

Study I provides a solid foundation for follow-up research and offers important insights into the role of SPN, RewP, and theta oscillation in the pursuit of dating relationships. I introduced a novel online speed dating task and pioneering research on the behavioral and EEG responses to the decision-making stage (choosing a potential romantic partner), the anticipatory stage (waiting to receive romance-related feedback), and outcome evaluation stages (processing of romance-related feedback) during the pursuit of a romantic relationship. Our behavioral data showed that participants more often judged their speed dates as a non-potential romantic partner than as a potential romantic partner. At the same time, the participants showed greater emotional responses (self-reported pleasantness ratings) when they received feedback from potential romantic partners than when they received feedback from their non-potential romantic partners. More specifically, participants reported more pleasantness when they received acceptance from their potential romantic partner than when they received rejection from their potential romantic partner. However, there was no significant difference between the rejection and acceptance conditions when the feedback came from their non-potential romantic partner. For the EEG data, participants showed a more negative SPN when waiting for the social feedback from their potential romantic partners than when waiting for the feedback from their non-potential romantic partners. During the outcome evaluation stage (receiving feedback from the speed dates), the Match outcome (both participants and their speed dates chose "yes") was observed with the largest RewP in all four conditions (match, rejection, unrequited, and disinterest conditions). In addition, I observed the greatest theta power in response to the Rejection outcome (participants chose "yes" and their speed dates chose "no"). The further source-localized result showed that the burst of theta power was localized at the anterior cingulate cortex, dlPFC, and supplementary motor cortex, which is related to physical and social pain processing (Cristofori et al., 2013; Eisenberg et al., 2003; Peyron et al., 2000). To our knowledge, Study I is the first to explore patterns of neural activity when "pursuing dating relationships" and offers important insights into the role of SPN, RewP, and theta oscillations in the pursuit of dating relationships.

For Study II, I used the same paradigm as Study I. I focused on the effect of waiting time on social feedback processing. Based on our previous results, I directly focused on the Reward positivity (RewP) component of the ERP during the feedback processing stage. I also investigated the emotional reactions to the different waiting time and social feedback conditions. The self-reported questionnaires revealed differences in motivation, pleasantness, and worthiness rating depending on participants' subjective preference in response to waiting time and different feedback types. For the EEG data, the participants showed a larger RewP amplitude after a long wait than after a short wait when the social evaluation came from peers that the participant liked. Conversely, the participants showed a smaller RewP amplitude after a long wait than after a short wait when the social evaluation came from a peer the participants disliked. This study provides the first electrophysiological evidence of the effect of waiting time during real social interaction context, and reveals distinct psychological activity and neural responses in its sensitivity to waiting time, subjective preference, and feedback valence. Specifically, I have shown that, in a social interaction context, the time effect on reward value related to feedback from peers varies (either decreasing or increasing) depending on individual preferences, such as liking or not liking the people who provide the feedback.

Study III examined the effect of oxytocin on social rejection. The results replicated those reported in Study I and found that romantic rejection evoked intense distress experiences while showing increased frontal midline theta oscillations. Importantly, the burst of theta power found in the placebo group was attenuated in the oxytocin group. In other words, theta power was significantly reduced in the romantic rejection condition when the participants were administered oxytocin treatment rather than placebo treatment. Further, the correlation analysis showed a negative correlation between self-report pleasantness and theta power, but this result was only seen in the placebo group and disappeared in the oxytocin group. To our knowledge, this study is the first to demonstrate a pain-reducing role of oxytocin in social pain and to provide behavioral and neurological evidence that oxytocin modulates social pain during social interaction.

4.1 Behavior patterns of seeking for interpersonal relationships

Satisfaction with work, entertainment, and family life depends largely on the quality of our friendships and the romantic love we have (Jackson-Dwyer, 2013). Friendship is universal across all ages, all classes, cultures, and genders (Lu et al., 2021). In the adult world, friendship includes positive characteristics such as interpersonal trust, commitment, and self-disclosure. The presence of friends is an important reason why we feel meaning, happiness, love, and excitement in our lives. Also, for most people, choosing their romantic partner is one of the most important and far-reaching decisions in life (Joel et., 2019). Unlike other social relationships, romantic relationships offer love, social support, sexuality, and emotional intimacy (Jackson-Dwyer. 2013). Therefore, building friendships as well as romantic relationships is important. In the present study, whether choosing a potential romantic relationship (Studies I and III) or a potential friendship (Study II), participants' behavioral data showed fewer "yes" choices (judging others as potential romantic partners or potential friends) than "no" choices (judging others as non-potential romantic partners or non-potential friends). At the same time, participants spent more time making judgments of the "yes" choices than the "no" choices, which was reflected by the longer response time to choose the "yes" button than the "no" button. From the previous studies, a good friendship and romantic relationship will bring us happiness and joy, but a bad relationship will bring disaster and pain (Lieberman, 2013; Lu et al., 2021; Saeri et al., 2018). Therefore, the behavior data in Study I suggest that people may be more careful about who they choose to enter into a new social relationship with, since friends or romantic partners may have a profound impact on their lives.

Another reason for the difference in RT of the judgments is the conflict between the motivation to approach social relationships and the motivation to avoid social rejection. Previous research has shown that rejection is a threat signal to humans and that rejection is instinctively averse and avoidant, and an important goal of humans is to avoid rejection (Baker & McNulty, 2013; Baumeister & Leary, 1995). In addition, a factor that can influence people's decision to attempt a new relationship is whether they are at risk of experiencing the pain of rejection if their intentions are exposed to others (Joel et al., 2019). In Study I, the longer reaction time to express their interest to their speed dates compared to express disinterest to their speed dates may reflect the conflict in the decision – a desire to pursue a relationship, but also a desire to reduce adverse effects, because when interest to others is shown, the risk of being rejected also arises. Thus, reaction time and the number of trials in Study I provided an implied index of participants' ambivalence and cautious behavior when choosing potential friends and romantic partners.

4.2 Emotional responses to social evaluations

Self-reported pleasantness ratings showed a similar trend across our three studies. After the end of the EEG session, participants were asked to complete a subjective self-pleasantness questionnaire to report their emotional experience under different conditions during the experiment. In all three studies, participants reported pleasantness in receiving social acceptance and unpleasantness in receiving social rejection from their liked person. Indeed, humans have a strong need to belong and a desire to establish and maintain close, lasting relationships with other people (Baumeister & Leary, 1995). From an evolutionary perspective, positive and lasting relationships were key to the survival of early humans, because when confronted with wild animals and hostile environments, social connections meant water, food and protection, increasing the likelihood of survival and reproduction (Agnew & South, 2014; Buss, 2019; Leary, 2006). Therefore, social exclusion is a threat signal and social rejection is "painful" because it can mean low survival and death (Baumeister & Leary, 1995; MacDonald & Leary, 2005). Social acceptance, by contrast, is considered "sweet" and a positively reinforcing state of reward because it implies group support, shared food and protection from danger, and higher survival rates (DeWall & Bushman, 2011).

Interestingly, I did not find the difference in self-reported ratings between rejection and acceptance feedback, when the social feedback came from non-potential romantic partners and from non-potential friends. In other words, when participants were confronted with people they disliked, there was no significant fluctuation in their emotional experience, whether they received positive (social acceptance) or negative (social rejection) feedback. Previous research has shown that losing an emotional connection with an intimate partner makes people feel more threatened than losing an emotional connection with someone they do not care about (Chaiken & Derlega, 1974; Gilbert & Whiteneck, 1976; Leary, 2001). Therefore, not all evaluations are equal; on the contrary, the source of social evaluation will reshape the value of social evaluation to some extent (Hughes et al., 2018). Recent studies have found that people showed more pleasantness and reward-related brain activity in response to social reward (such as cooperation, connection, and conformity) for close others than for distant others (Fareri, Niznikiewicz, Lee, Delgado, 2012; Hughes & Beer, 2012; Hughes, Ambady & Zaki, 2017). Compared to strangers, people are more motivated to receive evaluations from people they like and view those people's evaluations as more valuable (Hughes et al., 2018; van der Veen et al., 2019). Consistent with these studies, the results of the self-reported motivation scale revealed that participants showed a stronger motivation to know the evaluation from liked than disliked ones. Thus, our results suggest that individual preferences in the interpersonal environment influence emotional responses to social evaluation.

4.3 Brain responses to social evaluations

In Study I, our EEG data provided important neural evidence in the pursuit of interpersonal relationships, emphasizing the important roles of stimulus preceding negativity (SPN), reward positivity (RewP), and theta oscillation in the anticipatory (waiting to receive social feedback) and outcome processing stages (processing of social feedback) during social relationships pursuit.

During the anticipatory stage in Study I, participants showed greater SPN when they were waiting for social feedback from potential romantic partners than from non-potential romantic partners. Given the previous studies, SPN is generally considered to be a neuro indicator that individuals use to measure affective or motivational valence before they get the results of their own actions (Böcker et al., 2001; Brunia et al., 2011; Pornpattananangkul & Nusslock, 2015; Van der Molen et al., 2014). The SPN results may reflect the fact that the participants had higher motivation to know their potential romantic partners' feedback than to know their non-potential romantic partners. This result was consistent with the participants' self-reported ratings, suggesting that participants have a strong motivation to know potential romantic partners' social evaluation. Furthermore, the results in Study I may provide evidence that receiving feedback from liked ones is rewarding. In Study I, anticipating social acceptance from a potential romantic partner implies the opportunity to develop social relationships in the future; previous research has shown that forming romantic relationships is an important social reward (Cooper et al., 2013). This assumption may be supported by previous research on money and social rewards. In a study using a slot machine game, the results indicated that if the first two icons were the same, the SPN was higher when people waited for the third icon compared to when the first two icons were different, which reflected that the participants would show a stronger SPN when they had the expectation of getting a reward (Donkers, Nieuwenhuis, & van Boxtel, 2005). Similarly, Pornpattananangkul and Nusslock (2015) found that the reward condition increased the SPN compared to the non-reward condition during the anticipatory stage (waiting for monetary feedback). In addition to monetary reward, another study found that when participants expected others to give them positive social evaluations (that is, social acceptance), compared to when they expected others to give them negative social evaluations (social rejection), they showed a larger SPN before feedback appeared (van der Molen et al., 2014). Therefore, the relatively large SPN in Study I may provide evidence that the social feedback from their potential romantic partner is rewarding. Taken together, our findings suggest that pursuing a romantic partner is a highly motivating behavior, and that enhanced SPN could reflect participants' strong desire to form social relationships with potential romantic partners.

During the outcome evaluation stage in Study I, our original waveform of RewP and PCA results both revealed the largest RewP amplitudes in the Matched condition (both participants and their partner said "yes"), suggesting a larger reward value for social acceptance by potential romantic partners than non-potential romantic partners. Intriguingly, a recent EEG study found that individual preference is an important factor that affects feedback processing (Peterburs et al., 2019). Specifically, the high preference outcomes induce a more positive RewP than medium and low preference outcomes. Although the feedback used in our study was social reward – which differs from Peterburs et al. (2019), who used food as a reward – our results also suggest that individual preferences influence subjective reward value, as reflected in RewP. In addition, our results are consistent with a prior fMRI study that showed increased activation of the reward system (that is, ventral striatum and ventromedial prefrontal cortex) when participants received romantic interest from a potential romantic partner (Cooper et al., 2013). Thus, our study revealed that romantic interest (romantic acceptance) is a social reward signal that can be measured by RewP and reflected in increased RewP during the pursuit of relationships.

In the time-frequency domain in Study I, I observed that theta power was stronger for Rejection outcomes ("no" from potential romantic partner) compared to the Match (both the participants and their speed dates chose "yes"), Disinterest (both the participants and their speed dates chose "yes"), and Unrequited (the participants chose "no" and their speed dates chose "yes") conditions. These results are consistent with the previous EEG studies, in which the researcher regarded the unexpected rejection from others as a threatening signal to induce social pain (Van der Molen et al., 2017, 2018). Eisenberger and Lieberman (2004) proposed that social rejection is a warning signal and that humans try to protect themselves from social disconnection. An intracranial EEG study by Cristofori and colleagues (2013) provided evidence of increased theta power during exclusion (participants are rarely passed the ball) versus inclusion (the others pass the ball to participants) in a cyberball task, and the authors interpreted the theta signal as a neural signature of social pain. In Study I, the participants reported more unpleasantness when they received rejection from their potential romantic partner than when they received acceptance from their potential romantic partner. Thus, the results of theta oscillation confirm the view that midfrontal theta oscillation can be a neural signature of social pain and the results also suggest that being rejected by potential romantic dates may be painful.

The current theta source results revealed that the significant differences of the theta power between rejection conditions and other conditions (match, unrequited, and disinterest) were mainly located in the anterior cingulate cortex (ACC). This observation is consistent with previous intracranial and source localization studies on social rejection (Cristofori et al., 2013; Smith et al., 2015; Van der Molen et al., 2017, 2018). Thus, the currently observed mid-frontal theta oscillatory reactivity during romantic rejection may offer a valuable index for future studies to explore the role of ACC in the romantic rejection.

Notably, a recent EEG study used a speed dating task to focus on feedback processing of a romantic expression, but did not observe a significant difference in the RewP component (van der Veen et al., 2019). Our modified speed dating task differs somewhat from the above studies. First, the romantic expression is more concise in our paradigm, where participants only need to focus on the partner's choice (that is, social feedback). In previous studies, however, participants' choices, a portrait of their speed dates, and their speed date's decisions were simultaneously shown on a screen (Cooper et al., 2013; van der Veen et al., 2019). Our manipulation may avoid the confusion of other mental processes during the feedback processing. At the same time, this manipulation also reduced the horizontal eye movement during the experiment, which is more suitable for EEG research. Second, in our study, participants evaluated their partners directly during the EEG session, rather than passively watching their choices made weeks earlier (Cooper et al., 2013; van der Veen et al., 2019), which may result in 'second thoughts' when participants see their judgments during the EEG session. Finally, in our study, I used the method of free choice rather than forced-choice (forced-choice 50 percent of the speed dates as "dateable"), which greatly increased the ecological validity and task engagement. The degree of involvement in the experiment affects the amplitude of RewP (Bellebaum et al., 2010; Warren & Holroyd, 2012).

In conclusion, Study I highlights the different reward values, motivation, and emotion processing in the pursuit of social relationships. Specifically, our results confirm a neural link between SPN and reward anticipation and extend this idea to the anticipation of rewards arising from potential social relationships. This study also indicates that RewP reflects the neural response of the reward system to romantic expression, and reveals that receiving romantic interest from a liked person can be a strong social reward. Furthermore, our results support the idea that frontal-midline theta oscillation is a neural signal of social pain caused by social rejection in pursuit of social relationships. Additionally, Study I provides a novel paradigm with high ecological validity. Our results highlight the important role of SPN, RewP, and theta oscillation in different stages of social relationship pursuit and provide electrophysiological indicators and theoretical support for Studies II and III.

4.4 Waiting time reshapes the value of social evaluations

Reflecting on the results of Study I, participants reported high motivation when they waited for social evaluation (rejection or acceptance) from their liked person. This kind of waiting is common in life, and we do not always get immediate feedback. For example, we may need to wait for a meal or the result of a job application. Waiting for feedback from others in the pursuit of social relationships is another example. In Study I, I did not manipulate the time interval before the social feedback presented, but in Study II I added short wait (800–1200ms) and long wait (5000–6000ms) conditions before participants received the social feedback from their peers in order to investigate the influence of waiting time on social feedback processing.

Consistent with Study I, the results of Study II indicated that the participants did report higher motivation to know the feedback from their liked peers than from disliked peers. To investigate the effect of the waiting time on social evaluation processing in Study II, I used a self-reported worthiness questionnaire to record the feeling of eight possible outcomes. As I expected, the individual preference modulates the outcome evaluation and the evaluation of waiting. More specifically, when participants finally received peer feedback of "acceptance" (being accepted) from a liked person, they rated a long wait as more worthy than a short wait. However, when the feedback came from a disliked person, the participants rated the wait as unworthy, regardless of whether the final feedback was acceptance or rejection. Time is regarded as a scarce resource and humans are instinctively averse to investing large time costs, as the cost of time is regarded as an investment of effort (Dunn et al., 2019). However, relatively high motivation or rewards can counteract the time/effort cost (Dunn et al., 2019), and people tend to assign a higher value to the rewarded time/effort cost and devalue the unrewarded time/effort cost (Inzlicht, Shenhav, & Olivola, 2018). For example, a person who worked hard to gain entry into a group will like that group more than a person who did not work hard to acquire group membership, even though both people are evaluating the same group (Aronson & Mills, 1959). In addition, waiting increased the customers' feelings of product quality, purchase intention, and product satisfaction (Giebelhausen, Robinson, & Cronin, 2011). Overall, these results highlight the importance of individual preference for participants' subjective evaluation of waiting in a social interaction environment.

I also analyzed the influence of waiting time on feedback processing. The EEG results of Study I provide important evidence that RewP can be used as the neural indicator of socially rewarding feedback during the pursuit of social relationships. Therefore, I directly focused on RewP to investigate how waiting time affects subjective reward value for different types of feedback. I observed a reduced RewP amplitude in the long waiting time condition when receiving feedback from disliked peers; this result is consistent with previous monetary studies (Arbel et al., 2017; Peterburs et al., 2016; Weinberg et al., 2014; Zhang et al., 2018). However, our ERP results also revealed an opposite pattern: the RewP amplitude increased in the long waiting time condition when feedback came from liked peers.

Time/effort cost is intrinsically aversive, meaning that people tend to avoid it (Dunn et al., 2019). According to the self-control hypothesis, the human cognitive system attempts to find a balance between time/effort cost and expected reward (Inzlicht et al., 2014). Moreover, when the time/effort cost passes beyond some expected reward threshold, it becomes aversive and then the cognitive system attempts to disengage from the costly behavior or discount the reward value after time/effort investment (Inzlicht et al., 2014; Inzlicht et al., 2018). Therefore, the reduced RewP may be due to the imbalance between the extra time/effort cost and less meaningful feedback, which devalues the social feedback in long wait conditions.

However, the shift in motivation affects the trade-off between time/effort cost and reward (Inzlicht et al., 2014). For example, although the motivation and performance of the participants would decline after a long time/effort cost, when the motivation to complete the task is increased (for example, increasing the monetary reward or rest time), the behavioral (such as performance accuracy), and psychophysiological (error related negativity P3, pupil diameter) measures return to a high level (Boksem et al., 2006; Hopstaken et al., 2015). Similarly, when the costly behavior in the task is motivated, or the participants enjoy the task itself, then the cost of time/effort is counteracted (Moller et al., 2006; Muraven & Slessareva, 2003). That is, sufficient motivation offsets the aversiveness of time/effort cost. Furthermore, previous studies also have found that rewards with greater time/effort costs are valuable (Alessandri et al., 2008; Clement et al., 2000). For example, when participants worked to obtain the goal, they preferred the one that they had to work harder (such as pressing hard or long wait) to obtain over the one they had to work less hard to obtain (Alessandri et al., 2008; Klein, Bhatt, & Zentall, 2005). An fMRI study has revealed that the activation of reward-related brain areas (subgenual anterior cingulate cortex and nucleus accumbens) was greater after high effort gains than with low- or non-effort gains (Hernandez Lallement et al., 2014). Therefore, the increased RewP amplitude may reflect the added reward value of social evaluations from potential friends. According to the self-reported motivation questionnaire in Study II, the participants were highly motivated to know the social evaluation from liked peers rather than disliked ones. Therefore, our RewP results may suggest that participants have relatively sufficient motivation to wait for a social evaluation from the desired person and value the social evaluation more due to higher time/effort cost.

Overall, our results reflect that the different motivations caused by individual preference discount or increase/add to the social feedback value after a long waiting time, which is reflected in the RewP. The results may provide an explanation for the inconsistency of existing results of the waiting effect on monetary studies. In previous studies, Wang and colleagues (2014) did not find differences for RewP between short and long waiting feedback. Although other studies have shown that RewP decreases with an increase in waiting time, the reduced RewP shows two patterns: one is all-or-nothing (Weinberg et al., 2012; Arbel et al., 2017) and the other is linear decline (Peterburs et al., 2016). These previous studies have used two kinds of feedback types. One feedback type is not utilitarian (for example, a simple gambling task, time estimation task), where the feedback was random and not dependent on a participant's behavior (Wang et al., 2014; Weinberg et al., 2012; Zhang et al., 2018). In this circumstance, when the participant paid extra time and received the same reward as the immediate feedback, the participant discounted the value of the feedback (that is, time/effort discounting). The other type of feedback is utilitarian (for example, a probabilistic learning task). Although feedback provides meaningful information to learn about response-outcome association, the learning phase is usually completed in the early stage of the task (Peterburs et al., 2016). In the rest of the task, the delayed feedback also means an extra time/effort cost to receive a fixed reward, thus the reward value decreases due to extra waiting time. However, regardless of the type of paradigm, the specific reward probability is unclear to the participants. In order to maximize their own interests, the participants need to optimize their choices from feedback. Therefore, another possibility is that participants maintain high motivation throughout the experiment and try to obtain more rewards by learning from feedback, so the extra reward value of feedback enables participants to overcome the time/effort cost and even add value for the reward. Gu et al. (2010) found that even in the former type of paradigm (no specific rules between behavior and feedback), participants still reported that they learned the rules in the task. Therefore, I speculate that, due to different motivational states of the participants in the task, time/effort may decrease or increase the value of feedback, resulting in an inconsistent effect of waiting time on RewP.

Taken together, Study II provides the behavior and neural evidence of the effect of waiting time during real social interaction context and reveals the distinct psychological activity and neural responses in its sensitivity to waiting time, subjective preference, and feedback valence. Specifically, I have shown that, in a social interaction context, the waiting time reshapes the reward value of social feedback, either decreasing or increasing, depending on individual preference, such as important or unimportant others.

4.5 Oxytocin alleviates social pain

In Studies I and II, I found that social evaluations from important others (potential romantic partners and friends) tend to generate stronger emotional responses (self-reported pleasantness ratings) and brain activity (SPN, RewP, and theta oscillation) than from unimportant others. One of the noticeable events in social relationships is social rejection, which is a negative evaluation and a cause of social pain. Therefore, I tried to investigate the role of oxytocin in social relationships to test whether oxytocin alleviates social pain caused by social rejection. I used the same paradigm as Study I, and the results of Study III accurately replicated the results of study I; namely, rejection from an important other was rated as more unpleasant and induced a greater frontal-midline theta power than from unimportant others.

Importantly, a new finding is that a significantly decreased frontal-midline theta power was observed in the Rejection outcome (participants chose ”yes,” their peers chose ”no”) under the oxytocin group, compared with the placebo group. This suggested that oxytocin reduces the neural response to social pain, which is caused by social rejection. In the placebo group, the greater theta power was positively associated with rejection distress (self-reported pleasantness ratings). However, there was no association between theta power and rejection distress in the oxytocin group. The disappearance of the relationship between self-reported pleasantness rating and theta power may reflect oxytocin’s role in reducing negative emotions. Several recent studies support this explanation. More specifically, in studies using the Cyberball paradigm to induce social rejection, participants in the oxytocin group reported lower levels of social discomfort, happier moods, and felt accepted by others more often than those in the placebo group (Henningsson et al., 2021; Pfundmair & Echterhoff, 2021). An EEG study also revealed that oxytocin reduces the link between affective experience and neural activation for social exclusion (Petereit et al., 2019). Further, in romantically related situations, participants in the oxytocin group who experienced both imagined and actual infidelity reported reduced jealousy and emotional arousal compared to those in the placebo group (Zheng et al., 2021). Taken together, our results suggested that oxytocin showed the pain-reducing effect on social pain, which was manifested by the reduction of theta power and severed the link between the neural responses (that is, theta oscillation) and emotional distress (self-reported pleasantness).

The source-localized results indicate that the enhanced theta oscillation was localized to the somatosensory cortex, anterior cingulate cortex (ACC), and frontal pole for the "Rejection" outcome in the PLC group vs. the OT group. These regions are present in some major regions of the physical pain matrix. From previous studies, pain experience can be divided into sensory components and affective components (Eisenberger, 2015b; Peyron et al., 2000). Sensory components encode information related to the location, duration, and intensity of pain, which is processed by the primary and secondary somatosensory cortex (S1, S2), and the posterior insula; in addition, the affective component is responsible for the cognitive characteristics of pain stimulation, mainly processed by the ACC, frontal pole and anterior insula. Thus, our results reveal the possible pain-reducing effect of OT on social pain via the sensory and affective pathways. For this type of acute social pain (such as breakups or the loss of loved ones), our research may provide a possible intervention that uses OT to help overwhelmed people alleviate their negative emotions.

Furthermore, the social salience theory (Shamay-Tsoory et al., 2016) proposed that the effects of oxytocin can be conceptualized as a general increase in the salience of social stimuli in the environment. In this view, oxytocin should increase an individual's attention to the most threatening cue (romantic rejection), meaning a stronger theta power should be observed in the oxytocin group. Contrary to the social salience theory, I observed a decreased theta power in the oxytocin group when the participants received social rejection from their potential romantic partners in the oxytocin group. Alternatively, the affiliative-motivation hypothesis proposes that oxytocin promotes social ties and prosocial behavior (Bartz, 2016; Bartz et al., 2011). Indeed, oxytocin shows a prosocial role in maintaining and promoting romantic love (Algoe et al., 2017; Ditzen et al., 2009), which is consistent with our result whereby OT reduced romantic rejection-induced theta power. Furthermore, the affiliative-motivation hypothesis can also explain the observed opposite pattern of self-reported pleasantness between the oxytocin and the placebo group in Disinterest outcomes (both participants said "no" when they judged whether their speed date was a potential romantic partner). In fact, participants might feel guilt and embarrassment because of the unequal interest (that is, Unrequited outcome, participants said ″no″, the partner said ″yes″; Cooper et al., 2013) in social relationships. Therefore, the Disinterest result in the experiment is what the participants hope to obtain more of when they face the person they dislike. In other words, this result not only avoids embarrassment and guilt for the participants themselves, but also avoids negative emotional experiences for their partner. This expectation can be explained as a prosocial motive. The affiliative-motivation hypothesis emphasizes that oxytocin promotes individual prosocial behavior, which is influenced by their expectation motivation (Bartz, 2016). Oxytocin promotes prosocial behavior when the individual's expectation motivation is consistent with the prosocial motivation promoted by oxytocin. That would explain why the oxytocin group showed higher pleasure scores in the Disinterest outcomes even if it means they received the rejection feedback. Therefore, the affiliative-motivation is more suitable for explaining our results. However, our experiment itself is not designed to test which hypothesis is better, so our conclusions need to be confirmed by future studies to provide more direct evidence.

In conclusion, oxytocin attenuates theta power induced by social rejection and attenuates the association between distress experiences and theta oscillation. Study III confirms the pain-reducing effect of oxytocin on social pain and provides the first pharmacology-electrophysiological evidence.

4.6 General discussion

This dissertation mainly focuses on decision-making behaviors during relationship-seeking and related brain responses to feedback processing associated with potential social relationship outcomes.

The behavioral performance of the participants in the three studies showed consistent results. In the three studies, participants consistently showed fewer "yes" choices (judging others as potential important others) than "no" choices (judging others as non-potential important others). At the same time, participants spent more time making judgments of the "yes" choices than the "no" choices. This behavioral performance demonstrates the participant's careful and cautious behavior pattern in important others and social relationships.

Measures of motivation and emotional experience also showed consistent patterns across the three studies. Unsurprisingly, participants showed different motivational and emotional responses to potentially significant and non-significant others. When others were identified as potentially significant others, participants were more motivated to know whether it was possible to form social connections in the future (that is, more motivated to know the social feedback from others). At the same time, when receiving social feedback from significant others, the participants showed more pleasantness because of the social acceptance of others, whereas the participants showed more unpleasantness because of the social rejection of others. However, when faced with unimportant others, participants did not have stronger motivation to establish social connections, nor did they experience strong emotions, than when they faced important others. The results support the previous research that individual preference and motivation play an important role in social relationships (Leary, 2001; Huge et al., 2018).

In addition to behavioral and self-reported questionnaires, EEG results also provide important neural evidence in the pursuit of social relationships. Consistent with the behavioral results, participants showed stronger stimulus preceding negativity (SPN) when waiting for the social evaluation of significant others compared to non-significant others, which reflected stronger expectations and motivation. I also found that social acceptance from significant others induces stronger reward-related neural signaling (reward positivity; RewP). Furthermore, Study II revealed another important factor that affects the evaluation of social feedback value – waiting time. The participants thought that the social evaluation from significant others was more valuable after a long wait. However, the participants thought waiting was meaningless and reduced the evaluation value from non-significant others. The results also showed that participants showed a larger amplitude of RewP induced by long wait than short wait when the social evaluation came from significant others. However, the opposite result was that when the participants were faced with non-significant others, the long wait reduced the amplitude of RewP compared to the short wait.

Furthermore, the time frequency analysis at the single-trial level found that social rejection from significant others elicited strong social pain signals, manifested by an increased frontal-midline theta power. This result was confirmed by Studies I and III. Because social pain events are often accompanied by psychological and physical negative effects (Riva & Eck, 2016), I tried to explore the pain-reducing effect of oxytocin on social pain and found a decreased theta power when the participants received a social rejection from the significant social others in the oxytocin group. In addition, source localization results in Studies I and II indicated that theta source activity was mainly located at anterior cingulate cortex and frontal pole, which overlapped with the social-physical pain matrix (Cristofori et al., 2013; Eisenberger, 2015a, 2015b; Kross et al., 2011). This suggests that the neural mechanism of social pain and the effect of oxytocin on social pain may be similar to that of physical pain to some extent, but this conclusion needs to be confirmed by more studies in the future.

The problem of replication has received increasing attention in psychology in recent years (Schooler, 2014; Spellman, 2015). In the past decade, the high false positives and the inability to repeat the psychological research have made the field of psychology fall into a replication crisis (Open Science Collaboration, 2015; Simmons, Nelson, & Simonsohn, 2011). My three studies above, whether it is the same experimental paradigm or a variation of the experimental paradigm, showed consistent results in behavioral results (participants showed less often to judge others as potential important others, spend more time judging others as potential important others), self-reported questionnaires (negative emotions when rejected by potential important others, positive emotions when accepted by potential important others, strong motivation to know how their potential important others' evaluation), and the neural responses of social pain (social rejection from potential important others inducing burst of theta oscillations). My research has in part confirmed the relatively consistent behavioral and neural patterns in the pursuit of relationships. I believe that in the future, more transparent data, the use of more scientific statistical methods, stricter review standards and the joint efforts of researcher will better solve the replication crisis in psychology.

In conclusion, Studies I, II, and III expand our understanding of the pursuit of social relationships. The results revealed the different stages of social relationship pursuit (that is, the decision-making stage, the anticipatory stage, and the outcome evaluation stage), the corresponding anticipatory and feedback-related ERP components, and confirmed important neural indicators of social pain. It also highlights the important influence of individual preference and waiting time on social feedback processing. In addition, the pain-reducing effects of oxytocin also provide a new thought for the treatment of psychopathological disorders related to social rejection in the future.

4.7 Limitations

I created a novel online speed dating task. This paradigm simulates real dating scenarios and separates the decision-making stage (choosing important others), the anticipatory stage (waiting to receive others feedback), and the outcome evaluation stage (processing of others feedback) in the pursuit of social relationships. In contrast to previous social feedback anticipation studies, our current paradigm did not examine explicit expectancies from participants about the speed date's feedback. For example, studies that have examined explicit expectancies about social evaluative feedback have found enhanced negativities in the typical RewP time-window (Dekkers et al., 2015; Van der Molen et al., 2014, 2017; 2018), which increased significantly for unexpected social evaluative feedback. These studies used a social judgment paradigm in which participants were asked, "Do you think this person likes you?" Thus, explicit expectancies were measured that resulted in prediction errors (that is, when feedback is not in line with participant's expectancies). Instead, our study focused more on the participants' own subjective preferences by asking, "Do you like this person?" In this manner, I hoped to separate the expectancy factor from the social feedback processing (Somerville et al., 2006). However, the participants still seemed to expect the same feedback from others (Cooper et al., 2014). Therefore, future studies should verify our results by collecting participants' subjective expectations to control for the impact of expectations on social feedback processing in pursuit of social relationships.

In Studies I and III, although our results for source localization are consistent with previous neuroimaging (Fisher et al., 2010; Kross et al., 2011), intracranial (Cristofori et al., 2013), and EEG studies (van der Molen et., 2017, 2018), these results should still be interpreted with caution. Because the inverse problem is still controversial, there is no unique solution to the inverse of an EEG source localization analysis. To solve the problem of a finite number of sensors and an infinite number of possible source locations, additional constraints and theoretical assumptions are made. However, this also leads to the problem of low spatial resolution for source locations (Asadzadeh et al., 2020). Therefore, future studies still need to use high spatial resolution technologies, such as magnetic resonance technology to further verify our current research results.

Although behavioral and brain activation results in the dissertation support the pain-reducing effect of oxytocin on social rejection induced social pain, more research is needed to determine whether intranasal oxytocin can cross the blood-brain barrier and alter central and peripheral oxytocin concentrations. The mechanism of intranasal oxytocin is still unclear. How and when intranasal OT reaches the brain, and how oxytocin affects different brain regions to alter individual behavior and neural activity remains to be explored (Leng & Ludwig, 2016). Therefore, one limitation of Study III is that I did not directly examine the effectiveness of intranasal oxytocin, so future studies could demonstrate the effectiveness of intranasal oxytocin manipulation by measuring changes in blood or saliva levels before and after oxytocin administration.

4.8 Future directions

In Study II, I found the effect of waiting time on social evaluation, and our research found that individual preference led to the change of the individual's subjective valuation of social feedback after a long wait. This result seems to explain the current inconsistent results of the waiting effect on monetary reward processing. However, I did not manipulate monetary rewards in Study II. Future research could test this hypothesis by manipulating the participants' subjective preference for both monetary and social reward simultaneously.

In addition, previous studies have used continuous waiting time manipulation when studying the impact of waiting time on monetary rewards and further proved that the waiting effect varies linearly (Peterburs et al., 2016). In our study, I did not set the condition for multiple wait times. Therefore, future research should further verify whether the effect of waiting time on social feedback is also linear, which will help us to further understand the processing of waiting time effect on social feedback.

Finally, future research should also focus on the role of oxytocin in clinical treatment. Our study provides evidence for the potential effect of oxytocin on social pain relief, but the pain caused by breakups in real life may be more intense feelings. Recovering from a bad breakup or rejection can take time, although most people eventually get over the pain and hurt of rejection. However, there are still some people who can't get out of the shadows very well. Also, when people are chronically ostracized or rejected, the results can be severe.

Depression, substance abuse, and suicide are not uncommon reactions (Riva & Eck, 2016). Additionally, the people who experienced ostracized sometimes can become aggressive and resort to violence. In 2003, Leary and his colleagues (Leary, Kowalski, Smith, & Phillips, 2003) analyzed 15 school shootings and found that all but two suffered from social exclusion. Thus, whether oxytocin can reduce individual's negative emotions and corresponding harmful behaviors (such as suicide or homicide) is worth further investigation in future research.

YHTEENVETO (SUMMARY)

Ihmissuhteiden tavoittelu: Käyttäytymis- ja aivovasteet korreloivat sosiaalisen hyväksynnän ja hylkäämisen välillä

Ihmiset ovat pohjimmiltaan sosiaalisia olentoja, jotka luottavat ihmissuhteiden rakentamiseen ja ylläpitämiseen selviytyäkseen ja ylläpitääkseen mielenterveyttä. Sosiaalisten suhteiden solmiminen auttaa ihmiä täyttämään omat tarpeensa kuuluvuuden tunteesta. Positiivisten ja kestävien sosiaalisten suhteiden solmiminen voi parantaa yksilön hyvinvointia ja tyytyväisyyttä elämään. Siksi useimmat ihmiset tavoittelevat ja luovat tärkeitä sosiaalisia suhteita henkilöihin, joita he pitävät tärkeinä. Erilaisten päätöksentekokäyttäytymisen ja sosiaalisten vuorovaikutusten neurologiset taustat ihmisten välisten suhteiden tavoittelussa ovat kuitenkin epäselviä. Tämä väitöskirja sisältää kolme tutkimusta, joissa EEG-tekniikalla tutkittiin koehenkilöiden käyttäytymistä ja hermovasteita sosiaalisten suhteiden tavoittelussa.

Tutkimuksessa I loimme perustan uudenlaisen online-pikatreffitehtävän kehittämisessä tutkiaksemme käyttäytymistä ja hermotoimintaa päätöksentekovaiheessa, ennakointivaiheessa ja tulosten arviointivaiheessa, jotka liittyvät ihmisten välisen suhteen tavoittelemiseen. Samalla tämä tehtävä pystyy tehokkaasti erottamaan yksilölliset mieltymykset ja tutkimaan niiden vaikutusta sosiaalisten suhteiden etsinnän eri vaiheissa. Pyrittäessä luomaan ihmissuhdetta, sosiaalinen arviointi muiden taholta määrittää potentiaalisten suhteiden muodostumisen. Se on myös edellytys sosiaalisen suhteen alkamiselle. Toisaalta toisten sosiaalinen arviointi ei ole aina välitöntä, joten odottaminen on yleinen tilanne elämässä. Siksi tutkimuksessa II otettiin käyttöön samanlainen paradigma, jossa keskityttiin pääasiassa tulosten arviointivaiheeseen ja tarkasteltiin yksilöllisen mieltymyksen ja odotusajan vaikutuksia sosiaalisten tulosten arvioinnin käsittelyssä. Lisäksi olimme kiinnostuneita sosiaalisten suhteiden sosiaalisten arvioiden lisäksi myös niiden negatiivisista vaikutuksista (esim. sosiaalinen hylkääminen). Oksitosiinin on osoitettu säätelevän sosiaalista käyttäytymistä ja vähentävän negatiivisia tunteita. Tästä huolimatta on edelleen epäselvää voiko se tehokkaasti lievittää sosiaalisen hylkäämisen aiheuttamaa sosiaalista kipua. Joten tutkimuksessa III tutkittiin oksitosiinin vaikutusta sosiaaliseen kipuun.

Käyttäytymistulosten osalta kolmen tutkimusta olivat hyvin yhteneviä. Ne osoittiat, että osallistujat pitivät tovereitaan useammin ei-tärkeinä osapuolina kuin tärkeinä osapuolina (esim. mahdollisina romanttisina kumppaneina tai mahdollisina ystävinä). Koehenkilöt käyttivät enemmän aikaa arvostellakseen tovereitaan tärkeiksi osapuoliksi kuin arvioidakseen heitä ei-tärkeiksi. Lisäksi, kun koehenkilöt saivat palautetta tärkeiltä osapuolilta, heillä oli enemmän tunnereaktioita kuin saadessaan palautetta ei-tärkeiltä.

Tutkimuksen I EEG-tietojen osalta koehenkilöillä oli enemmän negatiivista ”ärsykettä edeltävää negatiivisuutta” (SPN) odottaessaan mahdollisen romanttisen kumppaninsa sosiaalista arviointia kuin ei-potentiaalisia pikatreffejä. Tulosarvioinnin aikana suurin palkitsemispositiivisuus (RewP) havaittiin, kun koehenkilöt saivat sosiaalisen hyväksynnän ihmisiltä, joita he pitivät tärkeinä, verrattuna tilanteeseen, jossa paluate saatiin ei-tärkeältä osapuolelta. Suurin theta-teho esiintyi, kun koehenkilöt saivat sosiaalisen hylkäämisen ihmisiltä, joita he pitivät tärkeinä osapuolina, verrattuna ei-tärkeiden osapuolien sosiaaliseen hylkäämiseen. Lähteen paikallistus osoitti, että theta-tehon purkaus lokalisoitui anterioriseen cingulaattikuoreen, dlPFC:hen, ja täydentävään motoriseen aivokuoreen, mikä liittyy fyysiseen ja sosiaaliseen kivun käsittelyyn. Tutkimuksessa II, kun sosiaalinen arviointi saatiin tärkeiltä osapuolilta, koehenkilöillä oli suurempi RewP-amplitudi pitkän odotuksen jälkeen kuin lyhyen odotuksen jälkeen. Kun sosiaalinen arviointi tuli ei-tärkeiltä osapuolilta, koehenkilöillä oli päinvastoin pienempi RewP-amplitudi pitkän odotuksen jälkeen kuin lyhyen odotuksen jälkeen. Tutkimus III osoitti tutkimuksen I toistetut tulokset, joissa todettiin, että sosiaalinen hylkääminen tärkeiden osapuolten taholta aiheutti voimakkaita ahdistuskokemuksia. Samalla se osoitti lisääntyneitä frontaalisen keskiviivan thetavärähtelyjä. Tärkeä havainto oli, että oksitosiiniryhmä osoitti vähentynyttä theta-tehoa verrattuna verokkiryhmään, kun he saivat sosiaalisen hylkäämisen tärkeiltä osapuolilta. Lisäksi korrelaatioanalyysi osoitti negatiivisen korrelaation itsensä ilmoittaman miellyttävyyden ja theta-voiman välillä, mutta tämä tulos nähtiin vain verokkiryhmässä eikä sitä havaittu oksitosiiniryhmässä.

Tutkimukset I, II ja III laajentavat ymmärrystämme sosiaalisten suhteiden tavoittelusta. Tulokset korostavat yksilöllisten mieltymysten ja odotusajan merkittävää vaikutusta sosiaalisen arvioinnin käsittelyssä. Ne paljastivat myös sosiaalisten suhteiden etsimisen eri vaiheeet, niitä vastaavat ennakoivat ja palautteeseen liittyvät EPR-komponentit ja vahvisti käsitystä tärkeistä sosiaalisen kivun hermoindikaattoreista. Lisäksi oksitosiinin analgeettiset vaikutukset tarjoavat myös uusia ideoita psykopatologisten häiriöiden hoitoon.

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ORIGINAL PAPERS

I

NEURAL CORRELATES OF ACCEPTANCE AND REJECTION IN ONLINE SPEED DATING: AN ELECTROENCEPHALOGRAPHY STUDY

by

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Neural correlates of acceptance and rejection in online speed dating: An electroencephalography Study

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Abstract

Pursuing dating relationships is important for many people's well-being, as it helps them fulfill the need for stable social relationships. However, the neural underpinnings of decision-making processes during the pursuit of dating interactions are unclear. In the present study we used a novel online speed dating paradigm where participants (undergraduate students, *N*=25, aged 18–25, 52 percent female) received direct information about acceptance or rejection of their various speed dates. We recorded EEG measurements during speed dating feedback anticipation and feedback processing stages to examine the stimulus preceding negativity (SPN) and feedback-related brain activity (Reward Positivity, RewP, and theta oscillatory power). The results indicated that the SPN was larger when participants anticipated interest vs. disinterest from their speed dates. A larger RewP was observed when participants received interest from their speed dates. Theta power was increased when participants received rejection from their speed dates. This theta response could be source-localized to brain areas that overlap with the physical pain matrix (anterior cingulate cortex, dorsolateral prefrontal cortex, and the supplementary motor area). This study demonstrates that decision-making processes – as evident in a speed date experiment – are characterized by distinct neurophysiological responses during anticipating a evaluation and processing thereof. Our results corroborate the involvement of the SPN in reward anticipation, RewP in reward processing and mid-frontal theta power in processing of negative social-evaluative feedback. These findings contribute to a better understanding of the neurocognitive mechanisms implicated in decision-making processes when pursuing dating relationships.

Keywords: dating, stimulus preceding negativity, reward positivity, theta oscillation, Source localization

Neural correlates of social acceptance and rejection in online speed dating: An electroencephalography Study

The pursuit of dating relationships reflects a need for social affiliation, serves as a secondary reward that provides subjective pleasure, and fulfills biologically related needs (Ait Oumeziane, Schryer-Praga, & Foti, 2017). Neuroimaging evidence has shown that people in intimate relationships activate the dopamine reward system (that is, the ventral tegmental area and caudate nucleus; Acevedo & Aron, 2014), which is associated with physical health and psychological well-being (Acevedo & Aron, 2014). Other studies have found that the break-up of an intimate relationship can cause social pain, which activates brain areas that overlap with experiencing physical pain (dorsal anterior cingulate cortex; dACC, dorsolateral prefrontal cortex; dLPFC and the anterior insula; AI; Eisenberger, 2015; Seminowicz & Moayedi, 2017). Rejection by a loved one is commonly identified as a negative event that has profound meaning, often accompanied by negative emotions, anxiety, and depression, or even suicide or homicide (Fisher et al. 2010; Joel, et al., 2019; Van der Veen, Burdzina, & Langeslag, 2019).

Although some studies have investigated the neural response to cues that either confirm an intimate relationship (e.g. Acevedo et al., 2012; Aron et al., 2005) or communicate romantic rejection (break-up; e.g. Fisher et al. 2010, Kross et al. 2011), less attention has been directed to the neural correlates of the *pursuit of* dating relationships – thus selecting potential dates and awaiting feedback regarding a match or mismatch. One of the challenges for this type of research is to simulate real-world situations that assess the pursuit of dating relationships in an ecologically valid way in a laboratory setting. Recently, Van der Veen, Burdzina, and Langeslag (2019) developed an online dating task in which participants were presented with profiles of individuals of the other sex. Participants were instructed to decide whether these individuals were desirable or not. In a subsequent EEG session, participants were again shown photos of the same individuals, together with the participants' evaluations of these individuals. The participants then received feedback from the speed date that could result in a match. That study found larger P3 responses when participants received positive vs. negative evaluations from their speed date, which was interpreted to reflect the processing of the rewarding characteristics of romantic interest. Thus, the above-cited study examined the neural correlates of processing feedback from potential dates, but did not examine the neural correlates of participants' motivation regarding their decision-making during speed dating. In the current study, we used a novel speed dating paradigm that allowed us to examine (1) the speed dating decision-making stage, (2) the speed dating feedback anticipation stage, and (3) the speed dating feedback processing stage. Capitalizing on the high temporal precision of the EEG technique, we focused on event-related potentials that characterize anticipatory processes, as well as the processing of rewarding feedback as indexed with Reward Positivity. We also used time-frequency analyses to examine frequency-specific modulations in the EEG during the feedback processing stage.

Previous studies have used the stimulus preceding negativity (SPN) to study anticipatory motivation. The SPN is a slow negative potential that increases gradually before the feedback stimulus (Van der Molen et al., 2014). The SPN was considered to be an indicator of affective or motivational valence before giving action feedback (Pornpattananangkul & Nusslock, 2015; Böcker et al., 2001). A large body of studies revealed larger SPN amplitudes when anticipating reward vs. non-reward (e.g. Donkers, Nieuwenhuis, & van Boxtel, 2005; Foti & Hajcak, 2012; Pornpattananangkul & Nusslock, 2015). Since the SPN reflects the anticipatory motivation before feedback

(Pornpattananangkul & Nusslock, 2015), the SPN would be a feasible indicator to reveal differences in anticipatory motivation between feedback from the various speed dates in our current study.

During feedback processing, the event-related potential displays a prominent deflection in the ERP at around 250–350 ms that is sensitive to the valence of the feedback (such as rewarding feedback). For example, feedback signaling reward is often associated with a positive deflection, which has been termed reward positivity (RewP) (Foti, Weinberg, Dien, & Hajcak, 2011). Previous studies have applied the RewP as a neural indicator for reward processing to monetary and social rewarding feedback (Ethridge et al., 2017). Several studies have also found that feedback signaling prediction errors (such as unexpected negative or positive feedback) result in a negative deflection in the ERP that co-occurs in the RewP time-window. This negative potential has been referred to as feedback-related negativity (FRN). According to reinforcement learning accounts, the FRN reflects the computation of negative reward prediction error (feedback is worse than expected) (Holroyd & Coles, 2002; Nieuwenhuis et al., 2004), whereas other accounts have found that the FRN is sensitive to unsigned prediction errors; that is, the FRN is increased for unexpected feedback regardless of its valence in both time-estimations tasks (Ferdinand et al., 2012), as well as social evaluative feedback processing (van der Molen et al., 2014; 2017; 2018).

There is ongoing debate on whether the feedback-related activity in the 250–350 ms time-window post-feedback reflects a single component (such as RewP or FRN), or whether it could reflect multiple components that are present dependent on the type of feedback presented (for example, reward or prediction errors during conflict monitoring; Holroyd et al., 2008, 2012; Proudfit et al., 2015; Cavanagh et al., 2010; Cohen et al., 2012). Therefore, for simplicity, we refer to this component as the RewP, but acknowledge the possibility that the ERP in this feedback processing time-window (250–350) is characterized by different aspects of processing of the feedback stimulus, and could therefore consist of multiple components.

Related to this issue of ERP component overlap, it has been recommended to examine ERPs in conjunction with time-frequency EEG activity, particularly when different components in the ERP hinder the appropriate quantification of these ERP components (Cohen et al., 2011). Studies using time-frequency decomposition of the EEG signal have revealed valuable information about the neural correlates of feedback processing in both cognitive and affective domains (Cavanagh et al., 2012; Yao et al., 2019). For example, enhanced frontal theta oscillatory activity has been observed when processing feedback that signals conflict, such as reward prediction errors (Janssen et al., 2016) and unexpected social rejection feedback (van der Molen et al., 2017; 2018, van der Veen et al., 2018). Notably, this enhancement in frontal theta power occurs in the same time-window as the RewP, and could therefore provide important and complementary information that will help elucidate the functional significance of feedback-related brain activity (for relevant discussions, see Cohen et al., 2011; Holroyd et al. 2012). Therefore, our study explores how EEG activity in the time domain (ERP) and time-frequency domain (theta power) is modulated by the processing of social feedback in a speed dating experiment.

Taken together, the present study assessed the neurophysiological activity associated with pursuing dating relationships in anticipating and experiencing speed dating feedback. We introduced a novel “online dating” task in which participants saw and chose their liked and disliked speed dates and saw each speed date’s decision. This allowed us to capture brain activity during different stages of the speed dating process. We tested the following hypotheses: (1) The SPN would be larger when awaiting acceptance feedback than rejection feedback due to the high motivation to establish dating relationships (Aron et al., 2005); (2) there would be larger RewP amplitudes for processing match feedback, whereas the RewP would be smaller for rejection feedback; and (3) based on recent findings suggesting enhanced midfrontal theta power for processing unexpected social rejection feedback (Cristofori et al., 2013; van der Molen et al., 2017; Kortink et al., 2014), rejection in our study would result in the largest increase in theta power relative to the other conditions. Exploratively, we performed source analyses to examine the neural underpinnings of the EEG components (SPN, RewP, theta power). Based on an intracranial and a recent EEG source-localization study of social exclusion (Cristofori et al., 2013) and unexpected rejection (Van der Molen et al., 2017), we expected that the rejection-induced theta power would be mainly associated with enhanced activity in neural regions associated with saliency detection with the ACC acting as a key neural source.

Method

Participants

Participants were recruited to participate in the experiment through posters, online ads, and school media. Twenty-six healthy participants aged 18–25 years were recruited from Shenzhen University in China. All of the participants reported being single and heterosexual. No participants had any current or past mental or psychiatric history. All participants were right-handed and had normal or corrected-to-normal vision. Data were excluded from one participant due to noisy EEG. Finally, data from 25 participants (mean age = 20.07, SD = 1.96, 13 women) were analyzed. Regarding the break-up status of the participants, 11 had never been in a romantic relationship and 14 had experienced a break-up within the previous few months (mean = 27.07 months; SD =

28.34 months; minimum = 6 months; maximum = 60 months).[1] The study protocol was approved by the ethics committee of the Faculty of Medicine at Shenzhen University and all participants signed informed consent before inclusion. All participants received a reward of 80 Yuan after the experiment.

Stimuli and experimental procedure

We introduced a novel online speed dating task that combined the social-judgment paradigm (Somerville et al., 2006) and the speed dating paradigm (Cooper et al., 2013). Participants were informed that they were taking part in a multi-university speed dating study and were required to submit a digital photo of themselves with a neutral expression. Furthermore, on the day of the photo submission, a standardized photo of the participant (processed to the same size and background as the experimental material) was sent to the participant to ensure that he or she was satisfied with the final photo presented to their speed dates. Participants were allowed to replace the photos within a week of the first experiment if they were not satisfied with the current version. According to an earlier study (Gunther Moor et al., 2010), fictional participants from other universities were photographed with neutral faces. These fictional participants acted as speed dates in our experiment. The Self-Assessment Manikin (SAM; Bradley and Lang, 1994) was used to ensure that the photos used in the experiment had neutral expressions. Finally, we selected a total of 340 photos (170 males and 170 females) of potential speed dates. These photos were taken from different universities. All photos

[1] Participants were divided into two groups according to whether they had been in a romantic relationship or not, which was used as a between-subject variable for subsequent analysis (behavioral data analysis and EEG data analysis). The main effects of the group were not significant (all *p*s > .151), and the interactions of any factor with the group were not significant (all *p*s > .086).

were cropped to a standard size (185 × 240 pixels) and replaced with a standard background color (R: 44, G: 44, B: 44).

Participants took part in three sessions: (1) a pre-task rating session, (2) the online speed dating session, and (3) the post-task rating session. During the pre-task rating session, participants were invited to the lab to provide their likeability rating of the speed dates. First, the participants provided their personal information, including name, gender, date of birth, height, weight, educational major and grade, phone number, and email address. The personal data were collected to increase the validity of involvement and were kept secure, with only research personnel having access to them. Identifiable personal information was not used in the analysis and was destroyed after experiment. Next, participants were shown photos of their speed dates (that is, individuals of the opposite sex). For each photograph, participants were instructed to rate how much they liked the speed date based on their first impression using a seven-point scale, ranging from “1, not at all”, to “7, very much” (Fig. 1A). After completing the pre-task rating session, participants were told that what they had just seen were the speed dates from other universities participating in this project. These speed dates would also complete ratings based on the first impressions of photos of the participant. In fact, the rating on the participants’ photos was not made by real speed dates, but manipulated by the experimenter.

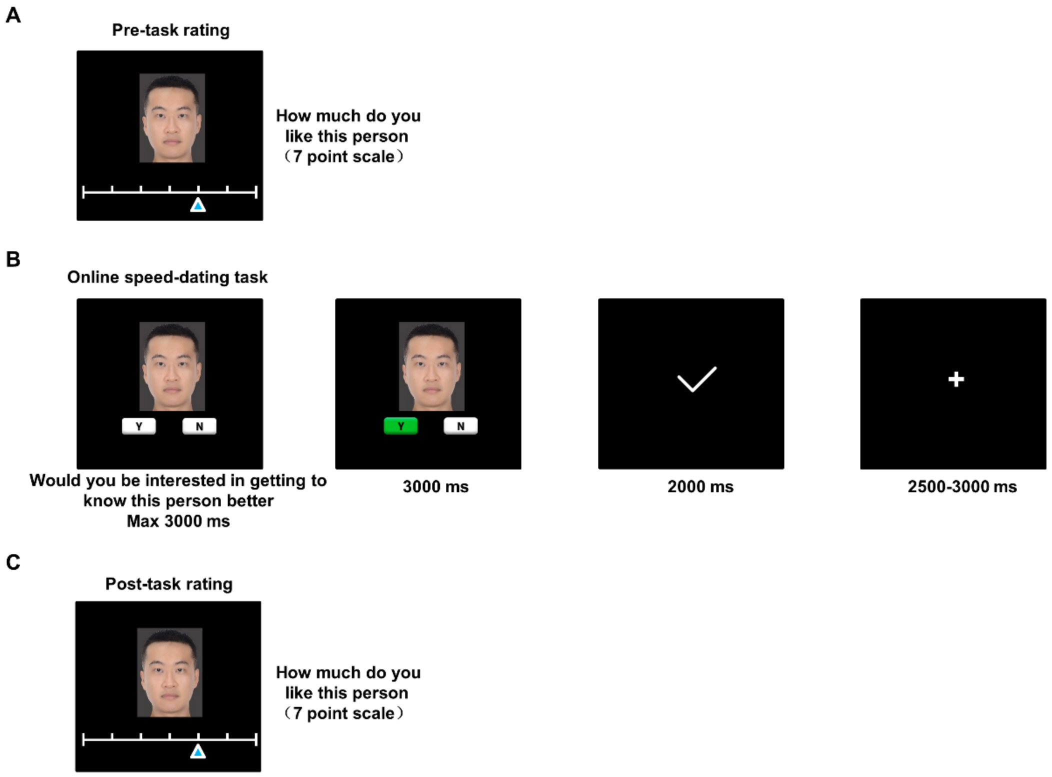

Figure 1. A schematic representation of the experimental task. (A) Participants rated the likability of the speed dates before the task. (B) During the EEG experiment, participants were first required to judge whether they were interested in getting to know the speed date better, with a response window of 3000 ms. Their choices were then highlighted and remained on the screen for 3000 ms. Finally, the feedback from their speed date was presented for 2000 ms, indicating whether they had been accepted or rejected by their speed date. (C) Participants rerated the likability of each speed date.

Approximately one or two weeks after the first session, participants came back to the laboratory to complete the EEG task during the online speed dating session. Participants were shown photos of the speed dates and were instructed to make a judgment regarding the question, “Would you be interested in getting to know this person better?” Thereafter, the participants were shown feedback from their speed dates. This resulted in four different conditions: a *Match* condition (both the participant and the speed date answered “yes” to the question), a *Rejection* condition (the participant said “yes”, but the speed date said “no”), a *Disinterest* condition (both the participant and the speed date answered “no”), and an *Unrequited* condition (the participant said “no” and the speed date said “yes”). In addition, participants were told that only in case of a *Match* would they receive contact information of the speed dates.

Notably, during the EEG task, participants were free to choose who they wanted as a potential date and who they did not want. This is an important difference from previous studies (Cooper et al., 2013; van der Veen et al., 2019), in which participants were forced to choose at least 50 percent of the “yes” choices. We believe this manipulation would enhance the trustworthiness of experimental manipulations, and thus contribute to the ecological validity of the experiment.

A schematic of the EEG session is presented in Fig. 1B. Participants were shown photographs of the speed dates and asked to judge whether they were interested in getting to know that person better. Judgments were made by pressing one of two buttons (“F” and “J”), which corresponded with the “Y” (yes) and “N” (no) buttons on the computer screen. The positions of the “Y” and “N” buttons on the screen were counterbalanced between the participants. Participants were required to make a judgment within a 3000 ms time window after the photo of the speed date appeared. If they did not respond within this time window, the trial ended and feedback from the speed date on that trial was not shown. Upon a button press, the button turned green for 3000 ms to indicate the participants’ choice. Finally, feedback of the speed date was presented for 2000 ms, with a “√” to indicate interest and “X” to indicate disinterest (210 × 210 pixels). In fact, the speed date’s feedback was randomly generated, so there was a 50 percent probability that the participant would receive feedback indicating interest from the speed date. Participants were only shown photos of speed dates of the opposite gender. For each participant, there were 10 practice trials (the same photos were used as practice trials for each gender) and 160 experimental trials.

Following the EEG session, participants completed a post-task likability rating in which they were again instructed to rate how much they liked each speed date (Fig. 1C). This allowed us to test whether participants' pre-task rating was influenced by the experimental manipulation. Participants also indicated, on a seven-point Likert scale, how motivated they were to know about what their speed date thought of them (ranging from 1 "not at all" to 7 "very much"), and how pleasant they felt about the evaluation from the speed date (ranging from 1 "very unhappy" to 7 "very happy"). In addition, we administered the Rejection Sensitivity Questionnaire, Rosenberg Self-Esteem Scale and BDI-II Depression scale before the EEG task. Further, the State-Trait Anxiety Inventory (STAI; Spielberger, 1983) and Positive and Negative Affect Schedule (PANAS; Watson et al. 1988) were used before and after the EEG session to measure state anxiety and mood changes, respectively. Moreover, participants were debriefed about the experiment after the last participant had finished the experiment and none of the participants reported suspicion about the experimental manipulation.

EEG recordings and processing

EEG data were recorded with 64 Ag/AgCl electrodes according to the 10–20 system (actiCAP, Brain Products, Germany; sampled at 1000 Hz). Electro-oculographic (EOG) signals were used to record ocular movements and eye blinks by using a surface electrode placed below the right eye. All impedances were kept below 10kΩ. EEG data were analyzed with BrainVision Analyzer 2.1 (Brain Products, Germany) and MATLAB (The MathWorks, Inc., Natick, Massachusetts, United States).

EEG data were re-referenced offline to the bilateral mastoid electrodes and band-pass filtered between 0.1–30 Hz (48 db/oct) with a 50 Hz notch filter. We created

6500 ms epochs that comprised 3500 ms before speed date feedback onset and 3000 ms after speed date feedback. Subsequently, independent component analysis (Lee, Girolami, & Sejnowski, 1999) was used to remove ocular artifacts. After additional baseline correction (see below for details on SPN and RewP), trials with voltage > ±80 μV were discarded. The number of artifact-free EEG epochs for further analyses is presented in Table 1. Although the number of trials differs between conditions (for example, match vs. rejection feedback) – which is inherent to this social-decision making process – internal consistencies (as an index of reliability) of the ERPs per condition were excellent.[2]

[2] The split-half reliability was used to measure the internal consistency of the SPN and RewP at pooled electrodes (Fz, FCz, Fz). The odd and even trials are averaged and the correlation between the two is calculated (Threadgill, Ryan, Jordan, & Hajcak, 2020), corrected using the Spearman-Brown prophecy formula (Nunnally, Bernstein, & Berge, 1967). Spearman-Brown corrected split-half *r* of RewP for Match = .96, Rejection = .92, Unrequited = .89 and Disinterest = .92, and SPN for Yes judgment = .83 and No judgment = .84.

Table 1 Means, standard deviations (SD), and range (minimum-maximum) of the number of trials that were used to calculate the SPN and the feedback-related brain potentials.

Component (condition)	Mean (SD)	Range (min.-max.)
SPN (interested in speed-date)	59.20 (16.48)	30-91
SPN (not interested in speed-date)	100.00 (16.37)	69-130
Feedback (Match)	28.80 (10.11)	12-47
Feedback (Rejection)	29.92 (8.18)	17-48
Feedback (Unrequited)	50.16 (10.01)	33-68
Feedback (Disinterest)	48.96 (7.69)	32-62

Note: Match = participant and speed-date said “yes”; Rejection = participant said “yes”, speed-date said “no”; Unrequited = participant said “no”, speed-date said “yes”; Disinterest = participant and speed-date said “no”.

Event-related brain potential analyses

For SPN analyses, 3500 ms artifact-free epochs were created comprising 3300 ms pre-feedback and 200 ms post-feedback. In accordance with Van der Molen et al. (2014), we used the -2400 to -2000 ms pre-feedback interval for baseline correction. This interval ensured that no residual motor activity or decision-making processes were evident in the baseline correction period. By collapsing over the two conditions (that is, interested and not interested in the speed date), we found a gradually increased SPN before the feedback onset. Thus, we calculated the mean amplitude of the 200 ms before the feedback onset at pooled frontocentral midline electrodes (Fz, FCz, Cz).[3]

For RewP analysis, 1000 ms artifact-free epochs were created, including 200 ms before feedback onset and 800 ms post-feedback. The 200 ms pre-feedback time window was used for baseline correction. By collapsing over the four conditions, we found a pronounced RewP after the feedback during 255–355 ms. Thus, this time-window and pooled frontocentral midline electrodes (Fz, FCz, Cz) were used for assessment of the RewP.[4]

Time-frequency power analyses

For each different type of feedback, artifact-free segments (-2000 before and 2000 ms after feedback onset) were transformed into the time-frequency domain using complex Morlet wavelets. For each segment, we obtained a complex time-frequency estimation with 30 logarithmically spaced steps, ranging from 1 to 30 Hz in the frequency domain. The Morlet parameter of the central frequency was set at 1 Hz and time resolution (in units of Full Width Half Maximum) was set to 5 s. The spectrogram was baseline-corrected using the subtraction approach at each frequency (Hu et al., 2014), in which -500 to -200 ms interval before the feedback onset was used as the baseline. By collapsing over the four conditions, we found a pronounced theta burst occurring 200–400 ms after the feedback at Fz, corresponding with findings from Van

[3] This grand-grand average method of determining the electrode of interest is in line with prior studies on the SPN (van der Molen et al., 2014), as well as with recommended methodology for determining electrodes for analyzing ERP peak amplitudes (Kappenman & Luck, 2015).

[4] This positivity in the feedback-related ERP was already evident around the P2 component, so our RewP measure might have been subject to component overlap. However, PCA analysis revealed a distinct positive component with central dominance that yielded similar results as described for the RewP in this study (see supplementary material for details).

der Molen et al. (2017, 2018). Thus, we calculated the averaged theta power (4–8 Hz) in the 200–400 ms time-window following the feedback onset at Fz.

Source-localization analyses

Source-localization of theta power was performed on the single-trial level for each feedback condition using Brainstorm (Tadel et al., 2011), which is a free and documented software package available in Matlab (http://neuroimage.usc.edu/brainstorm). The default ICBM152 anatomy, distributed by the Montreal Neurological Institute (MNI), was used as a tessellated cortical mesh template surface due to the lack of individual MRI templates. The BrainProducts Easycap 64 channel layout was co-registered with the ICBM152 anatomy. The EEG forward model of volume currents was calculated by a symmetric boundary element model with OpenMEEG (Gramfort et al., 2010), with which the default layers and conductivities parameters and the adaptive integration method were applied. This forward model uses three realistic layers corresponding to the scalp (1922 vertices, relative scalp conductivity = 1), the skull (1922 vertices, relative skull conductivity = .0125), and the brain (1922 vertices, relative brain conductivity = 1) (Ambrosini and Vallesi, 2016). The noise covariance matrix was based on the -500 to -200 ms baseline period before the feedback onset. Next, unconstrained cortical sources were calculated at the single trial level by using the depth-weighted minimum norm estimation (wMNE) approach (Baillet et al., 2001). This technique is robust to noisy EEG data and shows fair spatial resolution; it also provides reliable results for source-localization analysis of EEG data in the absence of individual MRI anatomies (Baillet et al., 2001). Finally, the source current strength (3 x 5005 vertices of the cortex surface) is obtained by multiplying the recorded EEG signal at each electrode on the time series by the wMNE inverse operator. Importantly, this linear transformation allows the time-frequency analysis to be calculated directly on the source space without changing the spectral characteristics of the underlying source (Ambrosini & Vallesi, 2016; Billeke et al., 2013). Z-score transformations were conducted to normalize the theta source results after averaging all the trials for each condition, using the 500 to -200 ms pre-feedback baseline as the reference interval. The Z-scores for source results were rectified in theta band (4–8 Hz) and averaged within the 200–400 ms post-feedback time windows for statistical analysis.

Statistical analysis

Statistical analyses were performed with IBM SPSS Statistics 21.0 (IBM, Armonk, NY). For behavioral data, we used *t*-tests to compare the reaction times (RTs) of two different choices (Participant Judgment: Yes or No), and the STAI and PANAS scores before and after the experiment (phase: pre and post). To investigate the change of likability ratings, we created the difference between post-task minus pre-task for the four feedback conditions (Match, Rejection, Unrequited, Disinterested). The difference scores as dependent variables were submitted to a 2 (Participant Judgment: Yes or No) × 2 (Speed date Feedback: Yes or No) ANOVA. The self-reported motivation ratings in two conditions (Participant Judgment: Yes or No) were compared by using paired *t*-test. Self-reported pleasantness ratings were submitted through a two-way ANOVA with Participant Judgment (Yes or No) by Speed date Feedback (Yes or No).

For EEG data, a paired t-test was used to compare the SPN of two judgments (Yes or No). Furthermore, RewP and Theta values were submitted separately into a 2 (Feedback Congruence: Congruent, Incongruent) by 2 (Feedback Valence:

Positive/Negative) repeated measures ANOVA. Greenhouse-Geisser correction was used when sphericity was violated.

For theta source localization data, nonparametric cluster-based permutation testing was used to test for significant difference in source activity between each condition in the source space (Maris & Oostenveld, 2007) using Fieldtrip's ft_sourcestatistics method (Oostenveld, Fries, Maris, & Schoffelen, 2011) as implemented in Brainstorm. The theta source data were averaged over frequency band (4–8 Hz) and time (200–400 ms), meaning that this test statistic only considered the spatial dimension. First, for every sample, a comparison of the two conditions was calculated based on the alpha level of 0.05 threshold. Samples that exceeded the critical *t*-values were then clustered and summed over *t*-values, which were based on spatial adjacency. Next, the cluster-level statistics were calculated. The Monte Carlo method was used for significance statistical testing with paired *t*-tests. The nonparametric cluster-level statistics was performed by calculating a *p*-value under 1000 random permutation distribution of the source data. The cluster-corrected alpha level of 0.05 was set for multiple comparisons.

Lastly, Pearson correlation analyses were performed to assess the association between self-reported pleasantness ratings and the condition-specific RewP and theta power, as well as the association between self-reported motivation and condition-specific SPN. No significant associations were found (all ps $> .23$).

Results

Behavioral data

A paired *t*-test indicated that the RTs for 'Yes' Judgments were significantly longer than 'No' Judgments, $t(1,24) = 5.425$, $p < .001$, Cohen's $d = 1.09$, indicating that it took longer for participants to show interest in their speed date (1380.87 ± 65.34 ms) than to show disinterest (1182.79 ± 50.51 ms; Fig. 2A). Furthermore, there was a significant main effect of Participant Judgment ($F(1, 24) = 11.21$; $p = .003$; $\eta_p^2 = .32$), suggesting that the participants significantly increased the likeability for their speed dates if they deemed them as potential dates vs. non-potential dates.[5] In addition, participants reported a stronger motivation to meet their potential dates (5.32 ± .15) than non-potential dates did (4.12 ± .15; t (1, 24) = 5.77, $p < .001$, Cohen's $d = 1.15$; Fig. 2B).

As depicted in Fig. 2C, we found a significant main effect of speed date feedback in self-reported pleasantness ratings: F (1, 24) = 42.69; $p <.001$; $\eta_p^2 =.64$. In addition, the interaction between judgment and speed date feedback was significant ($F(1,24)=33.65$, $p <.001$, $\eta_p^2 =.58$)), indicating that participants reported more pleasantness after Match outcomes (5.72 ± .19) than Rejection outcomes (3.08 ± .16; $p < 0.001$). However, there was no significant difference between Unrequited outcomes (4.20 ± .20) and Disinterest outcomes (4.00 ± .21; $p = .519$). We also decomposed the interaction for Judgment. Results indicated that participants reported more pleasantness after Match outcomes (5.72 ± .19) than Unrequited outcomes (4.20 ± .20; $p < .001$). In addition, participants reported less pleasantness after Rejection outcomes (3.08 ± .16) than Disinterest outcomes (4.00 ± .21; $p = .001$). The scores on the STAI-S and PANAS scales did not differ between administration moments (that is, before and after the speed dating task; all p values > .16).

[5] From here on we use the term *potential dates* to refer to speed dates that participants were romantically interested in, and *non-potential dates* to refer to speed dates that participants were not romantically interested in.

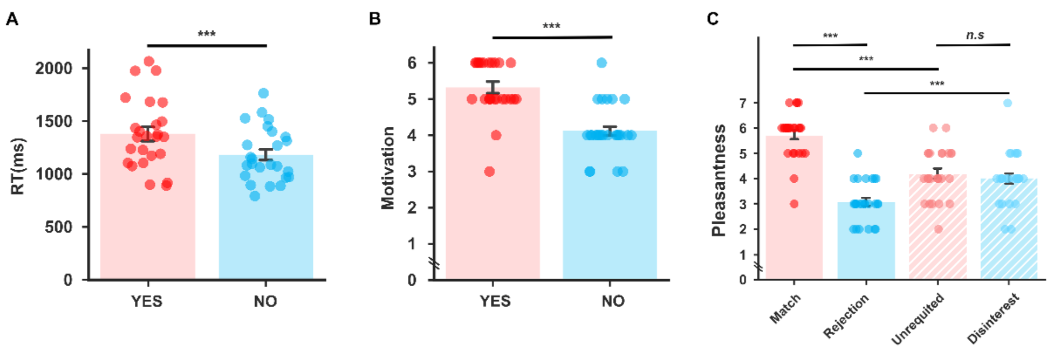

Figure 2. (A) The RTs the participants' judgment. (B) The self-reported motivation ratings. (C) The self-reported pleasantness ratings. Error bars represent standard errors. *** $p < .001$.

We also measured levels of Rosenberg Self-Esteem, BDI-II Depression, and Rejection Sensitivity. Mean scores on the self-report measures are presented in Table 2. The personality trait scores were used as covariates in the behavioral analysis and EEG data; we did not find these personality trait scores to be related to participants' behavioral responses (all *ps* > .075.) and EEG results (all *ps* > .11). Therefore, these personality trait scores were not used for further analysis.

Table 2 Means, standard deviations (SD), and range (minimum-maximum) of the scores on the self-reported questionnaires.

Questionnaire	Mean (SD)	Range (min.-max.)
Rosenberg Self-Esteem	31.40 (5.17)	22-40
BDI-II Depression	6.44 (5.45)	0-21
Rejection Sensitivity	10.22 (2.65)	5.89-14.72

Stimulus preceding negativity (SPN)

As depicted in Fig. 3, paired samples *t*-test indicated that the SPN was more negative when participants showed romantic interest (-3.98 ± .70µV) relative to disinterest (-2.39 ± .56µV) in their speed date; $t(1,24) = -3.31$, $p = .003$, Cohen's d = -0.66).

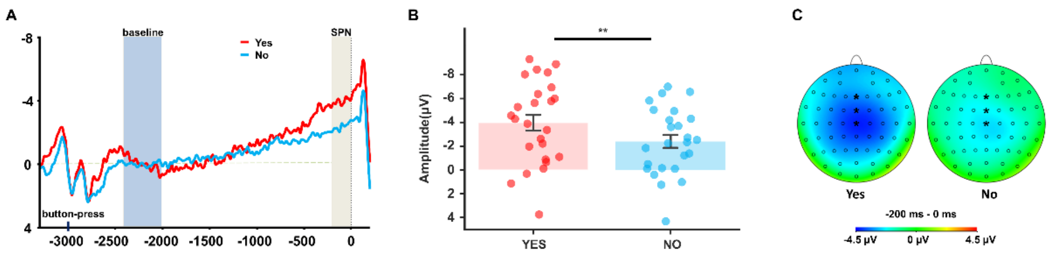

Figure 3. (A) Feedback-locked grand-averaged ERP waveforms at pooled electrodes (Fz, FCz, Cz) for two participants' judgments. (B) Average SPN amplitude for two participant's judgments. (C) Scalp distribution represented by the average amplitude in a -200 to 0 ms time window. The blue shaded area indicates the baseline time window (-2400 to 2000 ms) and the gray shaded area indicates the quantified time window (-200 to 0 ms). In the EEG topographic map, * represents the electrodes used for calculation (from top to bottom, Fz, FCz and Cz). Error bars represent standard errors. ** $p < .01$.

Reward positivity (RewP)

Grand-averaged ERPs at pooled electrodes (Fz, FCz, Cz) are depicted in Figure 4A. We found a significant main effect of Feedback Valence ($F(1,24) = 6.25$, $p = .020$, η_p^2 =.21) and a significant main effect of Feedback Congruency ($F(1,24) = 28.29$, $p <$ .001, η_p^2 =.54), which were included in a significant interaction between Feedback Valence x Feedback Congruency ($F(1,24)$ =14.32, p = .001, η_p^2 =.37)). Follow-up paired samples *t*-test revealed that the RewP to the speed date's feedback (7.54 ± 1.44µV) was significantly larger for Match outcomes relative to all other conditions (all *p*s < .001). The RewP was significantly larger for the Rejection condition (4.70 ± 1.25µV) than the Disinterest condition (2.73 ± .91µV; $t(1,24) = 3.08$, $p = .005$, Cohen's *d* = 0.62), while the RewP between the Rejection (4.70 ± 1.25μV) and Unrequited (4.04 ± .80μV) conditions was not significant ($t(1,24) = .96$, $p = .345$, Cohen's $d = 0.19$). In addition, the RewP was significantly larger for the Unrequited condition (4.04 ± .80μV) than for the Disinterest condition (2.73 ± .91μV; $t(1,24) = 2.78$, $p = .010$, Cohen's $d = 0.56$).

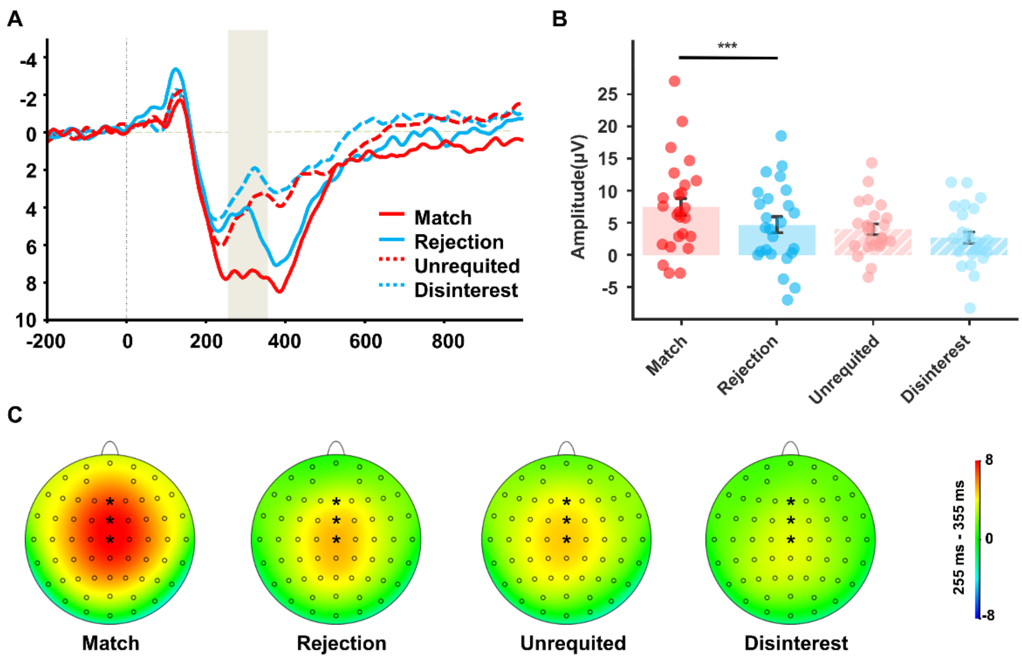

Figure 4. (A) Feedback-locked grand-averaged ERP waveforms at pooled electrodes (Fz, FCz and Cz) in four conditions. (B) Average RewP amplitude per outcomes (C) Scalp distribution in four conditions for the average amplitude in a 255–355 ms time window indicated in A by the grey shaded area. Error bars represent standard errors. In the EEG topographic map, * represents the electrodes used for calculation (from top to bottom, Fz, FCz and Cz). *** $p < .001$, ** $p < .01$, * $p < .05$.

Theta power

As depicted in Figure 5, we calculated the averaged theta power (4–8 Hz) in the 200–400 ms time-window following the feedback onset at Fz. The theta power yielded a significant main effect of Feedback Congruency ($F(1,24) = 6.92$, $p = .015$, $\eta_p^2 = .22$) and a main effect of Feedback Valence ($F(1,24) = 12.08$, $p = .002$, $\eta_p^2 = .34$), which were included in a significant interaction between Participant Judgment and Speed date Feedback ($F(1,24) = 14.02$, $p = .001$, $\eta_p^2 = .37$). Follow-up paired samples *t*-test indicated that theta power was significantly higher in the Rejection condition than in all other conditions (all *p*s < .001). All other contrasts were not significant (all *p*s > .54). Exploratively, we examined feedback-related delta power (see supplemental material S2 for details) and observed a significant enhancement in delta power in both the Match (*p*s < .036) and Rejection (*p*s < 0.001) conditions relative to the Unrequited and Disinterest conditions.

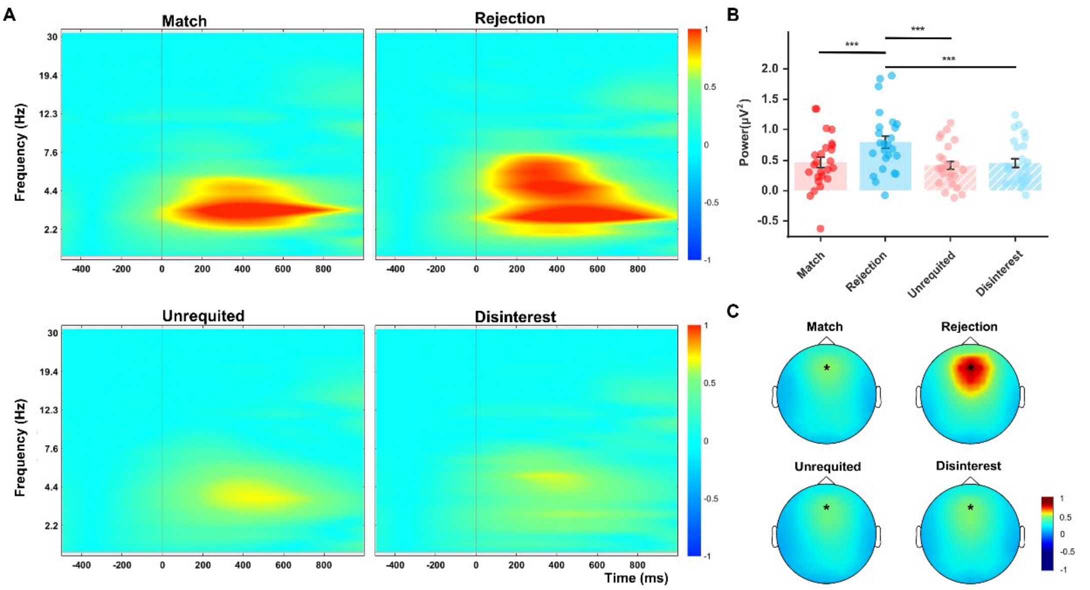

Figure 5. Time-frequency power at Fz during the 200–400 ms post-feedback interval. (A) Time-frequency plots for the four conditions. (B) Average theta power per outcomes (C) Scalp distribution of theta power. Error bars represent standard errors. In the EEG topographic map, * represents the Fz electrode site. *** $p < .001$.

Source localization for theta power

The neural sources underlying feedback-related theta activations are displayed in Figure 6. For the rejection condition, the source maps reveal a distinct increase in theta power in comparison to the other feedback conditions. Non-parametric permutation testing was performed to test for significant condition differences in the theta activation patterns. These results are presented in Figure 7. The contrasts between Rejection and the other conditions all revealed significant clusters, which suggests increased theta activation in the Rejection condition relative to the Match condition (cluster 1: size = 214, p =.024; cluster 2: size = 155, p =.045), the Disinterest condition (cluster 1: size = 181, p =.042; cluster 2: size = 175, p = .045), and the Unrequited condition (cluster: size = 174, p = 0.04). Although spatial precision of these condition differences cannot be inferred from these nonparametric permutation tests (Maris & Oostenveld, 2007; Sassenhagen & Draschkow, 2019), the source activity differences were observed within the 200–400 ms post-feedback interval over the prefrontal and cingulate cortices.

We also performed source analysis on SPN and RewP, but no significant differences were found in source clusters between conditions (see supplementary material for details).

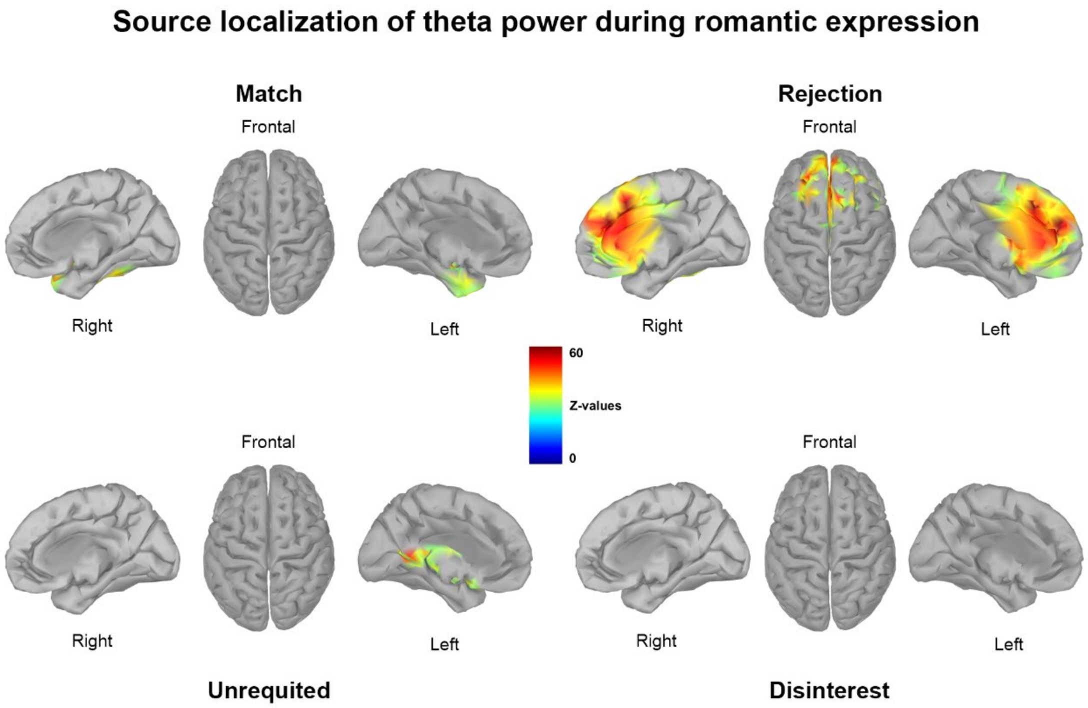

Figure 6. Theta oscillatory power source-localization maps during the 200–400 ms post-feedback window. Depicted are mid-sagittal slices (left and right) of theta power activation associated with the processing of romantic expression. The source activation maps are based on activation of at least 40 vertices (amplitude threshold of 50 percent).

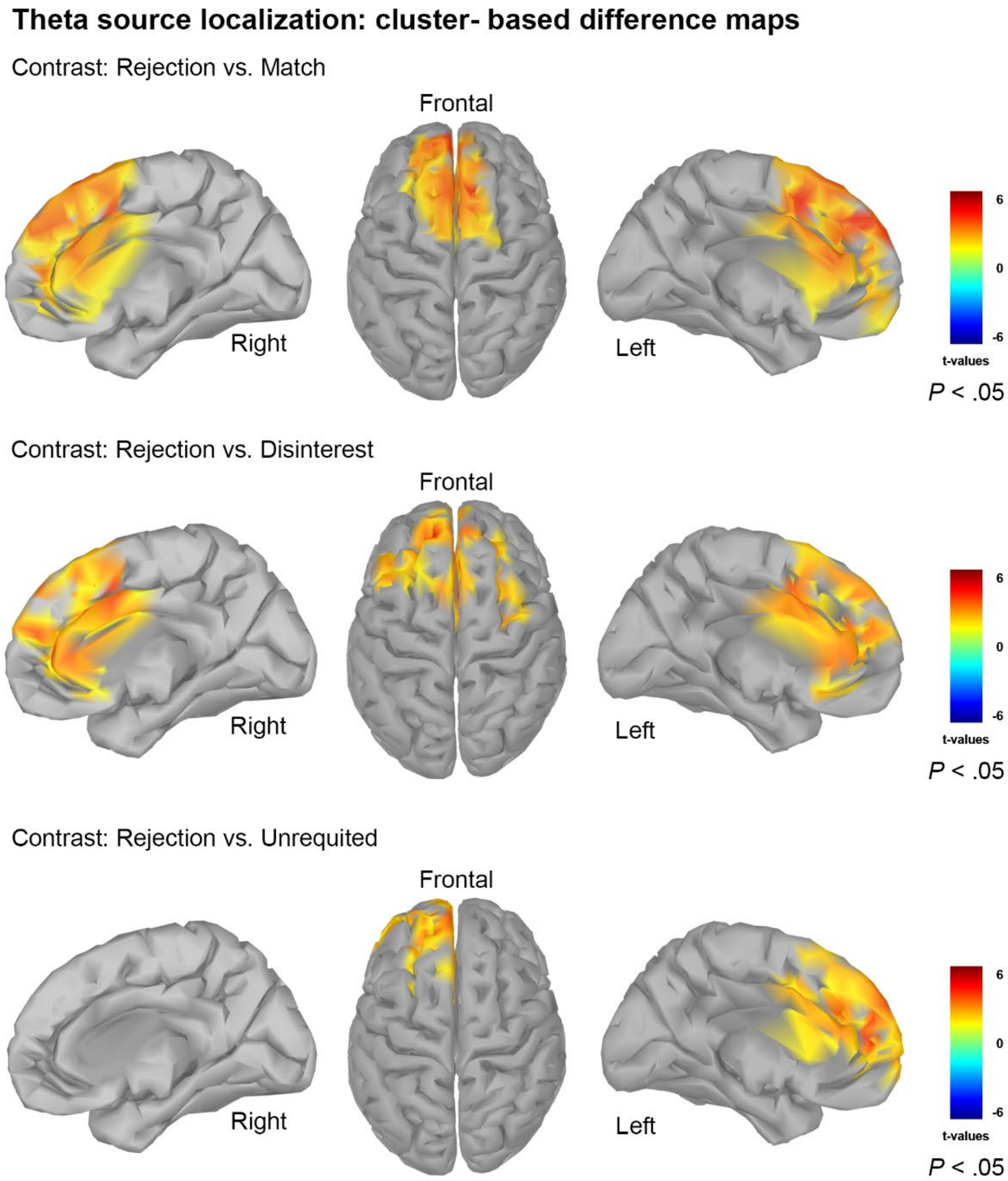

Figure 7. Contrast maps of theta source activity for Rejection with the other conditions. The mid-sagittal slices (left and right) and axial views of the three contrasts are depicted. Only clusters of theta source activity that have passed cluster-based nonparametric permutation test and survived the correction are presented.

Discussion

The goal of this study was to examine the neural correlates associated with the acceptance and rejection related to online dating. Using a novel speed dating, while measuring brain activity with ERPs and EEG, we examined the anticipatory stage (waiting to receive the speed date's feedback) and feedback processing stage (processing of the speed date's feedback signaling either interest or disinterest). This set-up allowed us to disentangle the effects of reward (interest by the speed dates) vs non-reward (disinterest by the speed dates), as well as feedback conflict (for example, when feedback from the speed date was not in line with the judgments of the participant). Our behavioral data (measured during EEG experiment) showed greater emotional reactivity, shown by self-reported pleasantness, when participants received feedback from potential dates compared to non-potential dates. For electrophysiological data, participants showed a more negative SPN amplitude while awaiting social evaluation from potential dates than from non-potential dates, as expected. During the social evaluation feedback stage, Match outcomes (where both the participant and the speed date said "yes") induced the largest RewP in all four conditions. Further, theta power was largest in response to Rejection outcomes (where the participant said "yes", the speed date said "no"). This burst of theta power during rejection was source-localized to brain regions known to be relevant for processing physical and social pain (Cristofori et al., 2013; Eisenberger et al., 2003; Peyron et al., 2000), such as the ACC, the dlPFC, and supplementary motor cortices. To our knowledge, the present study is the first to explore patterns of neural activity during "pursuing dating relationships" and offers important insights into the role of SPN, RewP, and theta oscillations in dating relationship pursuit.

Our behavioral data revealed that participants 'turned down' the majority of the speed date during the speed dating experiment, and that decision times were significantly longer for showing interest in a speed date than rejecting a speed date. This effect could be interpreted to suggest that when individuals show interest in potential dates, they expose themselves to potential adverse effects (that is, rejected by the speed date). Previous studies have shown that avoiding rejection is an important goal for most people (Baker & McNulty, 2013; Baumeister & Leary, 1995). When people try to pursue a new relationship, they consider whether exposing their intentions will make them experience the pain of rejection (Joel et al., 2019); in this case, the chance of being rejected by someone they like. In our study, the longer decision times for showing interest vs. disinterest could reflect minimization of the risk of adverse effects associated with the pursuit of dating relationships, and this risk is larger when showing interest vs. disinterest in a potential partner. As such, the decision times and trial numbers in our study provided an implicit index of the participants' prudent behavior in choosing a potential dating partner, which confirmed our experimental manipulation.

Also, participants rated acceptance from potential dates as more pleasant than rejection. Since humans have a strong evolutionary motivation to have social interactions and relationships, social acceptance is highly rewarding and desired (Baumeister & Leary, 1995). Interestingly, we found no differences in emotional responses for non-potential dates. That is, those speed dates for which the participant had no interest (Unrequited vs Disinterest condition) showed similar self-pleasantness ratings, regardless of the feedback from non-potential dates. In our study, the participants also reported a strong motivation to know the decision of potential dates, as shown by self-reported motivation. In fact, different social and motivational contexts affect how people feel about social feedback. People showed more pleasure and reward-related activity in response to social reward (for example, connection, cooperation, and conformity) for a close one rather than distant one (Hughes et al., 2018). Therefore, it is understandable that the participants had stronger motivation for potential dates, which may have increased the participants' arousal in response to social feedback.

Our brain response and EEG results suggested clear differences in neural reactivity associated with feedback anticipation and processing thereof. During the speed date's feedback anticipation stage, we observed a larger SPN when participants were hoping to receive interest. This result dovetails with prior findings on anticipating social evaluative feedback, where the SPN was found to be larger when individuals anticipated social acceptance feedback rather than rejection feedback (van der Molen et al., 2014). Our current SPN findings are also consistent with the participants' self-report ratings, suggesting that participants have a strong motivation to know the potential partner's social evaluation, and feel that receiving feedback from a potential partner is more rewarding. Previous studies have found a larger SPN when people are more likely to receive reward than punishment (Donkers, Nieuwenhuis, & van Boxtel, 2005) or social acceptance vs. rejection feedback (van der Molen et al., 2014). In our case, receiving interest from a potential dating partner meant the possibility of more subsequent communication, a strong social reward in a relationship (Cooper et al., 2013). This is consistent with previous studies that SPN reflects the anticipatory motivation before feedback (Pornpattananangkul & Nusslock, 2015). Thus, our results indicate that people have a high motivation to pursue interest from potential dates, which seems to be reflected in enhanced SPN amplitudes.

In contrast to previous social feedback anticipation studies, our current paradigm did not examine explicit expectancies from participants about the speed date's feedback. That is, we examined what participants hoped for in terms of the feedback from the speed date, which is different from examining what feedback participants might expect to receive. For example, studies that have examined explicit expectancies about social evaluative feedback have found enhanced negativities in the typical RewP time-window (Dekkers et al., 2015; van der Molen et al., 2014; 2017; 2018), which increased significantly for unexpected social evaluative feedback. These studies used a social judgment paradigm in which participants were asked, “Do you think this person likes you”, and thus explicit expectancies were measured that resulted in prediction errors (that is, when feedback is not in line with participant’s expectancies). Instead, our study focused more on the participants’ own subjective preferences regarding the speed date by asking the question, “Would you be interested in getting to know this person better?” In this manner, motivational processes (hoping to receive positive answers from the romantically interesting speed date) seem to be more relevant in the current design than expectancies. However, similarly to van der Molen et al. (2014), we found enhanced SPN amplitudes while hoping to receive acceptance rather than rejection. This might suggest that the valence effects on the SPN are similar for explicit feedback expectancies and motivationally driven feedback anticipation.

During the speed date’s feedback processing stage, our results revealed the largest RewP amplitudes in the Match condition, which suggests an increased reward value when participants were presented with feedback signaling social acceptance by potential dates than non-potential dates. This enhancement in the RewP after Match feedback might also relate to the participant’s individual preferences. A recent EEG study found that high preference outcomes induce larger RewP amplitudes than medium reward outcomes (Peterburs et al., 2019). Although that study used chocolate as a reward rather than social feedback, individual preferences about social feedback are likely to have influenced the RewP amplitudes. For example, we found that RewP amplitudes were largest for feedback conditions in which participants indicated interest in the speed date (Match and Rejection). This finding is in line with a similar speed dating study by Van der Veen et al. (2019), who reported increased P3 amplitudes for Match feedback relative to the other feedback conditions. These authors interpreted this

P3 enhancement after Match feedback to reflect the strong subjective motivational properties of this type of feedback. Future studies could further examine these potential subjective reward value effects on the RewP by examining participants' judgments about the speed date on an interval scale, rather than binary judgments (Yes vs. No). Since subjective preferences show different levels, the interval scale can examine whether RewP is modulated by the linear variation of subjective preferences.

The current study also adds an important dimension to the existing literature on brain responses to feedback processing of pursuing dating relationships. For example, Van der Veen et al. (2019) only tracked brain responses during the presentation of feedback from the potential dates, and presented the participants' judgment of the potential dates that was collected prior to the EEG session. Thus, participants passively watched their own judgments and the feedback of the potential dates. Moreover, participants in this study were forced to evaluate 50 percent of the speed date as "dateable". Together, these manipulations might have resulted in 'second thoughts' about participants' judgments about the partners during the online speed dating session, as well as reduced task engagement in finding out the evaluation from the partners, and thereby confounding the reward processes that elicit the RewP. In the current paradigm, the willingness of participants and their speed dates was communicated in real time and participants were not forced to consider a fixed percentage of candidates as dateable. This might have contributed to the ecological validity of the paradigm, and particularly participants' task engagement, a factor that is known to affect the amplitude of RewP (Bellebaum et al., 2010; Warren & Holroyd, 2012).

Previous studies have found that peer feedback incongruent with participants' feedback expectancies resulted in larger feedback negativities (Dekkers et al., 2015; van der Molen et al., 2014, 2017, 2018). We did not observe this conflict effect in the time-domain EEG (that is, ERPs), but we did find it in the time-frequency domain of the EEG. Specifically, we observed that midfrontal theta power was exclusively stronger in the Rejection condition, where the participant's interest in the potential partner was unanswered. This finding coincides with a series of EEG studies in which unexpected social rejection feedback resulted in a significant increase in mid-frontal theta power (van der Molen et al., 2017, 2018). This effect has been interpreted to reflect enhanced sensitivity of a social threat detection mechanism (Van der Molen et al., 2017, 2018). It has been postulated that humans have evolved a highly sensitive self-protection system that guards individuals from social disconnection (Eisenberger & Lieberman, 2004). Neuroimaging studies have revealed that the processing of social rejection cues is governed by brain regions that overlap with the physical pain matrix, such as the anterior insula (AI) and ACC, which are involved in cognitive-affective pathways that process information about the unpleasant value of a nociceptive stimulus (Eisenberger et al. 2003, 2007). Results from an intracranial EEG study by Cristofori et al. (2013) provided direct evidence that increased theta power during exclusion versus inclusion can be source-localized to brain areas overlapping with processing of physical pain, particularly the ACC and AI. Based on this overlap, those authors argued that enlarged theta power in response to social exclusion reflects a neural signature of social pain. Our source localization results show that theta-based source activity was significantly strongest in the Rejection condition. This activity was observed in the brain regions that cover the ACC and dlPFC – brain regions that have been shown to play a dominant role in the threat detection system (Eisenberger, 2015). However, source location results should be interpreted with caution because of their lack of precision compared to fMRI, for example. Due to the inverse problem, a limited number of electrodes and an infinite number of possible source locations result in relatively low spatial resolution (Asadzadeh, Rezaii, Beheshti, Delpak, & Meshgini, 2020). Our interpretation that the Rejection condition in this study elicited social pain is supported by the increased negative effect ratings from the participants self-reported pleasantness during rejection. However, this Rejection condition not only elicits intense social pain; it is also a condition that contains potential disconfirmation of an outcome that is hoped for and perhaps expected. Thus, implicit expectancies might have confounded the pure motivationally driven effects in this study.

In conclusion, this study has highlighted the different stages (speed dating decision making, awaiting, and processing of speed dating feedback) that characterize the pursuit of dating relationships. Specifically, our results confirm the notion that the stimulus preceding negativity is a neural correlate of reward anticipation and extend this view to anticipating a reward resulting from a potential dating relationship. We also suggest that the reward positivity reflects a neural response of the reward system related to receiving interest from potential dates, which is socially rewarding. Furthermore, our findings corroborate the idea that midfrontal theta oscillatory reactivity constitutes a neural signature of social pain resulting from social rejection by potential dates. Overall, our study highlights distinct sensitivity of anticipatory and feedback-related ERP components during the pursuit of dating relationships, and our results substantiate the important role of midfrontal theta oscillatory reactivity in regulating negative social effects.

Data and Code Availability Statement

The data and code that support the findings of this study are available from the corresponding author [Hong Li, E-mail: lihongwrm@vip.sina.com] upon reasonable request.

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II

ARE YOU WORTH THE WAIT? WAITING TIME ENHANCES SUBJECTIVE VALUE FROM A LIKED PEER AS INDICATED BY REWARD POSITIVITY

by

Xukai Zhang, Yi Lei, Susannah C.S.A. Otieno, Paavo H.T. Leppänen, and Hong Li, 2022

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III

OXYTOCIN REDUCES ROMANTIC REJECTION-INDUCED PAIN IN ONLINE SPEED DATING AS REVEALED BY DECREASED FRONTAL-MIDLINE THETA OSCILLATIONS

by

Xukai Zhang, Peng Li, Susannah C. S. A. Otieno, Hong Li and Paavo H. T. Leppänen, 2021

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Oxytocin reduces romantic rejection-induced pain in online speed-dating as revealed by decreased frontal-midline theta oscillations

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A R T I C L E I N F O

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A B S T R A C T

Background: Romantic rejection is an emotionally distressful experience profoundly affecting life, possibly leading to mental illness or suicide. Oxytocin (OT) is a neuropeptide widely implicated in reducing physical pain and negative emotions; however, whether OT has an effect on reducing intense social pain (e.g., romantic rejection) remains unknown. Here, we tested the effect of OT on social pain and investigated its role in the outcome evaluation phase of social decision-making.
Methods: Electroencephalographic recordings were obtained between August 2nd and October 20th, 2020 in Shenzhen University from 61 healthy participants in a double-blind, placebo-controlled study with a between-subject design. We defined frontal-midline theta oscillation as a neural signature of social pain and assessed self-reported pleasantness ratings for four possible romantic outcomes in an online speed-dating task.
Results: In the placebo group, greater theta power was induced by romantic rejection, being associated with rejection distress. This pattern was not observed in the OT group, where romantic rejection induced significantly decreased theta power compared to the placebo group; in the OT group, there was no association between theta power and rejection distress. Furthermore, the frontal-midline theta oscillation could be source-localized to brain areas overlapping with the physical-social pain matrix (i.e., somatosensory cortex, anterior cingulate cortex, frontal pole, and supplementary motor area).
Conclusions: OT relieves social pain caused by romantic rejection, reflected in decreased frontal-midline theta oscillations and a diminished connection between theta power and rejection distress. These findings can help understand and harness OT's pain-reducing effect on social pain.

1. Introduction

Rejection from a loved one is a distressing event and could be an important risk factor for emotional disorders like depression and anxiety (Riva and Eck, 2016), or even suicide or homicide (Fisher et al., 2010). From an evolutionary perspective, threats to the human needs of survival and reproduction (e.g., romantic rejection) are often hurtful and a cause of major emotional distress (MacDonald and Leary, 2005). It has been previously indicated that social pain (e.g., social rejection) activates the physical pain matrix, including the sensory and cognitive-affective pathways (Fisher et al., 2010; Kross et al., 2011), suggesting that romantic rejection can induce intense feelings of pain. Keeping this in mind, the biological mechanism of action of oxytocin (OT), revealed as one of the prime candidates for coping with social events and regulating social behaviors, is still not fully understood (Wigton et al., 2015). OT has been shown to be a promising neuromodulator for therapeutic interventions to treat physical and pathological pain, based on robust evidence of analgesic effects in animal studies (Boll et al., 2018; Tracy et al., 2015; Xin et al., 2017). Indeed, recent human studies have found that OT decreased physical pain sensitivity; for example, intranasal OT reduced pathologic pain (Yang, 1994) and decreased perceived pain intensity (Paloyelis et al., 2016;

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Rash and Campbell, 2014; Zunhammer et al., 2016). Besides, plasma OT levels have been positively correlated with pain tolerance (Grewen et al., 2008). However, not much is known about the effects of OT on social pain.

OT is known to promote prosocial behaviors, such as bonding and trust (Macdonald and Macdonald, 2010; Meyer-Lindenberg, 2008; Scheele et al., 2013). Specifically, Scheele et al. (2013) have suggested that OT contributes to romantic relationships because it makes males find their female partners more attractive and rewarding compared to other females. Additionally, previous studies have found that OT reduces negative emotions in single males after a negative evaluation from a female partner, and reduces jealousy in participants who experience imagined and real infidelity from their romantic partners (Zhao et al., 2018; Zheng et al., 2021). However, other studies have shown opposite or moderating effects, such as aggressive behavior (DeWall et al., 2014; Shamay-Tsoory et al., 2009), that render general OT's effects more subtle. The social salience hypothesis, which considers conflicting evidence, suggests that OT interacts with the salience coding and attentional orientation function of dopamine to increase an individual's attention to salient cues in a social context (Shamay-Tsoory and Abu-Akel, 2016). Additionally, unlike the traditional prosocial theory (Macdonald and Macdonald, 2010), in which OT unconditionally promotes prosocial behavior, the affiliation-motivation hypothesis suggests that OT promotes affiliation motivation depending on the influence of context and personal characteristics (Bartz, 2016). Although both theories are helpful in understanding the seemingly contradictory effects of OT, they cannot independently integrate all findings (Piva and Chang, 2018). A recent multistage framework posited that OT has different effects at various stages during social decision-making processing, as it may separately or simultaneously influence social perception, option valuation, and decision formulation stages (Piva and Chang, 2018). Thus, the aforementioned hypotheses may explain the effects of OT at different stages of social decision-making. However, surprisingly, this multistage framework does not include an outcome evaluation stage. Outcome evaluation is an important biological mechanism in social decision-making that can help people better understand the self and others, and effectively improve their future decisions to better navigate the social environment (Cooper et al., 2014). To the best of our knowledge, no study has investigated the role of OT during romantic decision-making, especially in the social feedback processing stage.

Further, the frontal-midline theta oscillation is typically related to negative affect, pain, and cognitive control (Cavanagh and Shackman, 2015). Specifically, Cristofori et al. (2013) provided robust evidence that theta activity represents the neural signature of social pain through intracranial electroencephalographic (EEG) recordings. At the scalp level, subsequent studies have also shown that threatening social evaluations can induce frontal-midline theta oscillation (Molen et al., 2017; van der Molen et al., 2018). Moreover, van Noordt et al. (2015) showed that frontal-midline theta oscillation tracked the experienced distress caused by social exclusion. In this study, frontal-midline theta power was measured as an electrophysiological index of the brain's response to social pain.

Here, we used a novel online speed-dating task to investigate the role of OT in romantic decisions, in which participants meet and choose potential romantic partners online and receive feedback. This paradigm has been proven to be a valid task to create a real and believable environment conducive to romantic expression (van der Veen et al., 2019), and allowed us to capture the effect of OT on brain activation during the outcome evaluation stage. The main goal of the current study was to test the assumption that OT modulates the neural activation associated with romantic rejection-induced social pain. According to the social salience hypothesis of OT, OT increases the salience of external threats and safety cues. In other words, in the current study, OT would highlight social rejection events, because social rejection threatens the human need for social bonds (Baumeister and Leary, 1995). Thus, we hypothesized that romantic rejection-induced theta power will increase in the OT group compared with that in the placebo group. On the other hand, the affiliation-motivation theory postulates that OT enhances the desire or goal to affiliate (Shamay-Tsoory and Abu-Akel, 2016). Indeed, OT has a positive effect on maintaining and promoting romantic relationships (Algoe et al., 2017; Ditzen et al., 2009). Based on this view, we hypothesized that romantic rejection-induced theta power will decrease in the OT group compared with that in the placebo group. Further, by testing these two hypotheses, our second goal was to incorporate the role of OT in the outcome evaluation stage in the multistage framework of social decision-making.

2. Methods and materials

2.1. Study design

A double-blind, placebo (PLC)-controlled study with a between-subject design was performed, in which participants randomly received either OT or PLC treatments. The study protocol was approved by the ethics committee of the Faculty of Medicine, Shenzhen University, and all the participants signed informed consent forms before inclusion. The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

2.2. Participants

Healthy male and female undergraduate students were enrolled through online advertising and school media at Shenzhen University. The exclusion criteria included 1) people who identified as homosexual or bisexual; 2) those who reported not being single (romantically); 3) medication-use, including prescription and over-the-counter drugs; 4) nasal disease or obstruction; or 5) diagnosis of psychiatric disorder(s).

Previous studies using similar speed-dating tasks (van der Molen et al., 2017; van der Veen et al., 2019) have reported the effect sizes of interaction of judgment and feedback as 0.33 and 0.38, respectively, which are lower than large effect sizes (i.e., 0.4). Therefore, we selected the medium effect size (effect size = 0.25, $\alpha = 0.05$, and power = 0.80) to estimate the required sample size for our study. G-power 3.1 (Faul et al., 2009) was used for this purpose, yielding a required sample size of 24 for each group. To avoid losing participants who did not completely believe in the online speed-dating activity, we increased the sample size. In this study, 65 students were enrolled and met the abovementioned criteria, and 63 of them successfully completed the two sessions of our task. Two participants were excluded from the subsequent analysis due to noisy EEG data. Thus, the final sample size was 61, consisting of 30 participants in the OT group (16 male, 14 female) and 31 in the PLC group (14 male, 17 female). All participants were right-handed except for two who were left-handed. Self-reported questionnaires indicated that none of the female participants were pregnant or using oral contraceptives. At the end of the experiment, participants received 120 Yuan as monetary compensation.

2.3. Procedures

First, all participants were informed that they were participating in a multi-university speed-dating program, and were required to submit a digital photo of them with a neutral expression. Once the participants submitted the photos, they were given standardized photos on the same day (similar to the experimental material), which allowed them to confirm that they had no concerns about the final photo presented to their speed-dates. Participants were allowed to replace the photos if they were not satisfied with the version provided to them.

After 1–2 weeks, the participants were required to complete an EEG task. We asked the participants to refrain from alcohol and caffeine for at least 24 h before the task and requested them to not eat or drink anything (except water) for at least 2 h before the task. These requirements were intended to minimize the impact of differences in the cardiovascular system or endogenous hormone levels before the task. A previous study found that the effect of OT is personality-dependent (Bartz et al., 2011). Thus, before the EEG task, the participants completed questionnaires on demographic variables (Table 1). We collected the Chinese version of the State-Trait Anxiety Inventory (STAI) (Spielberger, 2010) and Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988) scores as the baseline measurement.

After completing the questionnaires, participants were administered 24 IU of OT (OT spray; three puffs of 4 IU per nostril, with intervals of 45–60 s for each spray, until the participants felt no fluid flowing) or PLC (the same components as the OT spray except OT). The OT spray was formulated using a powdered version of the drug (ProSpec company, Israel). The solution was prepared by combining 5 mg of OT (2400 IU) with 6 ml of 0.9% sodium chloride solution. The mother liquor was stored in separate vials (1 ml per vial) at minus 80 °C. The vials were then thawed and refrigerated (4 °C) on the day of the study. A trained research assistant prepared the nasal spray by transferring OT or placebo from the vial to the sprayer. Participants used the nasal spray on their own under the supervision of trained and experienced experimenters. Administration followed the standard intranasal OT protocol (Guastella et al., 2013) based on the pharmacology of human intranasal OT (Spengler et al., 2017), approximately 45 min before the EEG task. In post-experiment interviews, participants were unable to correctly judge which treatment they had received ($\chi 2 = 0.81$, $p = 0.367$).

During this EEG session, participants were shown photos of individuals of the opposite sex (i.e., the speed-dates), and were asked to answer the following question, "Would you be interested in getting to know this person better?" After they made their decision, they were informed of the feedback choice from their speed-dates. Importantly, participants were told that if a "Match" (both individuals said yes) occurred, they would receive the contact information of the speed-dates. However, no matter which of the three conditions had occurred, "Rejection" (the participant said yes, but their speed-date said no), "Unrequited" (the participant said no and their speed-date said yes), or "Disinterest" (both the participant and their speed-date said no), they would not receive the contact information of their speed-dates. In fact, there was no real feedback, and the type of feedback was randomly generated by the computer (50% for each feedback). A total of 320 photos with neutral expressions (160 males and 160 females) were used

Table 1
Participant demographic and trait information, means, standard errors (SE) and number(n).

Measurements	OT	PLC		p value
Age (SD)	20.47 ± 1.91	20.06 ± 1.88	$t(59) = .83$	.410
Gender (n)				
Male	16	14	$\chi^2(1) = .41$	.523
Female	14	17		
Menstrual phase (n)				
Follicular phase	10	10	$\chi^2(1) = .53$	.465
Luteal phase	4	7		
Number of relationships (*mean* ± SE)	1.37 ± 1.91	1.35 ± 1.05	$t(59) = .04$	.972
Rejection Sensitivity Questionnaire (*mean* ± SE)	10.11 ± .43	10.54 ± .52	$t(59) = -.64$	.525
Rosenberg Self-Esteem Scale (*mean* ± SE)	31.73 ± .75	30.68 ± .99	$t(59) = .85$	.399
BDI-II Depression (*mean* ± SE)	9.17 ± 1.32	8.26 ± 1.28	$t(59) = .49$	.624
Fear of Negative Evaluation Scale (*mean* ± SE)	37.53 ± 2.01	39.77 ± 1.75	$t(59) = -.84$	.402
Liebowitz Social Anxiety Scale (*mean* ± SE)	40.77 ± 3.21	38.97 ± 3.25	$t(59) = .39$	.695

as fictitious participants from other universities, and the neutral faces were confirmed by the Self-Assessment Manikin (Bradley and Lang, 1994). All photos had the same dimensions and background colors (size: 185 × 240 pixels; background-color: R: 44, G: 44, B: 44).

A schematic of the EEG session is presented in Fig. 1. Participants were shown photographs of the speed-dates, and we judged whether they were interested in getting to know this person better. The F and J keys corresponded to the left button and right button on the screen, respectively. For example, in Fig. 1B, the Y represents yes and the N represents no, and the positions of Y and N were counterbalanced between the participants. Participants were required to make a judgment within 3000 ms after the photo of the speed-date appeared, and the feedback would not be presented if they did not respond within this time limit. Upon pressing an answer on the keyboard, the button on the screen turned green for 3000 ms to indicate the participant's choice. Finally, the feedback was presented for 2000 ms, with a "$\surd$" to indicate social acceptance and an "X" to indicate social rejection (210 × 210 pixels). The inter-trial interval varied randomly between 2500 and 3000 ms, with a fixation cross in the middle of the black screen.

Following the EEG session, we measured the STAI and PANAS again. Subjective ratings of pleasantness were obtained using a bipolar question (unhappy-happy), ranging from 1 to 7 with 1 corresponding to "very unhappy" and 7 corresponding to "very happy", for four possible outcomes (Match, Rejection, Unrequited, and Disinterest). Moreover, all the participants confirmed their belief in the cover story in the post-experiment debriefing.

2.4. EEG recordings and processing

EEG was recorded with 64 Ag/AgCl electrodes according to the 10–20 system at 1000 Hz (Brain Products, Germany). One surface electrode was used to record electro-oculographic signals and was placed below the right eye. The impedance of all electrodes was less than 10 kΩ. EEG data were analyzed with BrainVision Analyzer 2.1 (Brain Products, Germany).

The offline EEG data were re-referenced by using bilateral mastoid electrodes, and a 0.1–30 Hz band-pass filter (48 dB/oct) and a 50 Hz notch filter were applied. Data were epoched from − 3500 to 3000 ms relative to the speed-date feedback. Next, we removed ocular artifacts by an independent component analysis (Lee et al., 1999). Furthermore, trials with voltage values > ± 80 μV were discarded. The number of artifact-free EEG epochs for analyses are given in Supplementary Material S1.

2.5. Time-frequency analysis

For each type of feedback, at the single-trial level (− 2000 to 2000 ms artifact-free epochs), the EEG segments were transformed into the time-frequency domain by using complex Morlet wavelets. For each segment, we obtained a complex time-frequency estimation with 30 logarithmically spaced steps, ranging from 1 to 30 Hz in the frequency domain. The Morlet parameter of the central frequency was set to 1 Hz, and the time resolution was set to 3 s. The spectrogram was baseline-corrected using the subtraction approach at each frequency (Hu et al., 2014), in which the reference interval ranged between − 500 to − 200 ms before the feedback onset. By collapsing the four conditions, we found a pronounced theta-burst occurring 200–400 ms after the feedback at Fz. Thus, we calculated the averaged theta power (4–8 Hz) in the 200–400 ms time-window following the feedback onset at Fz.

2.6. Source-localization analyses

Source-localization of theta power was performed at the single-trial level for each feedback condition of each group using Brainstorm (Tadel et al., 2011), a free and documented software package available in Matlab (http://neuroimage.usc.edu/brainstorm). (See Supplementary

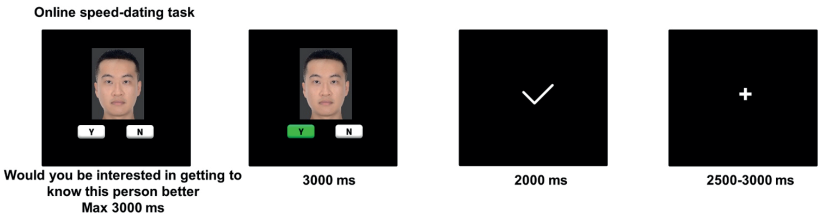

Fig. 1. Schematic representation of the experimental task.

Material S2 for detailed parameters). A Z-score was used to normalize the theta source results after averaging all the trials under each condition; the reference interval corresponded to the − 500 to − 200 ms pre-feedback baseline window. The Z-scores for source results were rectified in the theta band (4–8 Hz) and averaged within 200–400 ms post-feedback time windows for statistical analyses.

2.7. Statistical analysis

We used IBM SPSS version 21 (IBM Corporation) for statistical analysis. In the behavioral data, (1) for self-reported pleasantness ratings, we used a three-way repeated-measures analysis of variance (ANOVA) with "treatment" (OT or PLC) as a between-subjects factor, and "judgment" (yes or no) and "speed-date feedback" (acceptance or rejection) as within-subjects factors; and (2) for both the STAI and PANAS scores, we used a two-way repeated-measures ANOVA with "treatment" (OT or PLC) as a between-subjects factor and "phase" (pre or post) as a within-subjects factor.

For the EEG data, we included the theta oscillation magnitude in a three-way repeated-measures ANOVA with "treatment" (OT or PLC) as a between-subjects factor, and "judgment" (yes or no), and "speed-date feedback" (acceptance or rejection) as within-subjects factors. For all analyses, if there were significant interactions, we performed post-hoc comparisons. A Greenhouse-Geisser correction was used when sphericity was violated. To investigate the correlation between the neural oscillation and behavioral data, we performed a permutation test based on Pearson's linear correlation to calculate the correlations between theta oscillation and self-reported pleasantness ratings (Groppe et al., 2011). We used 10,000 permutations to approximate the possible permutations, and the alpha level was set as 0.05. When the correlation was significant, the cocor r package (Diedenhofen and Musch, 2015) was used to examine the correlation differences between the two groups.

For theta source localization data, nonparametric cluster-based permutation testing was used to identify significant differences of clusters between groups in the source space (Maris and Oostenveld, 2007); vid Fieldtrip's ft_sourcestatistics function in Brainstorm was used to this end (Oostenveld et al., 2011). First, for every sample, a comparison of the two conditions was calculated based on an alpha level threshold of 0.05. Then, the samples exceeding the critical t-values were clustered and summed over t-values, which were based on spatial adjacency. Next, cluster-level statistics were calculated. A Monte-Carlo method was used for statistical significance testing with paired *t*-tests. Nonparametric cluster-level statistics were performed by calculating a p-value according to a 10,000 random permutation distribution of the source data. A cluster-corrected alpha level threshold of 0.05 was set for multiple comparisons.

3. Results

3.1. Behavioral data

As shown in Fig. 2, for self-reported pleasantness ratings, the main effect of judgment (F (1, 59) = 6.32, p = .015, η_p^2 = .10) and speed-date feedback was significant (F (1, 59) = 66.76, $p < .001$, η_p^2 = .53). In addition, we found a significant interaction between judgment and speed-date feedback (F (1, 59) = 145.20, $p < .001$, η_p^2 = .71), and participants reported more unpleasantness in the "Rejection " condition ($p < .001$), and not in the "Unrequited" condition (p = .059). Moreover, we found a significant main effect of treatment, F (1, 59) = 14.77, $p < .001$, η_p^2 = .20; compared with the PLC group, the OT group reported more pleasantness. Importantly, the interaction between treatment, judgment, and speed-date feedback was significant, F (1, 59) = 12.43, p = .001, η_p^2 = .17. More specifically, in the PLC group, participants felt more unpleasant in the "Rejection" condition than in the "Match" condition ($p < 0.001$), and no difference was found between "Unrequited" outcomes and "Disinterest" outcomes (p = .309). With the administration of OT, however, participants felt more unpleasantness in the "Rejection" condition than in the "Match condition" ($p < 0.001$); contrastingly, participants felt more pleasantness in the "Disinterest" condition than in the "Unrequited" condition ($p < .001$). In order to directly reflect the change in pleasantness reported by the participants, we conducted paired sample *t*-tests on the self-rated pleasantness and anchor points (score 4) of the two groups under the four conditions. In the PLC group, participants reported increased pleasantness in the "Match" condition and increased unpleasantness in the "Rejection" condition, compared with the anchor point (both $p < .001$). However, neither the "Unrequited" nor "Disinterest" conditions were significantly different from the anchor point (both $p > .15$). In the OT group, participants reported increased pleasantness in the "Match" condition and increased unpleasantness in the "Rejection" condition, compared with the anchor point (both $p < .003$) Additionally, in the "Disinterest" condition, participants exhibited higher pleasantness compared to the anchor point ($p < .001$); however, there was no difference in the "Unrequited" condition (p = 1.00). We did not find any significant results with regard to the STAI and PANAS scores (all $p > .08$).

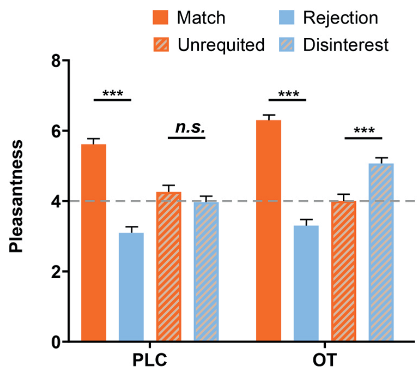

Fig. 2. Self-reported pleasantness ratings. Error bars represent standard errors. ***$p < .001$. *n.s.* indicates that the result did not reach significance.

3.2. EEG data

As depicted in Fig. 3, the theta magnitude revealed a significant main effect of judgment (F (1, 59) = 17.90, $p < .001$, $\eta_p^2 = .23$) and speed-date feedback (F (1, 59) = 12.83, $p = .001$, $\eta_p^2 = .18$). In addition, the interaction between judgment and speed-date feedback was significant, F (1, 59) = 15.20, $p < .001$, $\eta_p^2 = .21$. We also found a significant main effect of treatment, F (1, 59) = 5.00, $p = .029$, $\eta_p^2 = .08$; compared with the OT group, the PLC group showed increased theta power. Importantly, we observed a significant interaction between treatment, judgment, and speed-date feedback, F (1, 59) = 6.43, $p = .014$, $\eta_p^2 = .10$. Further decomposition indicated that the theta power was greater for a "Rejection" outcome in the PLC group than that in the OT group ($p = .002$); the differences were not significant between the two groups for the other conditions (for all, $p > .080$).

Thus, we further explored the neural sources that generated the increase in theta power in the "Rejection" condition in both the PLC and OT groups. As depicted in Fig. 4, the source map shows a distinct pattern of brain activity in the frontal-midline regions between both groups in the case of a "Rejection" outcome. Specifically, the source map suggested that for all conditions, the primary probable source for theta power is located in the anterior cingulate cortex (ACC). This finding was the most prominent for a "Rejection" outcome. Importantly, two significant clusters were found in the contrast between the PLC and OT groups, using a nonparametric cluster-based permutation (cluster 1: size = 478, $p = .005$; cluster 2: size = 343, $p = .015$). These significant group differences of source space encompassed the frontal pole (BA 9 and BA10), ACC (BA 24 and 32), subgenual cingulate cortex (BA 25), supplementary motor area (BA6), and somatosensory motor cortex (left BA2, left and right BA3), and right amygdala (BA 34).

Additionally, the theta magnitude was negatively correlated with the self-reported pleasantness rating ($r = -.56$, $p < .001$; Fig. 5) for the "Rejection" condition in the PLC group, whereas this correlation was diminished in the OT group ($r = -.10$, $p = .31$). Furthermore, the cocor r package (Diedenhofen and Musch, 2015) was used to compare these correlations, and a significant difference was observed between the two correlations (z = −1.97, $p = 0.048$, two-tailed). No other significant correlation was found between theta oscillation and self-reported pleasantness ratings (for all, $p > .10$).

4. Discussion

Our results indicated that romantic rejection is a painful experience and is reflected in the increased frontal-midline theta oscillation. These activations were weakened in the OT group such that theta oscillation was significantly decreased for romantic rejection compared with that in the PLC group, and there was no association between theta power and negative emotion. To the best of our knowledge, this study is the first to prove the pain-reducing effect of OT in social pain and provides new behavioral and neurological evidence of OT regulating pain processing

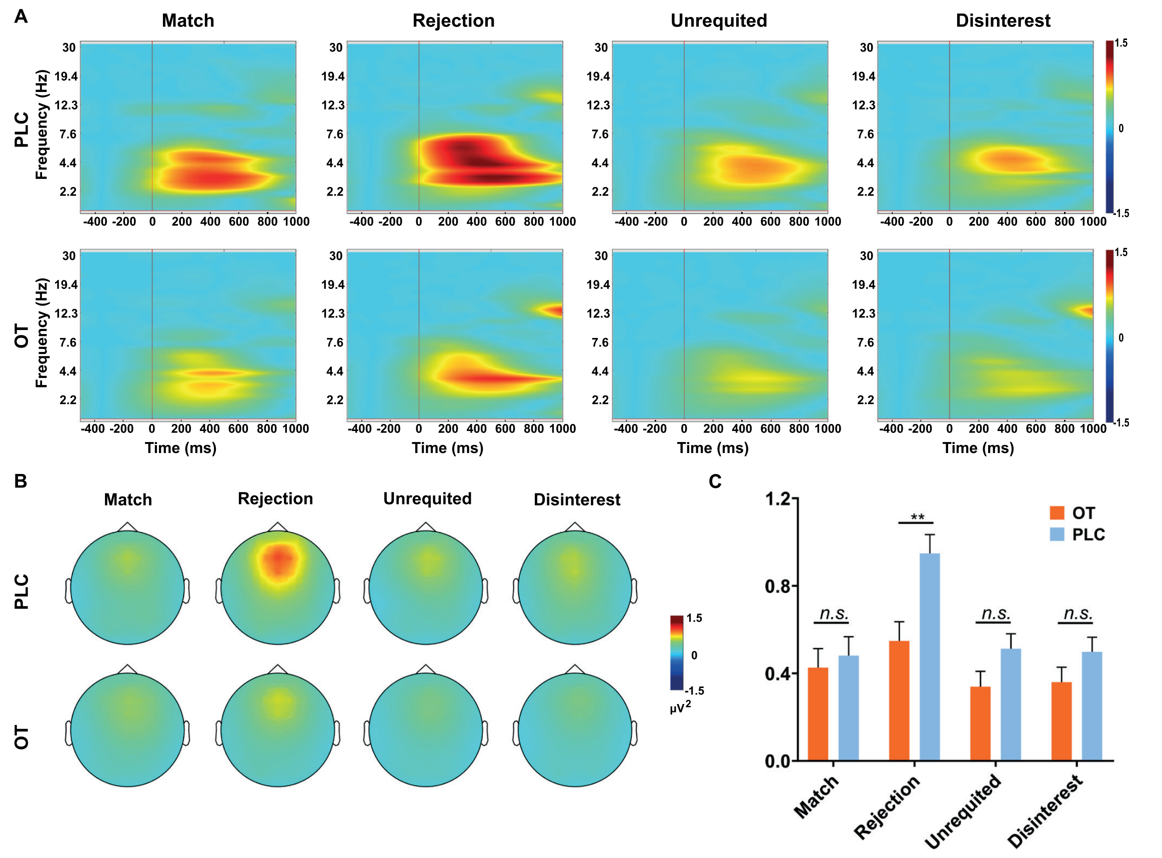

Fig. 3. Time-frequency power at Fz during the 200–400 ms post-feedback interval. (A) Time-frequency plots in four outcomes in response to placebo and oxytocin administration. (B) Theta power scalp distribution showing a frontal midline dominance. (C) Average theta power per outcome. Error bars represent standard errors. $^{**}p < .01$. *n.s.* indicates that the result did not reach significance.

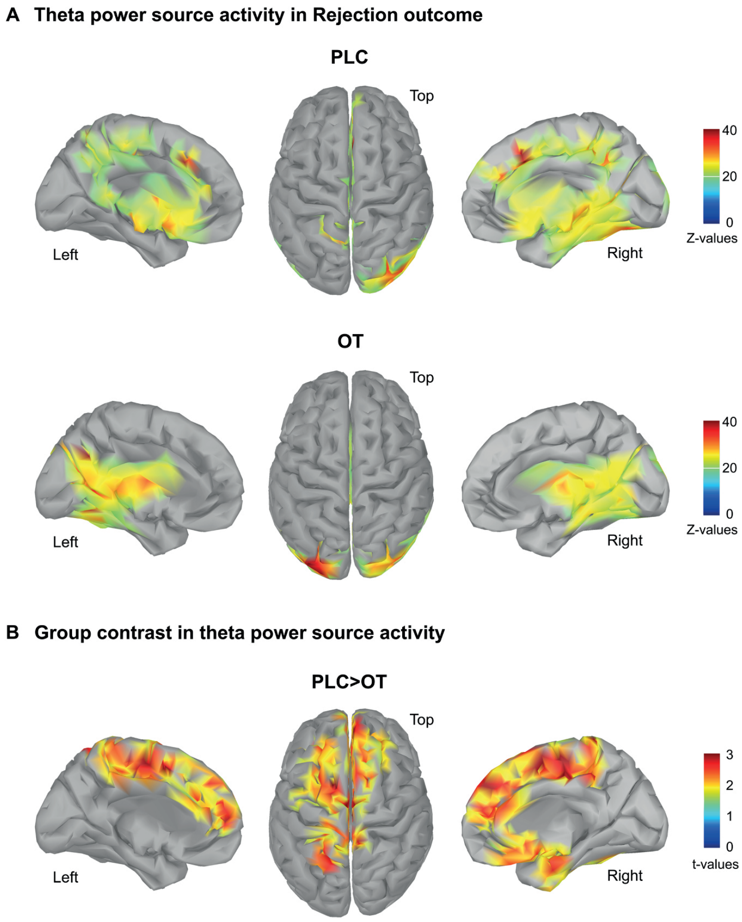

Fig. 4. (A) Source localization analyses showing theta source activity for placebo and oxytocin groups when receiving rejection feedback from the potential romantic partner. (B) Contrast maps of theta source activity for the "Rejection" outcome. Theta source activity indicates significantly higher theta activity in the placebo group relative to the oxytocin group. Only clusters of theta source activity that passed a cluster-based nonparametric permutation test and survived the correction are presented.

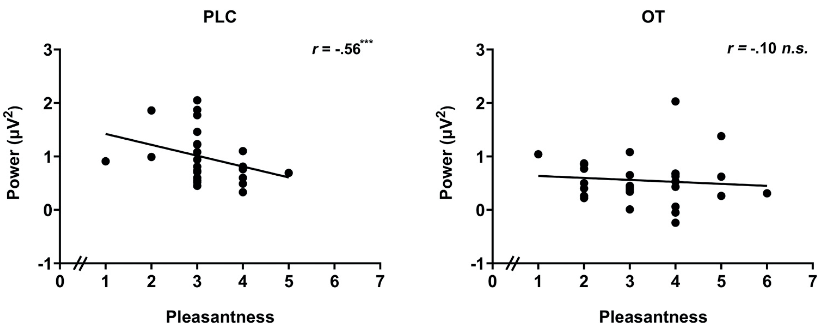

Fig. 5. Scatterplot and Pearson's correlation values between the theta power and the self-reported pleasantness ratings in the 'Rejection' outcome in the placebo (left panel) and oxytocin groups (right panel). ***$p < .001$. *n.s.* indicates that the result did not reach significance.

in a real social context.

The experience of disconnection is so profound that it is capable of triggering social pain, especially in romantic relationships (Eisenberger, 2015a, 2015b). Moreover, theta oscillation has been reported as a neural code that indicates pain-related brain processing in a previous study (Cristofori et al., 2013). Subsequent EEG studies have emphasized the role of the frontal-midline theta oscillation in processing threatening social information from strangers (van der Molen et al., 2017; van der Molen et al., 2018). Additionally, the frontal-midline theta oscillation also has a role in tracking self-reported ostracism distress, reflecting a positive correlation between negative emotions and theta power (van Noordt et al., 2015). Similarly, under PLC, our results showed that rejection from potential romantic partners induced greater frontal-midline theta power. Furthermore, the correlation between frontal-midline theta power and self-reported pleasantness may reflect different degrees of the participants' painful emotional responses to romantic rejection. Here, we add to the findings from previous studies by demonstrating that the frontal-midline theta oscillation is a neural signature of romantic rejection, linked to painful feelings during romantic decision-making.

Intriguingly, we found a significantly decreased frontal-midline theta power for the "Rejection" outcome in the OT group, compared with that in the PLC group. This suggests that OT alleviates the neural response associated with romantic rejection-induced social pain. Furthermore, we observed no relationship between romantic rejection-induced theta oscillation and rejection distress in the OT group. Previous studies have indicated that the unpleasantness value of the nociceptive stimulus was processed through a cognitive-affective pathway in the pain matrix (Cristofori et al., 2013; Peyron et al., 2000). Recently, a study found that OT reduces the link between neural and affective responses after social exclusion (Petereit et al., 2019). The lack of a relationship between self-reporting and neural response may reflect OT's role in alleviating negative emotions. Thus, our results suggest that OT has a clear effect on reducing social pain induced by social rejection, which manifests in the form of a reduction in theta power and severed connections between emotional distress and neural responses.

Additionally, this study adds an important dimension to existing research by examining the effect of OT on social rejection in a romantic context, i.e., online speed dating. Although previous studies have examined the effect of OT on social ostracism in non-romantic contexts, they have not found that OT regulates negative emotions induced by social ostracism. For example, Alvares et al. (2010) found that when participants were excluded during a virtual ball-tossing game, OT did not influence the negative affective and attachment-related reactions. Similarly, Xu et al. (2017) reported that OT did not alter the emotional experience of social rejection during the Cyberball task. This is not surprising, as numerous studies have shown that the effects of OT are context-dependent (Bartz, 2016; Bartz et al., 2011; Shamay-Tsoory and Abu-Akel, 2016; Xu et al., 2017). One of the important differences of social context is that different types of social exclusion were used. Previous studies have often interchanged rejection and ostracism; however, the psychological activities and behavioral responses of these two different types of social exclusion are different (Molden et al., 2009; Wesselmann and Williams, 2017). Moreover, the abovementioned studies did not involve a romantic context, and social rejection from someone one likes/loves is a more powerful social stimulus than from someone with whom one has no interaction at all (Kross et al., 2011). Interestingly, in the context of romance, a recent study showed that OT reduces single males' response to social rejection by females (Zhao et al., 2018). Another study found that OT reduced jealousy and arousal ratings in imagined and real infidelity situations (Zheng et al., 2021). Therefore, the context-dependence of OT is one of the important reasons why our results differ from those of previous studies. Furthermore, a recent review has suggested that the analgesic effect of OT may not always be captured by self-report (Boll et al., 2018). Various neuroimaging studies have found that OT does not alter subjective emotional ratings, but reduces neural activity related to negative evaluations and electric shock (Gozzi et al., 2017; Singer et al., 2008). Recently, Petereit et al. (2019) argued that OT does not alter the self-report of exclusion, but rather the link between neural activity and affective reaction. Therefore, our study provides important evidence that OT has a clear effect in reducing the brain's response (enhanced theta power) to social rejection, i.e., experience social pain, and because of the subtlety of this effect, the neural signal and the relationship between neural activity and self-reported measures of pain provide a promising way to measure the analgesic effect of OT in the future.

Over the past two decades, neuroimaging and intracranial studies have shown that the processing of social rejection cues is governed by brain regions that overlap with the physical pain matrix (Cristofori et al., 2013; Eisenberger, 2015a, 2015b; Kross et al., 2011). Classically, two different brain networks form the social-physical pain matrix: a physical one that describes the sensory properties of pain stimuli, which are processed by the primary and secondary somatosensory cortices and posterior insula; and an affective one, which describes the cognitive characteristics of pain stimuli and is processed by the ACC, frontal pole, and anterior insula. Our results found that the enhanced theta oscillation was localized to the somatosensory cortex, ACC, and frontal pole for the "Rejection" outcome in the PLC group vs. the OT group. Thus, our results reveal the possible pain-reducing effect of OT on social pain via the sensory and affective pathways. For this type of acute social pain (such as breakups or the loss of loved ones), our research may provide a viable intervention that uses OT to help overwhelmed people alleviate their negative emotions. However, the interpretation of our source localization results needs to be cautious. Inverse problem is a challenge during the EEG source-localization analysis, and there is no unique solution to it. To solve the problem of a finite number of sensors and an infinite number of possible source locations, additional constraints and theoretical assumptions are made; however, this also leads to the problem of low spatial resolution for source locations (Asadzadeh et al., 2020). Future studies could use high-spatial resolution techniques, such as functional magnetic resonance imaging, to explore the role of OT in social rejection in subcortical regions.

Furthermore, to attempt to settle the debate over the existing OT hypotheses, the multistage framework of OT has proposed that OT may have different mechanisms at different stages of social decision-making (Piva and Chang, 2018). According to this framework, OT mainly affects social perception, the valuation of potential behavior, and decision formulation during social decision-making. However, this framework does not take the outcome evaluation stage into consideration. Importantly, the outcome of an individual's behaviors provides an important basis for subsequent decisions, which means that the outcome evaluation stage subsequently affects other stages in future trials. In our study, we mainly focused on social feedback processing, which may offer novel insights to improve the multistage framework by combining the current popular theories regarding the outcome evaluation stage. The social salience theory (Shamay-Tsoory and Abu-Akel, 2016) emphasizes the role of OT in highlighting social cues, regardless of valence. According to this theory, OT should theoretically increase an individual's attention to the most threatening cue (i.e., romantic rejection) in the current online speed dating experiment. This means that a stronger theta power should have been observed in the OT group. What we found, however, was that OT reduced theta power during romantic rejection. Thus, the social salience hypothesis does not appropriately explain the results regarding the outcome evaluation stage in our study.

Alternatively, our results seem to be consistent with the affiliative-motivation hypothesis, which proposes that OT promotes prosocial behavior and social bonds (Bartz, 2016; Bartz et al., 2011). OT has been known to maintain and promote romantic bonds (Algoe et al., 2017; Ditzen et al., 2009; Scheele et al., 2013), which is consistent with our result whereby OT reduced romantic rejection-induced theta power. Additionally, the opposite effect of self-reported pleasantness in the "Disinterest" outcome between the OT and PLC groups can be explained by the affiliative-motivation hypothesis. In the OT group, participants reported even higher pleasantness when they received a rejection rather than a "match" from the speed-dates whom they did not like (cases where the participant rejected the speed-date). Based on the affiliative-motivation hypothesis, expectancy has been proposed as an important moderator in promoting prosocial behavior (Bartz, 2016). A previous study has shown that "Disinterest" outcomes help participants to avoid the guilt and embarrassment that might result from an unequal interest (i.e., "Unrequited" outcome) (Cooper et al., 2014). Therefore, receiving a rejection from an undesired speed-date is consistent with the participant's expectations, and it is consistent with the affiliation goal of the OT, leading to participants reporting relatively higher levels of pleasantness for "Disinterest" outcomes than for "Unrequited" outcomes in the OT group. Taken together, our results provide evidence of the affiliative-motivation role of OT in the outcome evaluation stage in social decision-making, suggesting that the outcome evaluation stage should be included in the multistage framework.

Although we have demonstrated the pain-reducing effect of OT on social pain from behavioral and neurological responses, it remains to be seen whether intranasal OT can actually cross the blood-brain barrier and affect both the central and peripheral concentration of OT. However, how and when intranasal OT reaches the brain, and how it affects behavior and neural activity by affecting the corresponding brain regions is still unclear (Leng and Ludwig, 2016). Therefore, one drawback of our study is that it did not directly examine the effectiveness of intranasal OT. Future studies should demonstrate the effectiveness of intranasal OT by measuring changes in OT concentrations in the blood or saliva. In addition, previous studies have shown a link between OT and stress regulation (Olff et al., 2013; Quirin et al., 2011). The social rejection event (e.g., romantic rejection) induced in our study is a common social stressor in daily life (Slavich et al., 2010). Thus, another possible explanation for the reduced theta effect is that OT increases tolerance to rejection by reducing stress and/or enhancing emotional regulation after rejection (Zhao et al., 2018; Zheng et al., 2021). Unfortunately, our study did not measure OT's effects on stress responses and emotional regulation, leaving an open question for future research on how OT modulates the stress response in social pain processing.

5. Conclusions

Our study provides the first pharmacological–electrophysiological evidence of the pain-reducing effect of OT on romantic rejection-induced social pain. Specifically, theta oscillation acts as a neural signature of social pain, and we found that OT reduced the theta power and weakened the connection between theta power and distress. These findings help us to better understand the pain-reducing effect of OT in social pain and lay forth a potential therapeutic intervention to deal with the psychological problems associated with social pain. Moreover, we evaluated the effects of OT in the outcome evaluation stage, which may provide a new perspective for integrating the effects of OT in social decision-making.

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Conflicts of Interest

None.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psyneuen.2021.105411.

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