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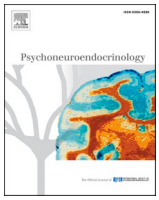

Oxytocin modulates neural activity during early perceptual salience attribution

Andreia F. Santiago [a,b,1], Maciej Kosilo [a,1], Carlotta Cogoni [a], Vasco Diogo [a,c], Rita Jerónimo [c], Diana Prata [a,d,*]

[a] Instituto de Biofísica e Engenharia Biomédica, Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal
[b] William James Center for Research, ISPA - Instituto Universitário, Lisbon, Portugal
[c] Instituto Universitário de Lisboa (Iscte-IUL), CIS_Iscte, Lisbon, Portugal
[d] Department of Old Age Psychiatry, Institute of Psychiatry, Psychology and Neuroscience, King's College London, UK

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ABSTRACT

Leading hypotheses of oxytocin's (OT) role in human cognition posit that it enhances salience attribution. However, whether OT exerts its effects predominantly in social (vs non-social) contexts remains debatable, and the time-course of intranasal OT's effects' on salience attribution processing is still unknown. We used the social Salience Attribution Task modified (sSAT) in a double-blind, placebo-controlled intranasal OT (inOT) administration, between-subjects design, with 54 male participants, to test existing theories of OT's role in cognition. Namely, we aimed to test whether inOT would differently affect salience attribution processing of social stimuli (expressing fearfulness) and non-social stimuli (fruits) made relevant via monetary reinforcement, and its neural processing time-course. During electroencephalography (EEG) recording, participants made speeded responses to emotional social (fearful faces) and non-emotional non-social (fruits) stimuli - which were matched for task-relevant motivational salience through their (color-dependent) probability of monetary reinforcement. InOT affected early (rather than late, P3b and LPP) EEG components, increasing N170 amplitude ($p = .041$) and P2b latency (p .001; albeit not of P1), regardless of stimuli's (emotional) socialness or reinforcement probability. Fear-related socialness affected salience attribution processing EEG (p .05) across time (N170, P2b and P3b), being later modulated by reinforcement probability (LPP). Our data suggest that OT's effects on neural activity during early perception, may exist irrespective of fear-related social- or reward-contexts. This partially supports the tri-phasic model of OT (which posits OT enhances salience attribution in an early perception stage regardless of socialness), and not the social salience nor the general approach-withdrawal hypotheses of OT, for early salience processing event-related potentials.

1. Introduction

Well-adapted social behaviour is crucial for humans' survival and reproduction (Frith, 2008). The neuropeptide oxytocin (OT) has been identified as a key neuromodulator of social behaviour in human and non-human social animals (Donaldson and Young, 2008). However, the exact cognitive processes it modulates are still to be established (Meyer-Lindenberg et al., 2011; Ma et al., 2016; Quintana and Guastella, 2020). Current research has departed from the simplistic idea that OT would act as a pure facilitator of pro-social behaviour (Nave et al., 2015) and is questioning OT's specificity to social contexts (Harari-Dahan and Bernstein, 2014, 2017; Quintana and Guastella, 2020). Such a more nuanced view of OT's role in cognition calls for increased preciseness in hypotheses and study design.

Two leading hypotheses for OT's role in human cognition focus on its effects on stimulus saliency. The social salience hypothesis states that OT facilitates the salience of social stimuli specifically by orienting responses to external contextual social cues (Shamay-Tsoory et al., 2009). It is supported by studies showing intranasal OT (inOT) increased, for example: gaze to the eye-region (Guastella, Mitchell, and Dadds, 2008),

* Correspondence to: Instituto de Biofísica e Engenharia Biomédica, Faculdade de Ciências da Universidade de Lisboa, Campo Grande 016, 1749-016 Lisboa, Portugal.
E-mail address: diana.prata@kcl.ac.uk (D. Prata).
[1] These authors contributed equally.

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memory recognition of social stimuli (Guastella, Mitchell, and Mathews, 2008; Rimmele et al., 2009; Marsh et al., 2010), and increased social over non-social stimuli dominance in a binocular rivalry paradigm (Hovey et al., 2020). InOT has also been shown repeatedly to strongly reduce amygdala reactivity to fear-inducing stimuli (Kirsch et al., 2005) which suggests that OT is implicated in modulating the salience to social and/or relevant stimuli, and perhaps with the consequence of facilitation approach behaviour by reducing aversion to fear. On the other hand, the approach-withdrawal hypothesis posits that OT facilitates the salience of 'personally relevant and emotionally evocative stimuli' (Harari-Dahan and Bernstein, 2014), which tend to be, but are not necessarily, social. This would be done by OT acting on approach/-motivation and avoidance/withdrawal circuitry – i.e. the 'wanting' mesocorticolimbic circuitry of approach motivation linked to reinforcement learning and the cortico-amygdala circuitry of withdrawal/avoidance motivation linked to threat and fear (Harari-Dahan and Bernstein, 2014). In other words, OT would enhance the salience of social cues because they have chronic and/or situational motivational relevance, or trigger emotions, and not because they are social per se (Harari-Dahan and Bernstein, 2014). In line with this, inOT has been shown to decrease, for example: avoidance of emotionally evocative negative stimuli (regardless of whether they were social) but not of emotionally evocative neutral stimuli (Harari-Dahan and Bernstein, 2017) or emotionally evocative positive stimuli (Alaerts et al., 2021), increased left-sided (approach-related) frontal alfa asymmetry for high emotional evocativeness (regardless of valence) (Alaerts et al., 2021), pupil dilation (a positive proxy of arousal) during the presentation of both emotional and neutral faces or a geometric shape (Quintana et al., 2019), and visual memory performance for both social and non-social stimuli (Herzmann et al., 2012). InOT has also increased midbrain activation during a reward task, suggesting OT may mediate reward processing (highly related to motivational salience and relevance) in humans, even in a purely non-social context (Mickey et al., 2016). Nevertheless, this plausible implication of OT in reinforcement learning and motivational processes is under-researched.

The above two hypotheses do not refer to the exact cognitive subprocesses OT might affect within the realm of salience attribution. Recently, a multistage model was proposed which integrates both theories and details the psychological processes OT might affect. It proposes OT affects both perception and salience of social stimuli, as well as the propensity to approach or avoid them, depending on the context (e.g., reward) or interindividual differences (e.g., sex) (Piva and Chang, 2018). However, this model did not take into consideration studies using electroencephalography (EEG), a technique with a high temporal resolution, well suited to disentangle the neural processing subjacent to salience attribution processes (Pehlivanoglu et al., 2020). Indeed, EEG-OT studies have shown time-dependent effects of OT. In terms of early ERPs, P1 amplitude, a face processing (Itier and Taylor, 2004) and early attentional processing ERP (Taylor, 2002) has been shown to be decreased in women, under inOT (vs. placebo) albeit not in men (Schiller et al., 2023). N170, a face-sensitive ERP (Eimer, 2011; Schindler et al., 2021), which has also been associated with task-relevance in working memory (Schreppel et al., 2008; Rutman et al., 2010), has been shown to be, under inOT: 1) larger for faces regardless of their characteristics (age and emotion) (Peltola et al., 2018), and 2) shorter latency to fearful than neutral faces (Tillman et al., 2019). In terms of middle ERPs, it is shown that frontal P2 (P2a) amplitude, associated with motivational salience (Riis et al., 2010), was decreased for self-related information (Liu et al., 2013) and increased for in-group members pain (Sheng et al., 2013), under inOT (vs placebo). Finally, in terms of late ERPs, it was shown that frontocentral P3 (P3a) amplitude, associated with stimulus driven attention (Polich, 2007), was increased for infant vs. adult faces (Rutherford et al., 2017), under inOT (vs placebo); and LPP amplitude, associated with emotional significant stimuli (Hajcak et al., 2010; Hajcak and Foti, 2020) and reward (Luque et al., 2015), was increased for faces (Huffmeijer et al., 2013) and other-related information (Herzmann et al., 2013) (but see (Rutherford et al., 2017; Peltola et al., 2018; Petereit et al., 2019) for null effects of inOT on LPP).

In gathering the above literature, a systematic review of inOT's effects on event-related potentials (ERPs) suggested a third hypothesis, more nuanced in time: the tri-phasic model for OT effects (TRIO). It posits OT enhances the salience of both social and non-social stimuli in an early perception stage (100–200 ms) but prioritizes social over non-social stimuli in later stages (selection, 200–300 ms; and evaluation, >300 ms) (Pehlivanoglu et al., 2020). In this realm, OT would increase early perceptual salience irrespectively of stimuli characteristics, and act as a 'filter' to guide attention selectively towards social (over non-social) stimuli in the selection stage and as a modulator of motivational salience (i.e., withdrawal vs. approach) for social stimuli in the evaluation stage. Nevertheless, this model fails to predict what would be OT's role in the processing of non-social but personally relevant and emotionally evocative stimuli (Pehlivanoglu et al., 2020).

Even though the above hypotheses have gained traction, studies comparing social and non-social stimuli have failed to address the relevance (either by manipulating it or measuring it) of the used stimuli, which is an important confounder due to the inherent high relevance of social stimuli (Lockwood et al., 2020). For example, studies that tested whether inOT would increase the perceptual salience of social stimuli in faces (Xue et al., 2020) using non-social stimuli of no particular motivational relevance (pictures of watches) cannot rule out that inOT increased salience for faces not because they are social, but because social stimuli are intrinsically more motivationally relevant (Frank et al., 2009; Santos et al., 2011). As such, with the available evidence, it is not possible to determine whether OT's effects are due to stimuli being social or (generally) relevant, a gap we aimed to tackle in the present EEG study.

In the present double-blind, between-subjects, placebo-controlled pharmaco-EEG study we aimed to test whether inOT affects the neural processing time-course of salience attribution processing of social stimuli (expressing fearfulness) and non-social stimuli (fruits) made relevant via monetary reinforcement, and. For the first time to our knowledge, in the present study, we adapted the Salience Attribution Task (SAT) (Roiser et al., 2009), a reinforcement learning task that measures the implicit and explicit attribution of salience to task-relevant and task-irrelevant stimuli, to include pictures of fearful faces as social stimuli (henceforth referred to as the social Salience Attribution Task, or sSAT). By adding the social dimension, we can orthogonally manipulate emotional 'socialness' (as task-irrelevant) and 'reinforcement probability (RP)' (as task-relevant). This way, we have obtained four conditions: social high-RP, social low-RP, non-social high-RP and non-social low-RP, so that a socialness by RP interaction can be estimated, as well as their interaction with drug. Moreover, regarding drug effects, at a neural and behavioural level, a 'drug x socialness' interaction would support the social salience hypothesis; a 'drug x RP' interaction would support the general approach-withdrawal hypothesis; and a 'drug x socialness x RP' interaction would support both hypotheses. Furthermore, time-course-wise, the presence of a main effect of inOT in early (i.e., perceptual), and of a 'drug x socialness' interaction in later ERPs, would support the TRIO hypothesis. For this exploration, unprecedented in sSAT, or its original non-social version (Roiser et al., 2009), we focused on the previously mentioned ERPs' (P1, N170, and LPP). We did not hypothesize P2a or the P3a would be elicited during the sSAT, as these ERPs have been elicited in the context of paradigms with novel (Kok, 2001; Riis et al., 2010) or distractor stimuli (Bledowski et al., 2004; Sawaki, 2006; Pontifex et al., 2009; Szuromi et al., 2011), requiring detection, explicit discrimination and classification of the stimuli, which do not take place in sSAT. Instead, we did expect posterior P2 (P2b), (associated with face processing (Latinus and Taylor, 2006), attention (Crowley and Colrain, 2004) and perceptual salience (Straube et al., 2010)) and P3b (associated with attentional resource allocation and working memory updates (Polich, 2007), stimulus salience (Hajcak et al., 2010; Hajcak and Foti, 2020) and reward (Luque

et al., 2015)) to be elicited during the sSAT. As such, in sum, based on prior evidence, we selected P1, N170, LPP, P2b and P3b amplitudes' for analysis. For completeness, we also analysed the latencies for three of these ERPs, N170, P2b, and P3b, as they might provide insights regarding salience attribution processing. In particular, N170 latency has been associated with the speed of face cognition (Kaltwasser et al., 2014) and object recognition (Herzmann et al., 2010), and shown to be affected by inOT (Tillman et al., 2019); P2b latency has been associated with the speed of stimulus categorization (Pernet et al., 2003), as well as P3b latency, reflecting the timing of mental process (Kok, 2001) and mental ability (Kapanci et al., 2019). Such a range of ERPs will allow us to characterize the neurocorrelates of salience-related cognitive processes, e.g. early components (such as P1, N170 and P2b) would mainly reflect perceptual salience (even if they can be influenced by motivational salience), and later components (such as P3b and LPP) tagging higher-level cognitive processing such as allocation of, and sustained attention towards, motivationally salient stimuli (see elsewhere (Ahmadi et al., 2018) for a similar approach). Complementarily, we also report any effects on behavioural measures response time and subjective reinforcement probability.

2. Methods

2.1. Power

As obtained using G-power 3.1, an a priori power analysis indicated a minimum sample size of 54, to detect a medium effect size of $\eta_p^2 = .06$ (Cohen, 1988), with alfa of.05, power of.95, for a repeated measures between-subjects ANOVA, with two groups (placebo vs. inOT), two repeated measures (socialness and RP), correlation among repeated measures of 0.5 and non-sphericity correction factor of 1.

2.2. Participants

A total of 62 subjects were recruited through online advertisement in social media and word-of-mouth. Five participants were excluded from all data analysis due to data acquisition problems. For behavioural analysis only, two participants with > 25% of omissions and premature responses (i.e. before the probe's appearance) were excluded (Roiser et al., 2009) and one was excluded to exactly match the drug groups in terms of the task version (i.e. where task version refers to the red or blue colour being reinforced), totalling a sample of N = 54, with a random allocation to either inOT (n = 26, 13 in each task version) or placebo (n = 28, 14 in each task version) groups. For EEG analysis only, two were excluded due to EEG data acquisition problems, and one was excluded to exactly match the drug groups in terms of the task's reinforced colour version, totalling a sample of N = 54, with a random allocation to either inOT (n = 28, 14 in each task version) or placebo (n = 26, 13 in each task version) groups. All were white Portuguese, healthy males, aged 20–35 years old (recruited by design, as OT's effects have shown to be affected by sex and age (Bartz et al., 2011)), right-handed, not-colour blind, had European Portuguese as a first language and at least 12 years of education. Exclusion criteria were self-reported premature birth (≤36 weeks) with associated health consequences, prior head trauma with loss of consciousness or seizures, prior or current neurological or psychiatric disorders, history of drug or substance abuse, use of psychotropic or hormonal medication in the last 3 months, and colour-blindness. Twenty-four hours before the experiment, participants were asked to abstain from consuming caffeine, alcohol, tobacco or drugs, and intense physical (sports) and sexual activity; as well as to abstain from cannabis consumption for 1 week before the experiment. A drug screening test (for amphetamine, benzodiazepine, cocaine, methamphetamine, morphine/opiates, tetrahydrocannabinol (THC); nal von minden Drug-Screen®) and an interview were conducted on the day of the experiment to confirm pre-requisites were followed.

2.3. General procedure

Following the drug test, participants completed the Digit Span test from WAIS-III (Wechsler, 2008), the anxiety state subscale (Y1) of STAI Y Form (Silva, 2003) and the Empathy Quotient (Rodrigues et al., 2011) (for approx. 10 min) and a colour blindness test. This was followed by an sSAT tutorial and practice session (see below) and the EEG setup. A blood sample was collected, and a random inOT/placebo administration was performed (17 min after, on average). A second blood sample was collected (17 min after, on average), after which we recorded a 3-min resting-state EEG, calibrated an eye tracking device, and ran a second sSAT practice session (see below). The main sSAT task started, on average, 29 min following drug administration (this was chosen in order to capture as much as possible a time-window around the expected inOT brain-effect peak at 45 mn (Spengler et al., 2017). The session took place at the LAPSO lab of ISCTE-IUL (Lisbon, Portugal), was approved by its ethics committee (Ref 19/2019), and was part of an umbrella project, which involved the collection of other measures, such as eye-tracking, not analysed herein. All participants signed a written informed consent and were monetarily compensated for their time, receiving 15–35€ in gift vouchers, depending on their task performance (see below).

2.4. Social Salience Attribution Task (sSAT)

The sSAT, as the non-social Salience Attribution Task (Roiser et al., 2009), required participants to respond as fast as possible (by pressing the space bar on a computer keyboard) following the appearance of a probe (black square) to earn money [Fig. 1, top], which was measured as reaction time (RT). For a more detailed description of the tutorial and practice sessions, see Supplementary Material A. The standard deviation (SD) of the fastest half of the trials (SDF) from the 2nd practice session was used to set the minimum and maximum probe durations during the 1st block of the task (for details, see Supplementary Material A). On reinforced trials, the reward was dependent on how fast participants responded, with feedback in the center of the screen indicating how much money they received. The probability of reinforcement in a given trial was signalled by one of four types of conditioned stimuli (CS), which varied in two orthogonal visual dimensions: colour (blue or red) and socialness (fruit or fearful face) [Fig. 1, bottom]. The colour dimension was task-relevant, meaning one colour was reinforced in 35 out of 40 trials (87.5%) and the other colour in 5 out of 40 trials (12.5%), randomised between participants and kept the same across one participant session. The socialness dimension was task-irrelevant, meaning both fruits and faces were reinforced in 20 out of 40 trials (50%). Participants were not informed of these contingencies but were instructed to work out the probability of the reward associated with every stimulus type, and asked to estimate it at the end of each block, with the help of a visual analogue scale going from 0 to 100%, in increments of 5%, as a means to measure SRP (subjective reinforcement probability). The SDF calculations were performed again after the first block to optimize the minimum and maximum probe durations for the second block (across participants, on average, minimum and maximum probe duration was 165.25 ms, and 340.70 ms, respectively). For quality control, the main effect of RP and of socialness on omissions and premature responses was tested with a non-parametric Friedman test, as their residuals did not follow a normal distribution. As expected, high-RP showed fewer omissions [χ^2 (1) = 12.45, $p < .001$], and more premature responses [χ^2 (1) = 6.75, $p = .009$] than low-RP stimuli; with no main effects of socialness.

2.5. Stimuli

There were two blocks of 80 trials each. Each of the 40 unique stimuli were presented in both blocks, once in each block. The social stimuli consisted of 20 pictures of fearful faces (10 male and 10 female, all white Caucasian), obtained from the "Warsaw Set of Emotional Facial

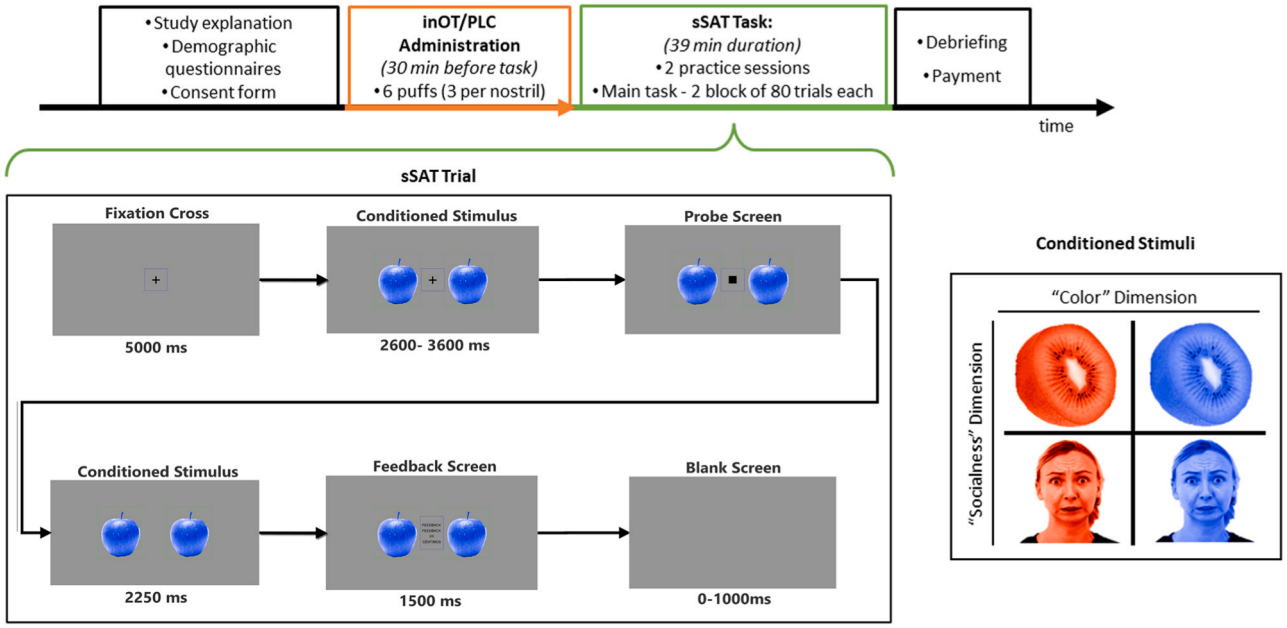

Fig. 1. Top: Outline of an experimental session. Bottom left: Outline of an sSAT trial: participants were presented with stimuli on either side of the fixation cross. A probe (black square) then replaced the fixation cross, and participants were required to respond to it as quickly as possible via button press. The response was followed by an outcome message. Bottom right: Example of the four types of conditioned stimuli, divided according to their visual dimensions: colour (blue/red) and socialness (face/fruit), each colour being associated with a high or low (counterbalanced between subjects) reinforcement probability.

Expression Pictures", selected based on their purity score (i.e., if the emotion being displayed was evident rather than mixed with other emotions) (Olszanowski et al., 2015). We selected the fearful facial expression because – among all emotions - it is the one most repeatedly shown to elicit a response to inOT - and has, for this reason, also been commonly the focus in studies of the neural effects of inOT (Kirsch et al., 2005; Domes et al., 2007; Petrovic et al., 2008; Eckstein et al., 2015; Kanat et al., 2015; Tully et al., 2018, 2023). Adding other emotions would have increased the task length over 40 min which would be too tiring to participants (please see also our "Limitations" section). Non-social stimuli consisted of 20 pictures of different fruits obtained from the Google Images website. We have chosen fruits as non-social stimuli, instead of the commonly used cars and houses, given: 1) their more ubiquitous presence and motivational/survival value across human evolutionary times, *en par* with faces; 2) their similarity in shape and complexity to faces; and 3) absence of potential anthropomorphic facial characteristics. All pictures were selected and/or equalized (no differences at $p < .05$; female vs. male, faces vs. fruits, and red vs. blue) for: luminance (using the mean value of the image when converted to grayscale with rgb2gray Matlab function, and adjusted in Photopea); complexity (combining several features (Corchs et al., 2016)); and coverage (i.e., percentage of pixels which were not background).

2.6. Drug administration

Participants self-administered a nasal spray containing 24 IU of inOT (AlfaSigma, Bologna, Italy) or placebo (VolksApotheke Schffhausen, Switzerland), following recommendations described elsewhere (Guastella et al., 2013). The spray bottles were blinded in Santa Maria pharmacy and were refrigerated until 1-hour maximum before administration. For details of the administration procedure, see Supplementary Material B. Drug groups did not differ significantly ($p < .05$) in age, or the digit span test scores, anxiety state, or empathy scores (total or its domains of cognitive empathy, emotional reactivity, social skills, and empathic difficulties), with results details in the Supplementary Material B. At the end of the experimental session, participants were asked what they thought had been administered to them (i.e., placebo or an active component), so we could ascertain that they had not been able to distinguish between them. Indeed, participants responses' did not depend on the real random drug group allocation [χ^2 (1) = .02, $p = .893$].

2.7. Behavioural data acquisition and analysis

For RT analysis, we first analysed only 'reactive' responses, i.e. happening after 100 ms since the probe's onset, as typically done in SAT studies (Whelan, 2008; Roiser et al., 2009). In a second analysis, we additionally included anticipatory (from 0 to 100 ms, N = 54) and premature responses (N = 434), given the possibility that participants might be responding faster to high-RP (vs. low-RP) *mostly* very early on, before the appearance of the probe. The SRP score was averaged across the two blocks. Once obtained, individuals' RT and SRP scores were grouped according to their stimulus' RP (high or low) regardless of their colour.

2.8. EEG data acquisition and preprocessing

Electrophysiological data was recorded at a 1000 Hz sampling rate with the BrainVision system (Brain Products, Munich, Germany), consisting of a 64-electrode ActiCap and BrainChamp amplifier, and FCz as the reference and AFz as the ground electrodes. Electrode impedance levels were maintained under 30 kΩ. EEG data was preprocessed using EEGLAB toolbox functions (Delorme & Makeig, 2004) developed for Matlab (Mathworks, Natick, Massachusetts) and analysed using our customised routines. Continuous data was down-sampled to 250 Hz and filtered with a 0.1 Hz edge high-pass (cutoff frequency: 0.05) and 40 Hz edge low-pass (cutoff: 45 Hz) zero-phase Hamming windowed sinc FIR filter, non-casual.

Bad channels were manually inspected and rejected, and data was re-referenced offline to the average. Next, EEG data was segmented into epochs relative to the onset of the stimuli (faces or fruits), from 100 ms pre-stimulus to 1500 ms post-stimulus onset. Bad epochs were also manually inspected and rejected, and artifact correction was performed using Independent Component Analysis (ICA) (Runica algorithm) for

detection and removal of eye-related movement and noise (muscle and channel noise activity). The removed electrodes were interpolated using the spherical spline interpolation method. This was followed by baseline correction using a pre-stimulus period (−100 to 0 ms) and, finally, the extraction of ERP amplitudes and latencies. The total average number of trials retained per participant is 154.5 (38 trials per condition on average), the average number of electrodes removed is 1.2 and the average number of ICs removed is 3.3.

The choice of electrodes and time-windows for the ERPs of interest was based on previous literature and visual inspection of grand-averaged data collapsed across experimental conditions ("collapsed localizers" approach) (Brooks and Zoumpoulaki, 2016; Luck and Gaspelin, 2017) (see Supplementary Figure 1 of Supplementary Material C). Based on this approach, electrodes were selected for the ERPs: P1 (electrodes P5/6/7/8, PO3/4/7/8, O1/2), N170 (electrodes O1/2, P4/5/6/7/8, PO3/4/7/8, CP6, TP8/9/10), P2b (electrodes Oz/1/2, POz/3/4/7/8), P3b (electrodes Pz/1/2/4/6/8, POz/3/4/8) and LPP (electrodes Pz/1/2, POz, CPz/2/4). Local peak amplitudes were extracted time-locked to stimulus onset for the components: P1 (time--window: 70–140 ms), N1/N170 (time-window: 120–200 ms), P2b (time-window: 195–295 ms), P3b (time-window: 310–600 ms) and LPP (time-window: 600–1500 ms). Mean amplitudes over the time-window were calculated for LPP, while local peak amplitudes, defined as the largest point in the time-window that is surrounded by lower voltages on both sides (Luck, 2005), were calculated for P1, N170, P2 and P3b. We measured the amplitude around the individually defined local peak to allow for a more precise measurement of its amplitude and latency. For a given condition, the peak was identified in a trial-averaged waveform for each participant, within the time-window of interest. Subsequently, the mean amplitude was measured around that peak, according to its width. The peak's width corresponded to a horizontal reference line positioned at half of the peak's height. This starting point of the reference line to the left of the local peak also served as a measure of the peak's latency, calculated for each of the components (N170, P2b and P3b), known as the fractional peak latency measure (Kiesel et al., 2008). If there was more than one local peak detected in the component's time-window, the largest was chosen; if no peaks were detected, an average amplitude from the entire time-window was calculated in its place.

2.9. Statistical analysis

We used a mixed repeated-measures analysis of variance (rmANOVA), with socialness (social, non-social) and RP (low-RP, high-RP) as within-subject factors, and drug (inOT, placebo) as a between-subject factor, to estimate the corresponding main and interactions effects on: 1) behavioural measures (as secondary/complementary measures): mean RT and mean SRP scores, 2) neural amplitudes measures (as primary measures): local peak P1, N170, P2b, P3b amplitudes and mean LPP amplitudes, as well as, 3) N170, P2b and P3b latencies (as secondary/complementary measures). All statistical analyses were performed using SPSS software (Version 24, IBM SPSS Inc.). Given that all five ERPs were pre-selected based on previous evidence in the literature (of inOT and/or saliency effects), and we do not perform comparisons outside a significant prior omnibus test, we have not applied corrections for multiple comparisons, and accepted a false positive rate of 5%. Interaction effects were followed by pairwise t-test comparisons. In the latency analysis, we could not obtain latency measures due to non-detectable peaks in some participants: 11 subjects for N170, two for P2b and P3b. Thus, further five (for N170) and three (for P2b and P3b) subjects – in addition to the abovementioned 5 excluded for all EEG analyses - were removed in order to exactly match drug groups in terms of task version (i.e. color being reinforced). To assess differences in the proportion of missing data (which happened for the latency analyses; or replacement with average data for the amplitude analyses) between conditions, we used a Chi-square test which retrieved a lower proportion in social vs. non-social stimuli [χ^2 (1) = 5.25, p = .022] (and no significant difference between high-RP and low-RP stimuli [χ^2 (1) = .98, p = .322]) for N170 (see Supplementary Material E for P2b and P3b data, where these were not significant, $p < .05$). However, there were no significant differences between drug groups, in the proportion of missing data for social stimuli [χ^2 (1) = .44, p = .509] or non-social stimuli [χ^2 (1) = .22, p = 637] for N170. To ascertain whether there were differences between the drug groups in terms of age, digit span, anxiety state and empathy scores, we used an independent sample t-test. Finally, for quality control, the main effect of RP and of socialness on omissions and premature responses was tested with a non-parametric Friedman test, as their residuals did not follow a normal distribution, and we used a Chi-square test for independence to make sure participants were not able to guess which drug was administered to them.

3. Results

Means and standard deviations of all behavioural and ERP measures, and details of the behavioural analysis are provided in Supplementary Material D, while the main results' full statistics are provided in Table 1.

3.1. Behavioural

3.1.1. Reaction time

No significant main or interaction effects of RP, socialness or drug were found on reactive RTs (i.e., restricting to only 100 ms after onset). However, a main effect of RP on RT of all response types (including reactive, anticipatory and premature) was found [F (1, 52) = 6.82, $p = .012$, $\eta_p^2 = .12$], with participants responding faster to high-RP vs. low-RP stimuli. We also found a main effect of socialness on RT including all response types [F (1, 52) = 5.58, $p = .022$, $\eta_p^2 = .10$), with participants responding faster to non-social vs. social stimuli.

3.1.2. Subjective reinforcement probability

We found no statistically significant effect of drug or socialness, nor their interaction, on SRP. A main effect of RP on SRP scores was found [F (1, 52) = 395.36, $p < .001$, $\eta_p^2 = .88$], with participants giving higher scores for high-RP in comparison to low-RP stimuli (Supplementary Table 2 of Supplementary Material D).

3.2. Event related potentials

3.2.1. P1 amplitude

No significant main or interaction effects were found on P1 amplitude.

3.2.2. N170 amplitude and latency

A main effect of drug on N170 amplitude was found [F (1, 52) = 4.40, $p = .041$, $\eta_p^2 = .08$], with increased amplitudes for inOT vs. placebo [Fig. 2*A*]. A main effect of socialness was also found on N170 amplitude [F (1, 52) = 100.75, $p < .001$, $\eta_p^2 = .66$], with increased amplitudes for social vs. non-social stimuli. (As a post-hoc exploration, we examined if this amplitude was correlated with RT, but such did not reach statistical significance at $p < .05$; data not shown.) Similarly, a main effect of socialness was found on N170 latency [F (1, 52) = 41.40, $p < .001$, $\eta_p^2 = .52$], with shorter latencies for social vs. non-social stimuli.

3.2.3. P2b amplitude and latency

A main effect of socialness was found on P2b amplitude [F (1, 52) = 12.94, $p < .001$, $\eta_p^2 = .20$], with increased amplitudes for non-social vs. social stimuli [Fig. 3*B*]. A main effect of drug on P2b latency was found [F (1, 52) = 16.49, $p < .001$, $\eta_p^2 = .26$], with increased latencies for inOT vs. placebo [Fig. 2*B*].

Table 1
Statistics for all main effects and interactions of drug (intranasal oxytocin, inOT), socialness and reinforcement probability (RP) on electroencephalography event-related potentials amplitude/latency. *p < .05; * *p < .001.

Measure	Effect	F (df)	p-value	η_p^2
P1 Amplitude	Drug	.09 (52)	.764	< .01
	Socialness	3.21 (52)	.079	.06
	RP	1.07 (52)	.306	.02
	Socialness x Drug	.24 (52)	.627	.01
	RP x Drug	1.14 (52)	.291	.02
	Socialness x RP	3.91 (52)	.053	.07
	Socialness x RP x Drug	.49 (52)	.489	.01
N170 Amplitude	**Drug**	**4.40 (52)**	**.041 * (inOT > placebo)**	**.08**
	Socialness	**100.75 (52)**	**< .001 * * (social > non-social)**	**.66**
	RP	.18 (52)	.673	< .01
	Socialness x Drug	.79 (52)	.378	.02
	RP x Drug	3.34 (52)	.073	.06
	Socialness x RP	.06 (52)	.808	< .01
	Socialness x RP x Drug	.13 (52)	.719	< .01
N170 Latency	Drug	.32 (38)	.578	.01
	Socialness	**41.40 (38)**	**< .001 * *(social < non-social)**	**.52**
	RP	2.13 (38)	.152	.05
	Socialness x Drug	.69 (38)	.412	.02
	RP x Drug	.04 (38)	.850	< .01
	Socialness x RP	.46 (38)	.501	.01
	Socialness x RP x Drug	.19 (38)	.668	.01
P2b Amplitude	Drug	1.06 (52)	.307	.02
	Socialness	**12.94 (52)**	**< .001 * * (non-social > social)**	**.20**
	RP	.24 (52)	.627	.01
	Socialness x Drug	.27 (52)	.606	.01
	RP x Drug	2.03 (52)	.160	.04
	Socialness x RP	.84 (52)	.363	.02
	Socialness x RP x Drug	<.001 (52)	.988	< .001
P2b Latency	**Drug**	**16.49 (48)**	**< .001 * * (inOT > placebo)**	**.26**
	Socialness	1.67 (48)	.202	.03
	RP	.33 (48)	.568	.01
	Socialness x Drug	.54 (48)	.466	.01
	RP x Drug	<.001 (48)	.998	< .001
	Socialness x RP	1.25 (48)	.270	.03
	Socialness x RP x Drug	.24 (48)	.628	.01
P3b Amplitude	Drug	.14 (52)	.712	< .01
	Socialness	**11.03 (52)**	**.002 * (non-social > social)**	**.18**
	Reinforcement probability	**19.15 (52)**	**< .001 * * (high-RP > low-RP)**	**.27**
	Socialness x Drug	1.30 (52)	.260	.02
	RP x Drug	.33 (52)	.567	.01
	Socialness x RP	.84 (52)	.363	.02
	Socialness x RP x Drug	.58 (52)	.451	.01
P3b Latency	Drug	2.71 (48)	.106	.05
	Socialness	3.93 (48)	.053	.08
	RP	.32 (48)	.575	.01
	Socialness x Drug	.64 (48)	.427	.01
	RP x Drug	.01 (48)	.933	< .001
	Socialness x RP	1.52 (48)	.224	< .01
	Socialness x RP x Drug	<.001 (48)	.989	< .001
LPP Amplitude	Drug	1.01 (52)	.319	.02
	Socialness	**8.76 (52)**	**.005 * (social > non-social)**	**.14**
	RP	2.09 (52)	.155	.04
	Socialness x Drug	.20 (52)	.657	< .01
	RP x Drug	1.23 (52)	.272	.02
	Socialness x RP	**7.23 (52)**	**.010 * (in non-social: high-RP > low-RP; in social: no sign. diff.)**	**.12**
	Socialness x RP x Drug	.19 (52)	.661	< .01

3.2.4. P3b amplitude and latency

A main effect of socialness was found on P3b amplitude [F (1, 52) = 11.03, $p = .002$, $\eta_p^2 = .18$], with increased amplitudes for non-social vs. social stimuli. A main effect of RP on P3b amplitude [F (1, 52) = 19.15, $p < .001$, $\eta_p^2 = .27$] was also found, with increased amplitudes for high-RP vs. low-RP stimuli [Fig. 3*C*]. There were no significant main effects or interactions on P3b latency.

3.2.5. LPP amplitude

We found a main effect of socialness on LPP amplitude [F (1, 52) = 8.76, $p = .005$, $\eta_p^2 = .14$], with increased amplitudes for social vs. non-social stimuli. A socialness x RP interaction was also present [F (1, 52) = 7.23, $p = .010$, $\eta_p^2 = .12$]. Pairwise comparisons revealed increased amplitudes for high-RP vs. low-RP ($p = .014$, $\eta_p^2 = .11$), but only for non-social stimuli [Fig. 3*A*].

4. Discussion

In this study, we investigated OT's role in salience attribution processing, by using a reinforcement learning task to determine whether inOT affects the processing of predominantly social stimuli (as posited by the social salience hypothesis, and in this case, the fearful facial expression), generally relevant stimuli (as posited by the general approach-withdrawal hypothesis), and/or following the time-course pattern posited by the TRIO hypothesis. To our knowledge, this is the first study examining inOT's effects on social and non-social stimuli processing whilst controlling for their relevance (i.e., where the fear-related socialness and RP variables are orthogonalized), thus allowing

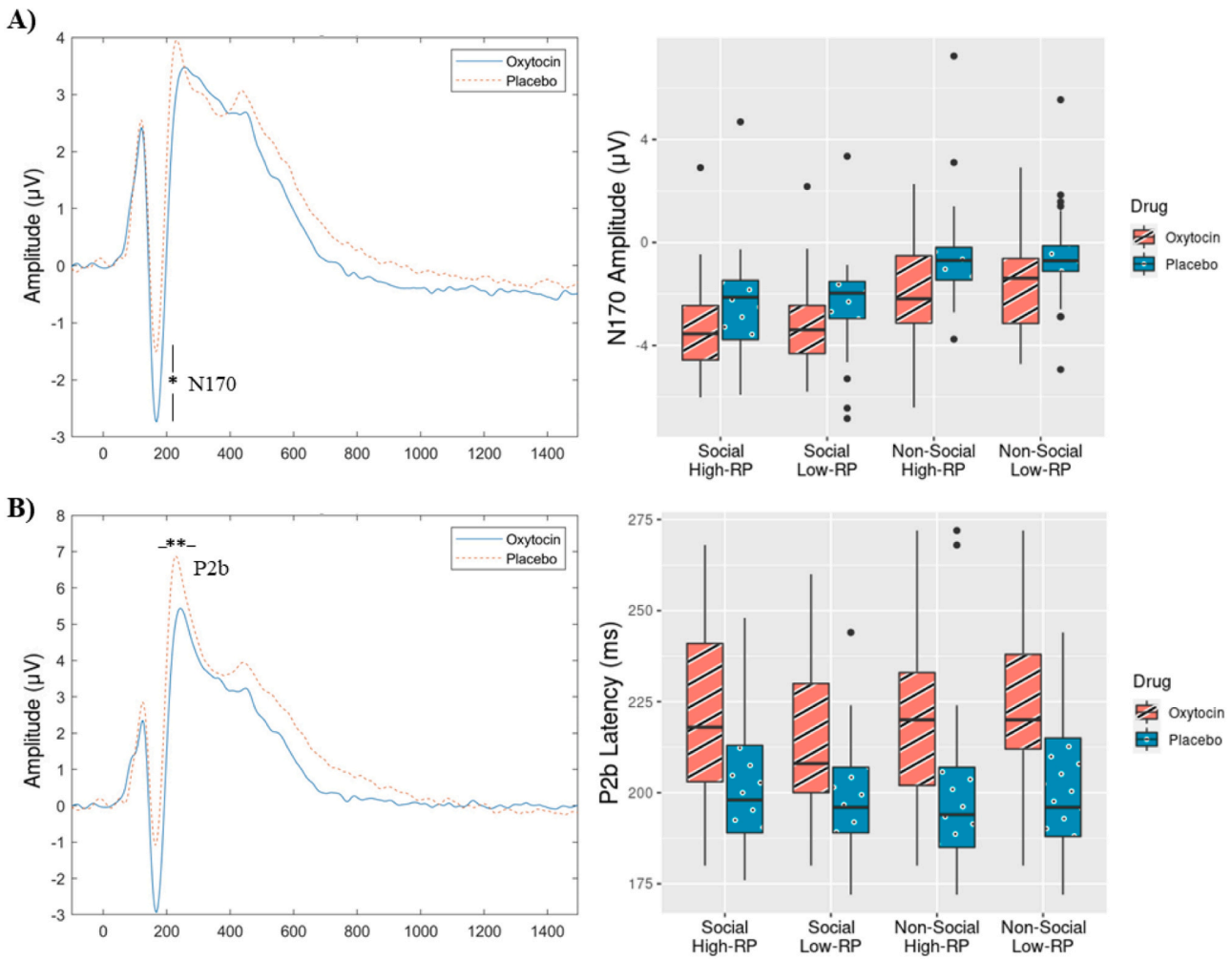

Fig. 2. Main effects of drug (intranasal oxytocin, inOT vs. placebo) in N170 amplitude and P2b latency, at $p < .05$. A) Graph with mean N170 amplitudes (in μV), showing increased N170 for inOT vs. placebo, and boxplots for all conditions. B) Graph with mean P2 amplitudes (in μV), showing increased P2 latency (in ms) for inOT vs. placebo, and boxplots for all conditions. *$p < .05$; * *$p < .001$.

for a fair juxtaposition of these hypotheses; and the EEG of the SAT paradigm. In summary, and as discussed below, our ERP findings revealed a global main effect of inOT (i.e., independent of fear-related socialness and RP) in ERPs during the early stages of salience attribution processing (N170 amplitude and P2b latency). Additionally, we also detected inOT-independent effects: general socialness effects throughout salience attribution processing (N170, P2b and P3b), which later became dependent on RP (LPP). As such, our results partially support the TRIO hypothesis but not the general approach/withdrawal hypothesis or the social salience hypothesis.

4.1. Oxytocin's effect on ERPs may be independent of (fear-related) socialness and reinforcement probability in early salience attribution processing – in support of the TRIO hypothesis

Our main findings of a global (i.e., main) effect of inOT on ERPs during the early stage of salience attribution, showed inOT (vs. placebo) eliciting larger N170 amplitudes and longer P2b latencies, regardless of socialness or RP. The main effect of drug on ERP measures explained a medium 8% and a large 26% of the variance for, respectively, N170 amplitude and P2b latency (left unexplained by socialness or RP or their possible interactions). This may suggest OT's role is larger in processing speed or efficiency (generally indexed by latency) rather than in the extension of the allocation of neural resources (generally indexed by amplitude).

The increase in the face-sensitive N170 (Eimer, 2011) is consistent with two previous studies showing inOT (vs. placebo) increased N170 amplitudes in a facial emotion categorization task (for both happy and sad faces) (Peltola et al., 2018), and in a flanker task for facial stimuli (both for happiness and disgust) (Huffmeijer et al., 2013). [Nevertheless, we note that as our finding's statistical significance was relatively low ($p = 0.041$), it would not have survived Bonferroni correction for multiple testing of the ERPs investigated ($N = 5$), which would have set the significance threshold to $p = .01$, and thus should be re-interpreted when further evidence is available.] Notably, the above studies have not used non-facial stimuli, but indeed our results show the same effect for both non-social and social stimuli. Thus, although N170 amplitude has been repeatedly shown to be increased by socialness, i.e., processing of faces versus non-facial images (Eimer, 2011), the increase facilitated by inOT did not depend on socialness (nor motivational relevance, i.e. RP of the stimuli) in our study and may thus reflect a more general-purpose increase of an early stage of salience attribution processing. As such, we speculate that this general increase in amplitude might reflect increased cognitive resources dedicated to evaluating the relevance of the stimuli's qualities in terms of their motivational/rewarding value, under inOT.

While there are no previous studies linking P2b latency and inOT, the increased posterior P2 (P2b) latency may suggest inOT induced slower processing at an early-mid stage of salience attribution. This is consistent with a study showing slower RTs for highly salient loss trials, under

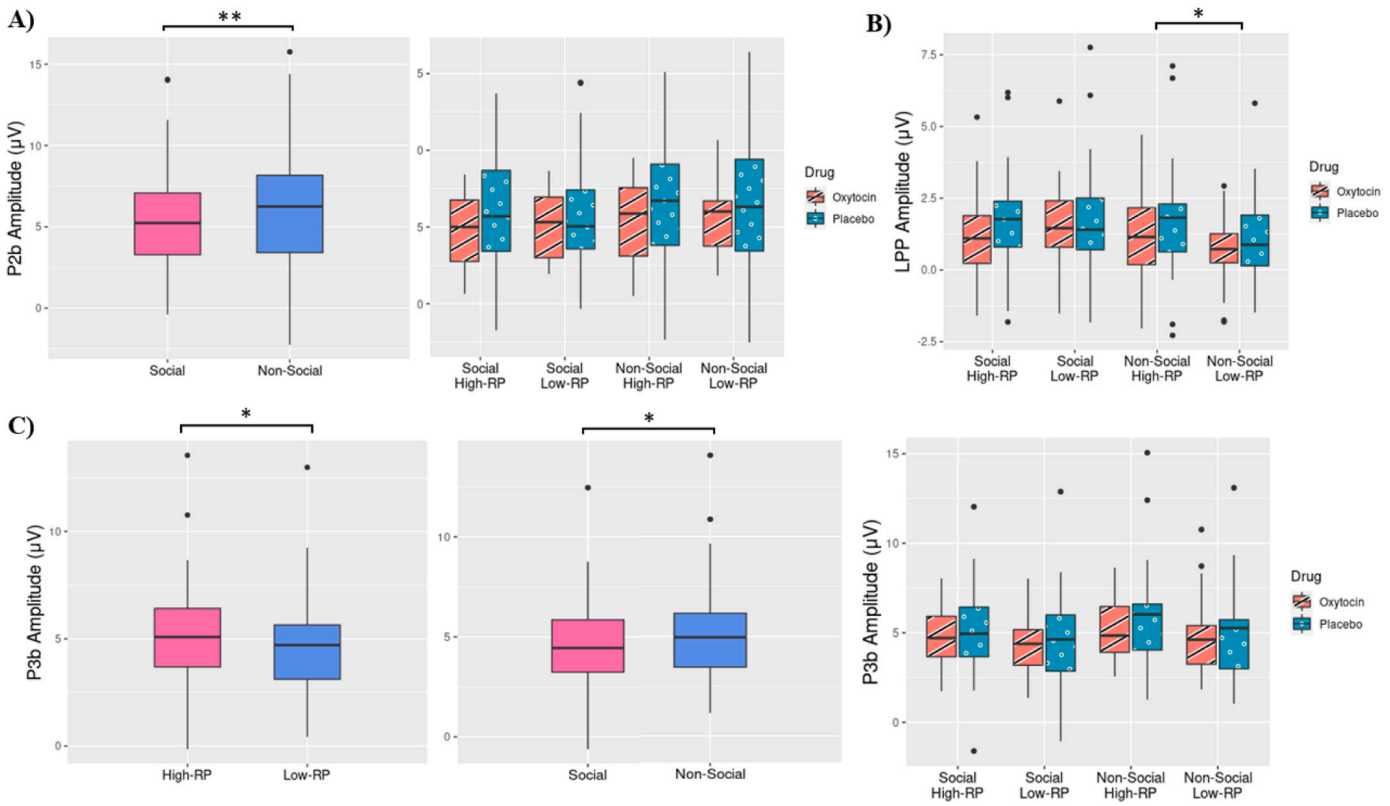

Fig. 3. Some main and interaction effects of socialness and reinforcement probability (RP), at $p < .05$. A) Boxplots with mean LPP amplitudes (in μV) as a function of all conditions, showcasing a socialness by RP interaction (increased LPP in non-social high-RP vs. non-social low-RP conditions, with no such effect in social conditions). B) Boxplots with mean P2b amplitude (in μV) showing increased P2b for non-social (vs. social) stimuli, and P2b as a function of all conditions. C) Boxplots with mean P3b amplitudes (in μV) showing increased P3b for non-social (vs. social) stimuli, increased P3b for high-RP (vs-low-RP) stimuli, and P3b as a function of all conditions. *$p < .05$; * *$p < .001$.

inOT (Mickey et al., 2016). The fact that P2 latency has also been previously shown to increase for hardly vs. easily categorizable stimuli (Pernet et al., 2003) may mean that inOT increased the level of salience attributed to the stimuli (social or not) in terms of time spent cognitively processing them. An alternative, but non-mutually exclusive, explanation for this slow-down effect is that inOT might have decreased anticipatory anxiety regarding the probe's appearance (since our participants anticipated to have to turn their attention to the probe at some point after the stimuli's appearance). Indeed, although in different experimental paradigms, inOT has been shown to reduce anxiety (Bartz et al., 2011) and, in particular, anticipatory anxiety (de Oliveira et al., 2012). (Rather than this occipital P2 (P2b) which has been associated with perceptual salience (Straube et al., 2010), the two studies that have reported significant inOT effects in the selection stage found a frontal effect (via P2a) (Liu et al., 2013; Sheng et al., 2013), but see (Waller et al., 2015) for null effect), which has been previously associated with motivational salience (Riis et al., 2010).).

The above results, of inOT-increased N170 amplitude and P2b latency, partly support the TRIO hypothesis, which posits OT increases salience of stimuli regardless of their characteristics (socialness, valence) in an early perception stage (Pehlivanoglu et al., 2020). However, TRIO also posits that OT increases the salience selectively toward social over non-social stimuli in later stages, namely the so-called selection (200–300 ms) and evaluation stages (> 300 ms). However, we did not find evidence for such social specificity of inOT effects in mid and late stages.

A possible explanation as to why we did not see social-specific inOT effects at the latter stages may be that self-related processing and empathy towards in-group members - which TRIO posits to stem from the selection stage (Pehlivanoglu et al., 2020) - are likely not present during sSAT. Similarly, in evaluation stages, inOT effects have previously not been found on P3b (Sheng et al., 2013; Ruissen and de Bruijn, 2015), which is consistent with our (lack of) results. In terms of LPP, the fact that we have not found inOT effects is likely, again, to be due to the sSAT not eliciting cognitive processes suggested by the TRIO in the evaluation stage, whereby OT is posited to shift the focus to other-related information (over self-related) and out-group members (over in-group) (Pehlivanoglu et al., 2020). Indeed, significant inOT effects have so far been found for trait judgement (of self and others) (Liu et al., 2013), in- vs. out-group membership (Herzmann et al., 2013), and during passive viewing (of houses and scenes) (Althaus et al., 2015, 2016). On the other hand, inOT has elicited larger LPP amplitudes for faces in a flanker task with emotional feedback (happy and disgusted faces) (Huffmeijer et al., 2013), but our ERPs were stimulus-locked and not feedback-locked, which might explain the discrepancy of results. Indeed, no effects of inOT on LPP were found with a facial emotion categorization task (Peltola et al., 2018), or a cyberball game (social vs. non-social context) (Petereit et al., 2019) or another passive viewing study (of houses, infant and adult faces) (Rutherford et al., 2017). Taken together, these results contribute to the evidence that inOT effects vary according to context (Bartz et al., 2011), particularly in mid-late stages of salience attribution processing.

4.2. Fear-related socialness and reinforcement probability may affect salience processing, regardless of oxytocin

Starting with the early ERP components, we found P1 amplitude was not affected by the socialness, reinforcement probability or drug. The lack of drug effects is in line with a previous study showing decreased P1 amplitude in woman, under OT (vs. placebo), but no drug effect was

present in men (Schiller et al., 2023). P1 amplitude has also been associated with face processing (Itier and Taylor, 2004) and early attentional processing (Taylor, 2002), it is an ERP sensitive to low-level characteristics (e.g., luminance) (Johannes et al., 1995). Our lack of socialness and RP effects suggest that: 1) participants were paying attention to all of the stimuli, in a very early stage, probably in order to learn stimuli-reward associations and 2) we were able to reasonably match social and non-social stimuli for their low-level properties. We also found that: 1) N170 amplitude was increased for social in relation to non-social stimuli, as expected given that N170 face-sensitivity is a robust finding in the literature (Eimer, 2011); and 2) N170 latency decreased for social vs. non-social stimuli, also in accordance with the literature, suggesting faster processing of the former (Pascalis and Kelly, 2008). However, we did not see a similar effect of RP on N170 amplitude, unlike other studies that have shown an increase for task-relevant (vs. task-irrelevant) stimuli, irrespective of their socialness (Schreppel et al., 2008; Biehl et al., 2013) which could be due to the largely different task designs: (Biehl et al., 2013) and (Schreppel et al., 2008) have used a 1-back task presenting relevant and irrelevant stimuli alternatively, with faces relevant or scenes/houses relevant. In our sSAT paradigm design, relevant and irrelevant stimuli were presented in a randomized order, and the stimuli (fearful faces and fruits) were the same for relevant and irrelevant conditions, differing only in colour (which was a proxy of relevance). Additionally, social and non-social stimuli were equally reinforced (i.e., equally relevant for the task performance).

Our results also showed social stimuli to be perceived as more salient than non-social, as expected, via a decreased P2b amplitude. Consistent with this, decreased P2b amplitude has been associated with increased levels of attention (Crowley and Colrain, 2004) and increased perceptual salience (Straube et al., 2010). Moreover, P2b amplitudes have also been shown to be increased for non-facial stimuli in relation to facial stimuli (Latinus and Taylor, 2006).

In the late-stage processing, we found increased P3b amplitudes for high-RP compared to low-RP, as expected. This ERP is generally considered to reflect top-down and capacity-limited allocation of neural resources and subsequent memory context-updating processes (Polich, 2007). In accordance with our finding, it has been shown to be sensitive to incentive value, with increased amplitudes in response to more rewarding stimuli (Luque et al., 2015). However, unexpectedly, as this ERP amplitude is also associated with attentional resource allocation (Polich, 2007), and social stimuli are typically more salient than non-social stimuli, we found increased P3b amplitudes for non-social compared to social stimuli. Since participants were paying more attention to social (vs. non-social stimuli) at early-mid processing stages (P2b amplitude), and at later stages, participants were getting closer to the moment when they needed to respond to the probe, this decreased in P3b amplitude might reflect an adjustment effort to stop attending to the more salient, and potentially distracting, social stimuli and perform the task accordingly. In the latest processing stage (i.e., for LPP), we found increased amplitudes for high-RP compared to low-RP, when stimuli were non-social. This is in line with previous evidence which has associated LPP with sustained attention to motivationally salient stimuli (Hajcak et al., 2010), as well as incentive and predictive value (Luque et al., 2015). However, we did not see this effect for social stimuli, suggesting social stimuli might have been motivationally salient to the point of producing a ceiling effect on LPP, with no distinction between low- and high-RP.

4.3. *In a social salience attribution task, reinforcement probability can be correctly inferred, and impulsive behaviour detected in high reinforcement probability trials*

Behaviourally, SRP scores showed that participants scored high-RP as more rewarding than low-RP stimuli, assuring that they correctly learned the stimulus-reward association. (This observation combined with the fact socialness did not affect the SRP score, is also reassuring in that it indicates that the effect of RP and socialness could be dissociated at least at the behavioural level.) Also, subjects performed significantly better (fewer omissions) and more impulsively (more premature responses) in high-RP vs. low-RP, as expected. Indeed, when we considered all response types including anticipatory and premature (i.e. pre-probe) responses (but not when we did not), participants responded faster to high-RP (vs. low-RP) stimuli, suggesting higher impulsivity (but not higher reactivity to the probe) associated to RP. The absence of an effect of RP on reactive RT could be due to our stimuli (faces and fruits, in sSAT) being more intrinsically salient than those in the original SAT version (animals and household objects), which might have made participants more attentive to the stimuli in general, reducing any reactive RT differences in the high-RP conditions due to a ceiling effect. When including all RT resposte types, we also found participants responded faster (i.e. in pressing the button) when non-social (vs. social stimuli) were presented. This is consistent with neural results showing social stimuli were more salient and participants allocated more attentional resources to them (P2b amplitude), and thus less to the probe resulting in slower responses. This means that even though socialness was task-irrelevant, participants would have been more distracted by faces than fruits, at the time of attending to the probe. The fact that this effect of socialness was not seen when only reactive RTs were considered supports the above interpretation of P3b amplitude, whereby participants adjusted social stimuli processing. In sum, the fact that social stimuli were more salient and potentially more distracting, seems to have lead to an increase in impulsivity but did not translate into performance costs, as they showed equal reactivity to the probe in the presence of social and non-social stimuli.

Regarding inOT, we did not find it to influence RT or SRP scores suggesting behavioural effects of the drug, if any, might be subtle. Indeed, behavioural studies focused on facial emotion processing show weak and inconsistent results (Leppanen et al., 2017). They point towards inOT improving recognition of emotions, particularly fear (Leppanen et al., 2017), but as this is not required during the sSAT, our findings are not comparable. On the other hand, our results are consistent with three studies showing no effects of inOT on RT during a reward task involving monetary reward (Nawijn et al., 2016), social reward (Groppe et al., 2013), and both (Mayer et al., 2021), albeit not with a reward study showing inOT decreased RT during high-salience loss trials (Mickey et al., 2016). These studies varied in the sex studied: one had only female participants (Groppe et al., 2013), the other two had both male and female (Mayer et al., 2021; Nawijn et al., 2016), and the positive results' study had only male participants (Mickey et al., 2016). Given that our population was of the same sex as the latter study's, the discrepancy between our results might be due methodological differences, namely that they used a within-subject design ($N = 18$), while we had a between-subject design ($N = 54$), and the inclusion of gain/loss trials, while we only included reward and no reward.

4.4. *Limitations*

Our results have limited generalizability due to our attempt to: 1) reduce noise arising from demographic variability (only young, heterosexual male participants of European Portuguese ethnicity were included) as inOT's effect has shown to be dependent on sex and age (Bartz et al., 2011) at least; 2) prevent participants' tiredness due to experimental session length at the cost of using a variety of facial emotion expression categories and of non-social item categories (as detailed in Methods). The later limitation means that effects of socialness in our study pertain to social fearfulness in specific, and may not be extrapolatable to other socio-emotional expressions. Also, although we have purposefully attempted to balance social and non-social stimuli for their motivational (task-)relevance via our RP manipulation, we did not balance them for emotion evocativeness. In natural settings, social stimuli (vs. non-social) tend to be more emotionally-evocative than

fruits. As such, the (main) effects of socialness we found (on N170 amplitude and latency, P2b amplitude and P3b amplitude) could theoretically have been confounded by emotion. We cannot exclude this possibility for N170 amplitude, as there is previous evidence that N170 amplitudes are greater for emotional facial expressions (anger, fear and happy) compared to neutral (Hinojosa et al., 2015). However, a confounding effect could not have been the case for both P2b or P3b, since previous evidence has been for greater amplitudes for emotional stimuli compared to neutral, whilst we found a socialness effect in the opposite direction (i.e. higher amplitudes for the non-social vs social stimuli). As such, our results for P2b (Delplanque et al., 2004; Dennis and Chen, 2007) and P3b (Hajcak et al., 2010; Hajcak and Foti, 2020) are not confounded by emotion. Regarding N170, we note that there was a lower proportion of missing data in social stimuli than non-social, and as such we cannot exclude the possibility that that has contributed to the statistically significant higher latency and lower amplitude in non-social stimuli (vs. social); nevertheless while the missing data effect had a significance of $p = .022$, the latency/amplitude effect was several orders of magnitude higher ($p < .001$), and thus we think it is unlikely the former would have explained the latter. Another limitation is the fact that the sSAT did not elicit mid-late latency ERPs that have been shown to be affected by inOT in a social-specific way (P2a, P3a) (Herzmann et al., 2013; Liu et al., 2013; Sheng et al., 2013; Althaus et al., 2015, 2016), probably due to its probe-focused design (opposed to stimulus-focused), and which could be a reason for the lack of support for current OT hypotheses: the social salience and the general approach-withdrawal hypotheses of OT. These theories would predict a 'drug x socialness' and 'drug x RP' interaction, respectively, neither of which were found on the ERPs we analysed, at least as medium-sized effects of OT which our study was powered for.

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CRediT authorship contribution statement

Kosilo Maciej: Data curation, Formal analysis, Methodology, Supervision, Writing – original draft. **Cogoni Carlotta:** Methodology. **Santiago Andreia:** Formal analysis, Investigation, Writing – original draft. **Prata Diana:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Diogo Vasco:** Data curation, Methodology, Writing – review & editing. **Jerónimo Rita:** Writing – review & editing.

Declaration of Competing Interest

All authors declare no conflict of interest.

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Author contributions

AS was involved in data collection, ran the statistical analysis and co-drafted the manuscript. MK co-designed experimental protocols and managed data collection, collected the data, designed and supervised data analysis and co-drafted the manuscript. CC co-designed the experiment and experimental protocols. VD was involved in task design and data collection. RJ contributed to the interpretation of results and study design. DP co-drafted the manuscript, and supervised all stages of the study, from design to publication. All authors contributed to results interpretation, critically revised the manuscript, and approved its final version.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psyneuen.2023.106950.

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