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Your presence soothes me: a neural process model of aversive emotion regulation via social buffering

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Abstract

The reduction of aversive emotions by a conspecific's presence—called social buffering—is a universal phenomenon in the mammalian world and a powerful form of human social emotion regulation. Animal and human studies on neural pathways underlying social buffering typically examined physiological reactions or regional brain activations. However, direct links between emotional and social stimuli, distinct neural processes and behavioural outcomes are still missing. Using data of 27 female participants, the current study delineated a large-scale process model of social buffering's neural underpinnings, connecting changes in neural activity to emotional behaviour by means of voxel-wise multilevel mediation analysis. Our results confirmed that three processes underlie human social buffering: (i) social support-related reduction of activity in the orbitofrontal cortex, ventromedial and dorsolateral prefrontal cortices, anterior and mid-cingulate; (ii) downregulation of aversive emotion-induced brain activity in the superficial cortex-like amygdala and mediodorsal thalamus; and (iii) downregulation of reported aversive feelings. Results of the current study provide evidence for a distinct neural process model of aversive emotion regulation in humans by social buffering.

Key words: social buffering; social support; social emotion regulation; mediation analysis; fMRI

Introduction

Social buffering, the phenomenon by which the simple presence of a conspecific reduces responses to negative stimuli, is universal in the mammalian world (Hostinar *et al.*, 2014; Kiyokawa and Hennessy, 2018). In humans, even with our ability to regulate another's emotional state using language-based strategies, simple supportive presence (the so-called social support) remains a fundamental and powerful form of social emotion regulation (Coan, 2011; Zaki and Williams, 2013). Considering its relevance, various animal and human studies have investigated social buffering (for reviews, see Eisenberger, 2013; Hostinar *et al.*, 2014). Human studies found that viewing pictures of their romantic partner reduced participants' pain ratings and induced activity changes in the orbitofrontal cortex (OFC); ventromedial and dorsolateral prefrontal cortex (VMPFC and DLPFC); anterior, mid- and posterior cingulate (ACC, MCC and PCC); thalamus; and amygdala (Coan *et al.*, 2006; Younger *et al.*, 2010; Eisenberger *et al.*, 2011). However, our knowledge of neural systems and how they interact during social buffering remains largely incomplete, because existing studies examined physiological reactions (e.g. cortisol changes) or regional brain activations without establishing a direct link between these processes and behavioural

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outcomes. The current study addressed this knowledge gap by delineating a process model of neural systems involved in social buffering.

The aim of any neuroimaging study is to establish a link between brain activity and behaviour, to explain how a certain behaviour is generated by the brain. However, standard activation analysis performed by the majority of neuroimaging studies does not offer a clear interpretation of the brain–behaviour link, only providing a univariate correlation. Recently developed mediation analysis, in contrast, allows one to assess how changes in brain activity induced by an experimental manipulation lead to specific behavioural outcomes (Wager *et al.*, 2008). The current study employed voxel-wise trial-by-trial mediation analysis to examine the process by which brain activity changes brought about by social buffering lead to reductions in aversive emotion-related brain activity and reported emotions on a trial-by-trial basis.

Importantly, human neuroimaging studies have mainly focused on a single paradigm, the buffering of pain by a romantic partner (reviewed in Eisenberger, 2013). With this canonical experimental setting, studies confirmed the effectiveness of social support by a romantic partner in reducing both the expectation (Coan *et al.*, 2006) and the experience of pain (Younger *et al.*, 2010; Eisenberger *et al.*, 2011). However, to our knowledge, no neuroimaging study to date has gone beyond the romantic partner as a source of support or beyond pain as the aversive stimulus of choice. The current study thus examined (i) whether a previously unknown but trustworthy conspecific (a psychotherapist) also induces a social buffering effect and (ii) the general neural system underlying social buffering of both physically (in the form of electric shocks) and socially (in the form of fearful screams) evoked negative emotions.

To uncover a large-scale process model of neural underpinnings of social buffering, the current study asked which neural systems mediated the effect of social support by a non-familiar conspecific on aversive emotional feelings. We hypothesized that three processes underlay the implementation of social support: (i) a change in brain activity induced by social support, (ii) the following downregulation of aversive emotion-related brain activity and (iii) the resulting downregulation of reported aversive feelings. Based on previous social support studies (Coan *et al.*, 2006; Younger *et al.*, 2010; Eisenberger *et al.*, 2011), we expected a network including OFC, VMPFC, DLPFC and the cingulate cortex (PCC, MCC and ACC) to respond to social support. Based on previous studies showing that the amygdala and thalamus decrease their activity during emotion regulation (Buhle *et al.*, 2014; Mulej Bratec *et al.*, 2015; Xie *et al.*, 2016; Brandl *et al.*, 2018), and considering their role in emotional processing (Lindquist *et al.*, 2012), we expected a reduction of aversive emotion-related brain activity in the amygdala and thalamus. Finally, we anticipated that brain activity changes in the amygdala and thalamus would predict reported trial-wise emotional valence ratings.

Materials and methods

Participants

Thirty-one healthy subjects (all female, mean age = 23.5, s.d. = 2.4 years) participated in the experiment, all native German speakers, right-handed, with normal or corrected-to-normal vision and no history of neurological or psychiatric disorders or intake of psychotropic medication. After excluding four participants due to excessive head movement during imaging (translation >2 mm, rotation >2°), 27 were used for analysis (mean age = 23.6 years, s.d. = 2.5 years). Owing to previous reports of gender differences regarding socio-emotional processing, only female participants were tested (McRae *et al.*, 2008; Whittle *et al.*, 2011; Nolen-Hoeksema, 2012; Eagly and Wood, 2013). After completion, participants received a financial reward for their participation. Written informed consent from all participants was obtained, and the study was approved by the local ethics committee of the Klinikum rechts der Isar at the Technical University of Munich.

Experimental design

Participants were exposed to two types of aversive stimuli (mild electric shocks and fearful screams) while lying in the fMRI scanner. In the social support condition, a female psychotherapist communicated with them at the beginning of every trial, simply conveying the fact that she was present and available. Participants had briefly met her in person before the start of the experiment and were told that she would sit in the scanner-adjacent room, communicating with them via a camera system. In reality, pre-recorded videos of the psychotherapist wearing the same clothes were used for consistency across subjects. In the no-support session (which took place on a separate day), participants were exposed to the aversive stimuli while alone and were shown unrecognizable, scrambled versions of the psychotherapist's videos at the beginning of each trial.

A fully trained, practising psychotherapist acted as the support figure. A psychotherapist was chosen as they are typically perceived, and perceive themselves, as being able to cope better with negative emotions compared to others, making them an ideal candidate for the role of social emotional support (Jennings and Skovholt, 1999; Pletzer *et al.*, 2015). A mean score of 4 (out of 5, s.d. = 0.6) on the subscale trust in psychotherapists confirmed that participants of the current study regarded psychotherapists as highly trustworthy. The latter subscale was part of the administered German interpersonal trust questionnaire ('Inventar zur Erfassung interpersonellen Vertrauens') (Kassenbaum, 2004).

The trial structure is presented in Figure 1. Each trial started with a video: in the social support condition, a video of the psychotherapist (4 s), and in the no-support condition, a scrambled (completely unrecognizable) version of the social video (4 s), and then followed a fixation cross (1.25 s) and the expectation stimulus, which signalled that the aversive stimulus might follow (6 s). The aversive stimulus appeared on 50% of the trials and was briefly presented, after which a blank screen was shown until this part of the trial lasted 6 s. In the electric shock run, the expectation stimuli were a blue square and a yellow pentagon, while the aversive stimuli were electric shocks paired with a lightning picture (presented for 2 ms). In the fearful scream run, the expectation stimuli were two neutral (i.e. non-emotional) faces, while the aversive stimuli were these same faces showing a fearful expression paired with a scream audio recording (presented for 3 s). At the end of every trial, participants had 3 s to indicate their emotional state via a button press on a scale from −3 to 3 (increments of 1; set to 0 on each trial). The inter-trial interval lasted for 5 ± 2 s. The analysis of the current study focused on brain activity during the video presentation and aversive stimulus exposure. Each participant completed both social support and no-support runs, on different days, with the run order counterbalanced across subjects.

The social support run was inspired by previous studies of social support (Coan *et al.*, 2006; Younger *et al.*, 2010; Eisenberger *et al.*, 2011) but was adapted to resemble a more realistic social

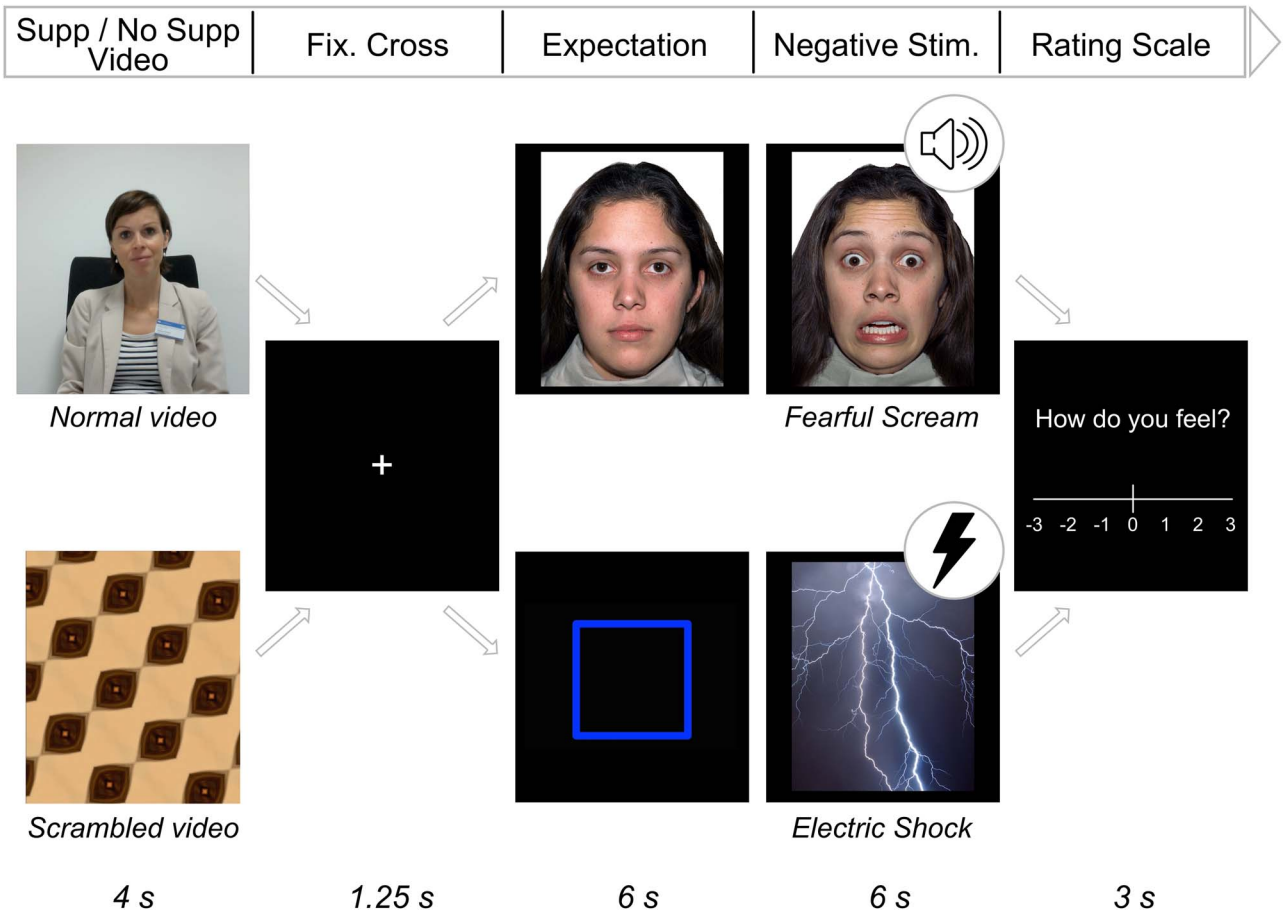

Fig. 1. Experimental design and trial structure. On every trial, a video was shown first, either featuring the psychotherapist in the social support condition or a scrambled (unrecognizable) version of a social support video in the no-support condition. After a subsequent fixation cross and depending on the aversive stimulus-type run, participants saw a face or a shape, signalling the type of upcoming aversive stimulation and then followed either a fearful face together with a scream or a lighting paired with painful electrical stimulation. Finally, participants rated their emotional feeling on a 7-point rating scale. Supp, support; Fix. Cross, fixation cross; Negative Stim., negative stimulus.

interaction with a previously unknown trustworthy individual. Each trial in the social support session started with a 4 s video of a female psychotherapist, whom participants briefly met and interacted with before the experiment. She wore the exact same clothes and haircut as in the videos, and participants were told that sitting in the scanner-adjacent room, the psychotherapist will have the opportunity to briefly speak to them at the beginning of each trial. To enhance the effect of a natural social interaction, the psychotherapist uttered one short sentence per video, such as 'Stay calm, I am here', 'Don't worry, I am here for you', 'You are not alone, I am here with you' or 'We can do this together'. Post-scanning interview confirmed that all participants believed our cover story regarding the online presence of the psychotherapist and that none of the participants doubted her (real) status of being an in-house psychotherapist.

The two experimental conditions (social support and no support) consisted of 80 trials each, with an equal proportion (40 trials) of each stimulus version (i.e. the two electric shock-lightning stimuli and the two face-scream stimuli). The expectation—aversive stimulus contingency fluctuated throughout each run (low-frequency sine wave function, with 1.75 and 1.5 cycles for CS1 and CS2, respectively) (Mulej Bratec *et al.*, 2015), with subject-specific event trains.

To familiarize participants with the task, they all completed a short training immediately before the scanning session, in which a picture instead of a video was shown at the beginning of each trial, and only visual parts of the two aversive stimuli were shown, without the fearful scream or electric shock being administered. After training and before experiment started, participants were introduced to electric shock stimuli in a calibration procedure that culminated in a personalized level of the administered stimuli (8 out of 10 on the subjective unpleasantness rating scale).

Behavioural measures

Emotional valence ratings were gathered at the end of each trial, on a scale from −3 to 3 (increments of 1, set to 0 on each trial). Participants responded with a button box, such that each button press moved the cursor by 1 place in the desired direction. The exact wording of the question was 'How do you feel?' (presented to participants in German: 'Wie fühlen Sie sich?'), and participants were explained in the initial instructions that they will be presented with this question on each trial, immediately after the presentation of the aversive stimulus and that they should rate how they felt in that moment. The instructions, given to each participant verbally, were as follows: 'After each electrical impulse (/fearful scream), you will see a scale from −3 to 3. −3 means that your current feeling is very negative. +3 means that your current feeling is very positive. At the beginning, the

pointer will be at 0, which stands for a neutral feeling. From there, you can use the left button to move the pointer to the left and the right button to move the pointer to the right. There is no right or wrong answer, please simply choose the number that best describes your feeling in that moment'. They practised the emotional valence scale before the experiment and were given 3 s to give their final answer on each trial during the experiment. The ratings were subjected to a 2 × 2 ANOVA with factors social support (support, no support) and stimulus type (shock, scream). Importantly, trial-by-trial emotional valence ratings were also used in the mediation analysis to test for associations between brain- and behaviour-related changes induced by social support.

More general (as opposed to specific, e.g. fear-related) emotional valence ratings were chosen for the study, in order to be able to compare and combine measures of emotional feeling across the two aversive conditions of shock and scream. Mean emotional valence ratings per condition were as follows: shock during no support −1.05 (s.d. = 0.77), shock during support −0.77 (s.d. = 0.87), scream during no support −0.77 (s.d. = 0.84) and scream during support −0.44 (s.d. = 0.96).

MRI acquisition

Measurements were performed on a 3 T Siemens scanner at the Klinikum rechts der Isar (Technical University of Munich), using a 32-channel coil. Anatomical images were acquired with the magnetization-prepared rapid acquisition gradient echo (MP-RAGE) T1-weighted sequence (1 × 1 × 1 mm resolution) and functional scans with the contrast-gradient echo-planar T2∗-weighted sequence, using a multiband factor of 2, with a repetition time of 2.25 s, echo time of 28 ms, flip angle of 80°, acquisition matrix of 94 × 94, 62 slices, each 2 mm thick, without a gap, and an in-plane resolution of 2 × 2 mm.

Visual stimuli, presented with presentation software (Neurobehavioural Systems, Berkeley, US), were rear-projected on a screen at scanner head and were visible via an adjustable mirror mounted to the head coil. Presentation software also received trigger pulses from the scanner for time synchronization.

Statistical analysis

Analyses were carried out with SPM12 (Wellcome Department of Cognitive Neurology, London, UK) and the M3 MediationToolbox (CANlab neuroimaging analysis tools, https://github.com/canlab/MediationToolbox). The T2∗-weighted functional images were slice-timed and then realigned to the first image of the first run (after discarding the first two volumes) and unwarped. T1-weighted structural images were coregistered to the functional images, segmented and then normalized to a standard T1 template in the Montreal Neurological Institute (MNI) space with a 1 × 1 × 1 mm resolution. Normalization parameters from the latter were used to normalize the functional images, which were then resampled to 2 × 2 × 2 mm, smoothed with an 8 mm full-width-at-half-maximum Gaussian filter and temporally high-pass filtered with a cut-off of 128 s.

For the canonical activation analysis, general linear model (GLM)-based statistical analysis was performed, using the following regressors: hemodynamic response function (HRF)-convolved onsets of support/no-support videos, expectation stimuli, present and absent aversive stimuli, emotional valence value-based parametric modulation of the presented aversive stimuli and emotional valence rating scale, as well as six movement regressors derived from realignment as regressors of no interest. Focusing on aversive-stimuli-present trials only (Mulej Bratec *et al.*, 2015), negative emotion-related brain activity was examined by looking at the emotional valence value-based parametric modulation of the presented aversive stimuli. For this analysis, results were restricted to our regions of interest (ROIs)—amygdala and thalamus, and were false discovery rate (FDR)-corrected at $P < 0.05$, based on the small volume correction. All ROIs were based on the automated anatomical labelling atlas in SPM (Tzourio-Mazoyer *et al.*, 2002).

For the multilevel voxel-wise mediation analyses, further first-level GLMs were created, in which single-trial regressors were constructed for both the aversive stimuli and support/no-support video events, with all other event and movement-related regressors kept in the model as regressors of no interest (Woo *et al.*, 2015; Koban *et al.*, 2017). To control that single-trial beta estimates were not driven by movement artefacts or other noise in the data, trial estimates with a variance inflation factor of more than 2.5 were not included in further analyses (Atlas *et al.*, 2010; Koban *et al.*, 2017). Multilevel voxel-wise two-path or three-path mediation analysis was then run with the MediationToolbox, focused on a priori defined anatomical ROIs, namely, amygdala and thalamus, for the two-path mediation, and OFC, cingulate (ACC, MCC and PCC) and DLPFC (superior and middle frontal gyrus) for the three-path mediation. The primary focus of analysis were brain regions that formally mediated the relationship between social support and aversive emotions (path ab in the two-path mediation analysis) or between social support, amygdala and thalamic activity and aversive emotions (path b1b2b3 in the three-path mediation analysis) (see Figure 2C and D). Final activation maps were false discovery rate (FDR)-corrected at $P < 0.05$ across all included voxels and mediation paths (Atlas *et al.*, 2010; Koban *et al.*, 2017). For each activation map, adjacent voxels at thresholds $P < 0.005$ and $P < 0.01$ were also displayed, to provide a more comprehensive view of our results (Koban *et al.*, 2017).

Exploratory whole-brain analyses were carried out for all three contrasts of interest, corrected for multiple comparisons at the same threshold (0.05 FDR-corrected).

Results

We expected that three linked processes underlay the implementation of social buffering: (i) brain activity change in the OFC, VMPFC, DLPFC and cingulate cortex induced by social support, (ii) the following downregulation of aversive emotion-related brain activity in the amygdala and thalamus and (iii) the resulting downregulation of reported aversive feelings. To delineate the hypothesized process model of social buffering, we analysed each of the three hypothesized processes in a step-by-step manner, relating them to one another by building on the preceding result with every step.

Psychotherapist's presence successfully buffered aversive emotions

We first confirmed that the supportive presence of the psychotherapist indeed reduced participants' negative emotions induced by the aversive stimuli. To this end, we conducted a 2 × 2 ANOVA on aversive emotional valence ratings with factors social support (support, no support) and stimulus type (shock, scream), focusing on the main effect of social support. Indeed, emotional valence scores were less negative in the social support compared to the no-support condition, $F(1,26) = 4.779$, $P = 0.038$, $\eta_p^2 = 0.155$, indicating that the psychotherapist's presence reduced (i.e. buffered) participants' negative emotions (Figure 2A).

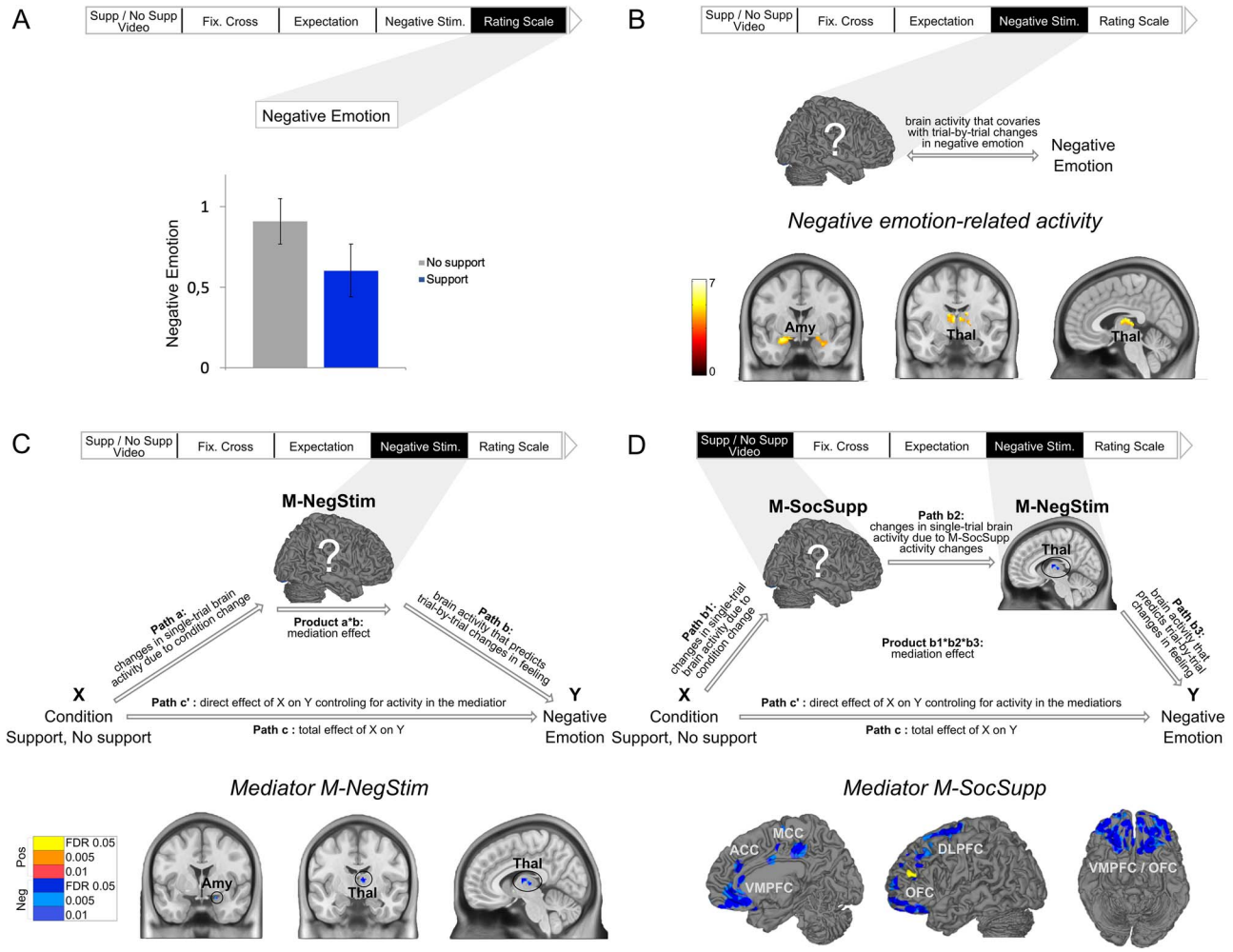

Fig. 2. Neural process model of social buffering. (A) Significant main effect of social support shows that social support reduced negative emotional valence ratings. (B) Parametric modulation of aversive stimulus presentations with emotional valence ratings confirmed that thalamic and amygdala activity indeed covaried with emotional rating scores. (C) Two-path multilevel voxel-wise mediation analysis examined which brain regions mediated the effect of social support on negative emotions, focusing on stimulus-related brain activity (i.e. mediator M-NegStim). It confirmed that the amygdala and thalamus served as mediators between social support and aversive emotions. (D) Three-path multilevel voxel-wise mediation analysis searched for social support-related brain mediators (M-SocSupp), building on the result under C. It confirmed that VMPFC, OFC, DLPFC, ACC and MCC mediated the effect of social support on both amygdala and thalamic activity and aversive emotions. All analyses were thresholded at 0.05 FDR-corrected. Supp, support; Fix. Cross, fixation cross; Negative Stim., negative stimulus.

Importantly, the interaction between social support and stimulus type was not significant ($F(1,26) = 0.133$, $P = 0.719$, $\eta_p^2 = 0.005$), indicating that social support was similarly effective for the two types of aversive stimuli.

FMRI activity in the thalamus and amygdala mediated the influence of social support on aversive emotions

Following our hypothesized model of social buffering, we next examined whether social support downregulated aversive emotion-related brain activity in the amygdala and thalamus, in turn reducing reported aversive feelings. In other words, whether activity changes in the amygdala and thalamus mediated the influence of social support on aversive emotions.

Amygdala and thalamus track aversive emotions. If the amygdala and thalamus are to serve as mediators between social support and reduced negative emotions, their activity needs to track a participant's emotional state. As the first step, we thus examined whether brain activity in the thalamus and amygdala covaried with trial-by-trial aversive emotional valence ratings, indicating that the level of activation in the amygdala and thalamus was directly related to the level of aversiveness a participant was feeling. We conducted an activation analysis in SPM12, using emotional valence ratings as a parametric modulation of aversive stimulus presentations. By parametrically modulating the presentation of aversive stimuli with emotional valence ratings, we could confirm that thalamic and amygdala activity indeed covaried with emotional rating scores (Figure 2B). Going beyond our hypothesis, we conducted an exploratory whole-brain analysis of the above contrast, which revealed that the emotion-tracking network additionally included the anterior insula, ACC, MCC, somatosensory cortex and cerebellum (Supplementary Figure S1A).

Amygdala and thalamus mediate the effect of social support on aversive feelings. Having confirmed that the amygdala and thalamus track negative feelings, we next checked whether thalamic and amygdala brain activity indeed mediated the relationship between social support and aversive feelings. In more detail, we expected social support to reduce BOLD activity in the thalamus

and amygdala, which would in turn reduce reported aversive feelings. We thus conducted a two-path voxel-wise multilevel mediation analysis, where X was social support (support, no support), Y was reported aversive feelings and M (the unknown variable of interest) was brain activity during the presentation of the aversive stimulus (M-NegStim; Figure 2C). As the analysis was multilevel, the three variables changed values on every trial. Furthermore, due to the voxel-wise approach, the mediation was run separately for each voxel in the brain, based on which significant clusters were then formed. Results confirmed that the amygdala, primarily the superficial cortex-like nuclei group, and thalamus, primarily the mediodorsal thalamic nucleus, indeed mediated the relationship between social support and reduced negative feelings. Focusing on our predefined regions of interest (ROIs) and using an FDR correction of 0.05 (corresponding to a height threshold of 0.0008 for negative mediators and 0.00000001 for positive mediators), we could confirm that social support reduced activity in the amygdala and thalamus, which in turn downregulated participants' negative emotions (Figure 2C). The amygdala and thalamus were identified as negative mediators, because for significant voxels within these regions, denoted as M-NegStim, the relationship between X and M-NegStim was a negative one, while the relationship between M-NegStim and Y was a positive one. An additional exploratory whole-brain analysis did not reveal the amygdala or thalamus, but portrayed TPJ, DLPFC, inferior temporal cortex and cerebellum as positive mediators (Supplementary Figure S1B).

OFC, VMPFC, DLPFC, ACC and MCC mediated the influence of social support on thalamic–amygdala activity and aversive emotions

To test the final part of our hypothesis and complete the process model of social support, we next examined whether those regions typically found to react to social support (i.e. OFC, VMPFC, DLPFC and the cingulate cortex) indeed have an effect on emotional brain activity in the amygdala and thalamus, which in turn influences participants' behaviour—the reported aversive emotions. We thus carried out a three-path voxel-wise multilevel mediation analysis, where X was social support (support, no support), Y was reported aversive feelings, M2 was amygdala and thalamic brain activity during the presentation of the aversive stimulus (i.e. M-NegStim, the result of the above reported two-path mediation), and M1, the unknown variable of interest, was brain activity during the presentation of the social support video (M-SocSupp; Figure 2D). Except for the additional mediator, the three-path analysis was comparable to the two-path analysis reported above, in that it was both multilevel and voxel-wise. Results confirmed that OFC, VMPFC, DLPFC, ACC and MCC indeed mediated the relationship between social support, activity in the amygdala and thalamus and negative feelings. Focusing on our predefined ROIs and using an FDR correction of 0.05 (corresponding to a height threshold of 0.0006 for negative mediators and 0.00001 for positive mediators), analysis revealed that social support reduced activity in the OFC, VMPFC, DLPFC, ACC and MCC, which then reduced activity in the amygdala and thalamus during stimulus presentation, finally resulting in the reduction of reported negative emotions (Figure 2C). OFC, VMPFC, DLPFC, ACC and MCC were identified as negative mediators, because for significant voxels within these regions, denoted as M-SocSupp, the relationship between X and M-SocSupp was a negative one, the relationship between M-SocSupp and M-NegStim was a positive one, and the relationship between M-SocSupp and Y was also a positive one. One small left DLPFC cluster was a positive mediator, such that increased activity in this region during social support was related with more activation in the amygdala and thalamus and more negative emotions. An additional exploratory whole-brain three-path mediation analysis also revealed the involvement of OFC, VMPFC and ACC and highlighted bilateral parietal and left posterior temporal cortices as additional negative mediators, as well as right superior and bilateral mid-temporal cortices as additional positive mediators (Supplementary Figure S1C).

Discussion

Social buffering, in human studies referred to as social support, is a fundamental and powerful form of social emotion regulation. However, its implementation by the brain is still incompletely understood. Using voxel-wise multilevel mediation analysis, the current study extended our knowledge of social support by showing that three processes, which influence and follow one another, underlie the implementation of social support. Confirming our hypothesis, the presence of a previously unknown psychotherapist first induced an activity decrease in a large-scale brain network including OFC, VMPFC, DLPFC, ACC and MCC. This change then induced an activity reduction in the amygdala and thalamus, which finally resulted in lower reported aversive emotions.

FMRI activity in the thalamus and amygdala mediated the influence of social support on aversive emotions

The amygdala and thalamus mediated the relationship between social support and aversive emotions as negative mediators, such that social support reduced the areas' activity, which in turn reduced reported aversive emotions (Figure 2C). This is in line with our hypothesis that the downregulation of aversive emotion-related brain activity would be centred on the amygdala and thalamus, as well as in accordance with previous studies showing that various nuclei of the amygdala and thalamus reduce their activity during self-initiated and social forms of emotion regulation (Buhle *et al.*, 2014; Mulej Bratec *et al.*, 2015; Xie *et al.*, 2016; Brandl *et al.*, 2018). Both regions have further been implicated in emotional processing, as well as cortico–subcortical and cortico–cortical integration, important for emotional processing (Metzger *et al.*, 2010; Pessoa and Adolphs, 2010; Lindquist *et al.*, 2012; Sherman, 2016).

The current mediation analysis identified the superficial nuclei group of the amygdala as the mediator between social support and reduced aversive emotions. Superficial cortex-like amygdala, a less-known amygdala subregion, has been implicated in processing socially relevant, emotion-related information (Bzdok *et al.*, 2013). Recent research highlights the role of superficial amygdala in both experimental pain (Simons *et al.*, 2014) and auditory-evoked fear (Koelsch *et al.*, 2013), coinciding with the two types of aversive stimuli used in the current study. Furthermore, superficial amygdala forms reciprocal connections with OFC (Bach *et al.*, 2011) and is functionally connected to MCC (Roy *et al.*, 2009), regions of the social support-responsive network identified by the current study.

In the thalamus, it was primarily the mediodorsal thalamic nucleus that mediated the influence of social support on aversive emotions, a higher-order thalamic nucleus, involved in a range of cognitive functions (e.g. working memory, cognitive flexibility) (Parnaudeau *et al.*, 2013, 2015; Saalmann, 2014; Delevich *et al.*, 2015). A direct anatomical and functional connection between the mediodorsal thalamic nucleus and the superficial

amygdala has been suggested (Behrens et al., 2003; Koelsch et al., 2013), linking the two subregions of the amygdala and thalamus identified in the current study. Furthermore, mediodorsal thalamus forms extensive reciprocal connections with the MPFC (Mitchell and Chakraborty, 2013), highlighting a link between this aversive emotion-responsive region and the social support-responsive network of the current study.

For the discussion of additional whole-brain analyses, please see the Supplementary data.

OFC, VMPFC, DLPFC, ACC and MCC mediated the influence of social support on thalamic–amygdala activity and aversive emotions

OFC, VMPFC, DLPFC, ACC and MCC mediated the relationship between social support on the one side and amygdala and thalamic activity as well as emotional valence ratings on the other side (Figure 2D). They were negative mediators, such that social support reduced the areas' brain activity, which in turn reduced activity in the amygdala and thalamus, finally reducing aversive emotional feelings. The result is in line with our hypothesis that the social support-responsive network would comprise OFC, VMPFC, DLPFC and the cingulate cortex, as well as in accordance with previous social support studies, highlighting these areas' involvement in social support (Coan et al., 2006; Younger et al., 2010; Eisenberger et al., 2011). For example, Eisenberger and colleagues showed that viewing a picture of your loved one during pain increased VMPFC activity (Eisenberger et al., 2011), while Younger and colleagues demonstrated that viewing pictures of your romantic partner increased activity in the ACC, MCC, OFC, precuneus, hypothalamus and amygdala (Younger et al., 2010). A further study revealed that holding a spouse's hand while expecting a painful stimulus decreased activity in a number of areas, including ACC, PCC and DLPFC (Coan et al., 2006). The direction of activity change in frontal and parietal areas differed across social support studies, which could be due to the nature of the employed social support. It is worth noting that less naturalistic forms of social support (i.e. watching partner's photos) resulted in increased brain activity in frontal and cingulate brain regions, while a simple and natural form of social support (i.e. holding a spouse's hand) was associated with reduced activity in similar brain areas. In the current study, regions linked to a reduction in aversive emotional ratings similarly showed decreases in activation during social support. In accordance with the above-mentioned dissociation between the nature of social support and the direction of brain activity, the current study employed a naturalistic form of social support, where participants were socially connected with the psychotherapist in real time. Conceivably, when the realization of social support is natural and does not require additional effort on the part of the recipient (such as, for instance, associating a picture of a loved one with their personality and imagining that they are present and being supportive), the presence of a warm and trustworthy conspecific might be associated with less brain activity because being surrounded by supportive others is less demanding compared to facing the world's challenges on your own (Beckes and Coan, 2011; Coan and Sbarra, 2015). In other words, unless additional cognitive processing is required, the presence of a conspecific, especially one with positive associations, is linked with less 'strenuous' brain activity, denoting a state of reduced vigilance (Beckes and Coan, 2011; Coan and Sbarra, 2015).

For the discussion of additional whole-brain analyses, please see the Supplementary data.

Social buffering in humans as opposed to non-human animals

Social buffering is a universal phenomenon, common to humans and non-human animals (Hostinar et al., 2014; Kiyokawa and Hennessy, 2018). However, its human implementation might differ due to our pervasive use of language. The current study emphasized a naturalistic social setting and thus allowed some language-based communication during social support. The sentences used by the psychotherapist were short and simple, requiring very low levels of processing. Their function was to convey the presence of the psychotherapist in a salient way, standing out against scanner noise and an experimental environment. Nevertheless, any use of language makes it difficult to directly compare human and animal social buffering.

Humans have a wider-reaching social environment compared to animals, such that we can additionally trust an unknown individual based on their normative (language-based) label, such as 'psychotherapist' (Tomasello and Vaish, 2013). Such a label conveys the person's expertise and characteristics; for example, a psychotherapist is likely to be perceived as competent and warm, attributes that help form a positive social perception (Fiske et al., 2007). In line with this, animal social buffering typically relies on familiar conspecifics, while our emotions can be socially regulated by both closely familiar and normatively familiar individuals, as shown by the current study. A few studies have tested whether strangers and close friends/romantic partners influence our neural circuits and behaviour in different ways, showing that highly familiar individuals can buffer our feelings of pain more effectively than strangers (reviewed in Krahé et al., 2013). However, the current study shows that a normatively familiar (yet personally unfamiliar) conspecific can similarly downregulate our negative emotions. Future studies could examine differences and similarities in social support between a familiar conspecific and an unfamiliar normatively labelled one.

Implications for psychotherapy and affective disorders

Psychotherapy is based on the social interaction with the psychotherapist and operates via interaction-based interventions (Barker and Pistrang, 2002; Sauer-Zavala et al., 2012; Grecucci et al., 2017). Especially for affective disorders, such as depression or anxiety, one of the goals of psychotherapy is to reduce the occurrence of negative emotions and the enhanced negative emotional reactions, to improve the patient's symptoms and long-term mental health (Sauer-Zavala et al., 2012; Boumparis et al., 2016). It is thus remarkable to note that the very presence of a psychotherapist has a buffering effect on current negative emotions, as shown by our findings. It may well be that therapeutic effects are to some extent achieved through supportive social presence of the psychotherapist as a normatively trustworthy person even before the formal therapy begins. Hence, the very act of starting therapy and meeting with a therapist already has some ameliorating effect on acute negative emotions. The current study represents an investigation of immediate behavioural and neural consequences of one, therapy type-independent, session with a psychotherapist. As such, for future studies testing a certain therapeutic approach or comparing different types of therapy, the present design might serve as the 'control condition', showing how much the therapeutic outcome depends on the social context itself and how much can be attributed to the therapeutic approach above and beyond the social buffering effect.

In certain psychotherapeutic procedures, however, decreases of negative emotions are considered counterproductive to long-term symptom improvement, such as during exposure therapy (e.g. as part of Cognitive Behavioural Therapy or Emotion Regulation Therapy) (Renna *et al.*, 2017; Hayes and Hofmann, 2018). Our findings indicate that negative emotions induced by the exposure therapy might be buffered by the presence of the therapist, interfering with the procedure. It has also been suggested that the presence of the psychotherapist during exposure therapy may worsen the generalization of the acquired neutral response to other contexts, due to the mechanisms of inhibitory learning (Craske *et al.*, 2008; Craske, 2015). Together, this suggests that the presence of the psychotherapist during exposure procedures might in fact be counterproductive to therapeutic outcomes. Further studies that take social buffering of the psychotherapist into account are needed to test this specific assumption.

The current findings raise interesting questions with regard to their application to various forms of psychopathology, especially affective disorders, the majority of which are associated with emotion dysregulation (Grecucci *et al.*, 2016, 2017; Sloan *et al.*, 2017). Specifically, it would be worth investigating whether patients that have difficulties regulating emotions might benefit to a greater extent from the psychotherapist's supportive presence compared to other more cognitive forms of social emotion regulation, which rely on the default mode network (Xie *et al.*, 2016)—a brain network that is impaired in affective disorders, including depression, autism and anxiety (Zhao *et al.*, 2007; Messina *et al.*, 2016; Padmanabhan *et al.*, 2017).

Limitations

Firstly, while social support and no-support conditions differed foremost with regard to availability and supportive presence of the psychotherapist, other social factors could have had an additional impact, such as salience of the psychotherapist and perception of her power, character and/or expertise. Secondly, since we only recruited female participants, we cannot generalize our results beyond the female population. Thirdly, while the current study used two types of aversive stimuli to go beyond the effect of social support on pain, we cannot generalize our results to all aversive stimuli. Further research could use a wider variety of negative stimuli and explore similarities and differences in the impact of social support on stimuli-evoked behavioural and neural responses. A further limitation is using a single social relationship, while the use of a psychotherapist goes beyond social support by a romantic partner and has some clinical implications, the current study did not compare the impact of the psychotherapist with that of a spouse/romantic partner and a complete stranger. Additionally, the current study explored a process that is present in both humans and non-human animals, yet only tested it on human participants. A formal cross-species comparison in the context of a single study could elucidate important similarities and differences in social buffering between humans and other animals. Furthermore, since participants rated their momentary feeling, a general emotional state, it is difficult to assess whether similar or different specific negative emotions were being buffered in the same or different ways in the two stimulus-type conditions. Future studies could employ additional rating scales pertaining to the specific emotions related to each stimulus type. Last but not least, the buffering effect of social support on negative emotions could have (at least in part) occurred due to an induction of positive mood by the psychotherapist's presence. To resolve this, an explicit investigation of the way or ways in which social support influences negative emotions is needed.

Supplementary data

Supplementary data are available at *SCAN* online.

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Conflict of interest

The authors report no conflicts of interest.

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