Neural Control of Emotional Actions in Response to Affective Vocalizations

Saskia B. J. Koch[1,2*], Alessandra Galli[1*], Inge Volman[3], Reinoud Kaldewaij[1,2], Ivan Toni[1#], and Karin Roelofs[1,2#]

Abstract

■ Social–emotional cues, such as affective vocalizations and emotional faces, automatically elicit emotional action tendencies. Adaptive social–emotional behavior depends on the ability to control these automatic action tendencies. It remains unknown whether neural control over automatic action tendencies is supramodal or relies on parallel modality-specific neural circuits. Here, we address this largely unexplored issue in humans. We consider neural circuits supporting emotional action control in response to affective vocalizations, using an approach–avoidance task known to reliably index control over emotional action tendencies elicited by emotional faces. We isolate supramodal neural contributions to emotional action control through a conjunction analysis of control-related neural activity evoked by auditory and visual affective stimuli, the latter from a previously published data set obtained in an independent sample. We show that the anterior pFC (aPFC) supports control of automatic action tendencies in a supramodal manner, that is, triggered by either emotional faces or affective vocalizations. When affective vocalizations are heard and emotional control is required, the aPFC supports control through negative functional connectivity with the posterior insula. When emotional faces are seen and emotional control is required, control relies on the same aPFC territory downregulating the amygdala. The findings provide evidence for a novel mechanism of emotional action control with a hybrid hierarchical architecture, relying on a supramodal node (aPFC) implementing an abstract goal by modulating modality-specific nodes (posterior insula, amygdala) involved in signaling motivational significance of either affective vocalizations or faces. ■

INTRODUCTION

Emotion regulation is essential for human social interactions (James, 1884), and failure to control emotional action tendencies is a core element of social psychopathologies like anxiety and aggression-related disorders (Bertsch et al., 2018; Volman et al., 2016; Roelofs et al., 2010). Over the past decades, cognitive neuroscience has provided insights in how humans control affective responses to visual cues signaling emotions, such as angry faces, negative scenes, and threat of shock (Morawetz, Bode, Derntl, & Heekeren, 2017; Etkin, Büchel, & Gross, 2015; Roelofs, Minelli, Mars, van Peer, & Toni, 2009; Ochsner & Gross, 2005). The frontoparietal neural circuit supporting emotional control is suspected to be stimulus independent (Morawetz et al., 2017). Yet, that circuit has been largely defined using visual material, and it is unknown how emotional control is implemented when automatic action tendencies are evoked by auditory emotional information. Besides being a stimulus category fundamental for primate ethology (Cheney & Seyfarth, 2018), affective vocalizations open the possibility to understand whether neural control over automatic action tendencies is supramodal or relies on separate, modality-specific neural circuits. There is evidence of higher order areas with modality-selective responses. For instance, within the pFC, differentiation of sensory responses has been observed, including gradients of prefrontal connectivity with visual and auditory cortices (Braga, Hellyer, Wise, & Leech, 2017) and a specialization of the rostral pFC for auditory inputs (Mayer, Schwiedrzik, Wibral, Singer, & Melloni, 2016). This study characterizes the neural network underlying control of action tendencies elicited by affective vocalizations, comparing it to neural circuits involved in controlling visually evoked emotional reactions.

Social–emotional stimuli, such as affective vocalizations and emotional faces, trigger automatic action tendencies generally aimed at approaching positive and avoiding negative stimuli (Lang, Bradley, & Cuthbert, 1990; Frijda, 1986). For example, hearing an anxious scream induces an automatic tendency to avoid the situation. Implementing these automatic action tendencies can be crucial for survival but may also interfere with goal-directed behavior. For instance, when the anxious scream comes from an unattended child, a parent may want to approach the situation, overriding the automatic avoidance bias. Adaptive social–emotional

[1]Donders Institute for Brain, Cognition and Behavior, Radboud University, [2]Behavioral Science Institute, Radboud University, [3]Wellcome Centre for Integrative Neuroimaging, Oxford, UK
[*,#]These authors contributed equally to the study.

Journal of Cognitive Neuroscience 32:5, pp. 977–988
https://doi.org/10.1162/jocn_a_01523

behavior depends on the ability to control automatic action tendencies (Roelofs et al., 2010; Heuer, Rinck, & Becker, 2007). The neural processing of affective sounds has been well documented (Frühholz, Trost, & Kotz, 2016), but it remains unknown how automatic responses toward those affective vocalizations are neurally controlled.

Previous fMRI studies investigating neural control over automatic responses to visual affective stimuli showed involvement of the anterior pFC (aPFC; Tyborowska, Volman, Smeekens, Toni, & Roelofs, 2016; Radke et al., 2015; Volman, Roelofs, Koch, Verhagen, & Toni, 2011; Volman, Toni, Verhagen, & Roelofs, 2011; Roelofs et al., 2009), modulating downstream activity in posterior parietal cortex, motor cortex, and amygdala (Bramson, Jensen, Toni, & Roelofs, 2018; Volman et al., 2013; Mars et al., 2011). The aPFC is anatomically defined as the lateral frontal pole, which consists of medial and lateral subdivisions with different connectivity patterns (Bludau et al., 2014; Neubert, Mars, Thomas, Sallet, & Rushworth, 2014). Inhibition of the aPFC with TMS impairs participants' ability to select rule-driven responses needed to override automatic action tendencies elicited by emotional faces (Volman, Roelofs, et al., 2011). This type of emotional control pertains to conflict between the emotional value of stimulus and response (Bramson et al., 2018), which is notably different from the control needed when conflicts occur at the stimulus level (e.g., emotional Stroop tasks). Besides aPFC involvement in emotional control (Koch, Mars, Toni, & Roelofs, 2018; Volman, Roelofs, et al., 2011), the aPFC has been associated with other forms of cognitive control, including implementing abstract goals, while controlling immediate action tendencies (Mansouri, Koechlin, Rosa, & Buckley, 2017; Koechlin, 2016; Boorman, Behrens, Woolrich, & Rushworth, 2009). Those empirical observations, together with suggestions of stimulus-independent emotional control (Morawetz et al., 2017; Morawetz, Bode, Baudewig, Jacobs, & Heekeren, 2016), led us to hypothesize that the aPFC exerts emotional action control irrespectively of the sensory modality of affective stimuli.

This hypothesis raises the question of how this putatively supramodal prefrontal control system would interact with networks involved in processing affective vocalizations. The amygdala is a core structure for processing affective sounds, receiving projections from the thalamus and auditory cortices (Pannese, Grandjean, & Frühholz, 2015; LeDoux, 2012). Via projections from the medial geniculate nucleus of the thalamus, the (basolateral) amygdala provides fast and coarse evaluation of simple and salient sounds, including nonverbal vocalizations (Frühholz et al., 2016; Frühholz, Trost, & Grandjean, 2014). The auditory cortex has also been implicated in processing auditory affect, possibly in a complementary manner to the limbic system (Frühholz et al., 2016; Bestelmeyer, Maurage, Rouger, Latinus, & Belin, 2014). Furthermore, the posterior insula supports processing of auditory information with motivational significance, including affective vocalizations (Bestelmeyer, Kotz, & Belin, 2017; Chang, Yarkoni, Khaw, & Sanfey, 2013; Schirmer, Fox, & Grandjean, 2012). Given its functional and structural connections with the auditory cortex, SMA, amygdala, and frontal cortex (Ghaziri et al., 2017; Chang et al., 2013), the posterior insula could play an important role in directing attention to salient auditory social–emotional events (Zhang et al., 2018). Here, we investigate whether those three regions (amygdala, auditory cortex, posterior insula) interact with the aPFC when automatic actions elicited by auditory affective stimuli need to be controlled.

To investigate the neural network underlying control of responses toward affective auditory stimuli, we combined affective vocalizations with an fMRI approach–avoidance (AA) task known to reliably index control over emotional action tendencies (Volman, Toni, et al., 2011; Roelofs et al., 2009). We formally test for a supramodal role of the aPFC in emotional control with a conjunction analysis of control-related neural activity evoked by auditory and visual affective stimuli, the latter previously obtained in a large independent sample (Kaldewaij et al., 2019a, 2019b). We also explore control-related modulations of interregional connectivity between the aPFC and other areas responding during incongruent actions to affective vocalizations.

METHODS

Participants

Twenty-nine healthy women, between 19 and 31 years of age, participated in the auditory AA task study after providing oral and written informed consent. We included female participants to eliminate sex differences in emotional processing and emotional control (Cahill, 2006). Participants had normal or corrected-to-normal vision, normal auditory acuity, and no history of psychiatric or neurological disorders. One participant was excluded from all analyses because of incomplete data, resulting in 28 participants for the final analyses (mean age = 24.11 years, SD = 3.48). The study was conducted in accordance with the principles of the Declaration of Helsinki and approved by the Committee on Research Involving Human Subjects Arnhem-Nijmegen, the Netherlands.

Procedure

Upon arrival in the laboratory, several questionnaires were administered for other research purposes. Immediately before entering the scanner room, the first saliva sample was collected for assessment of endogenous testosterone and cortisol levels. The subsequent functional neuroimaging session consisted of the auditory AA task and a control gender evaluation (GE) task (duration = 20 min per task), administered in a counterbalanced order between participants. The tasks were preceded by a short training of 5 min and interleaved with the acquisition of a structural T1-weighted scan. Finally, a second

saliva sample was collected for testosterone and cortisol assessments.

Experimental Tasks

The auditory AA and GE tasks were administered in separate fMRI runs (Figure 1A). Each task consisted of 16 blocks of 12 trials (interblock interval = 21–24 sec), requiring responses with joystick movements to positive and negative affective voices. Participants were instructed to move the joystick as fast as possible toward their body (approach) or away from their body (avoid), depending on the affective category (AA task) or gender (GE task) of the auditory stimuli. Critically, previous studies have shown that this response labeling (i.e., "move the joystick away from your body" as avoidance and "move the joystick toward your body" as approach) resulted in the expected behavioral AA congruency effects (Eder & Rothermund, 2008; Roelofs, Elzinga, & Rotteveel, 2005; Chen & Bargh, 1999). During the AA task, participants were instructed to either approach happy (laughing) and avoid anxious (screaming) voices (affect-congruent) or to approach anxious and avoid happy voices (affect-incongruent). During the control (GE) task, the same auditory stimuli were presented, but joystick movements were based on stimulus gender: Participants were instructed to approach male and avoid female voices in one condition and to approach female and avoid male voices in the other. Implicitly, this resulted again in affect-congruent (approach-happy, avoid-angry) and affect-incongruent (approach-angry, avoid-happy) task conditions. For both tasks, eight blocks of each condition were presented in alternating order. The first condition was counterbalanced between participants.

Each trial started with a fixation cross and a short beep (200 msec), followed by a vocalization (1000 msec), response period (2 sec), and intertrial interval (2–4 sec). Participants used an MR-compatible joystick (Fiber Optic Joystick, Current Designs), placed on the abdomen of the participants to enable pull and push movements. Stimuli presentations and joystick positions were controlled by Presentation software v16.

Auditory stimuli were taken from the Montreal Affective Voices database (Belin, Fillion-Bilodeau, & Gosselin, 2008). Positive ("ah" as during laughter) and negative ("ah" as during screaming) vocalizations were selected from the subcategories "happiness" and "fear," of which 10 were from the database, 2 were made available by the authors (P. Belin, personal communication), and 4 were in-house recorded from trained actors. We used 16 voices (eight male voices) for both valences (happy and anxious). Given that vocalizations varied in length (±150 msec), we adjusted all durations to 1 sec (preserving the original pitch) using Soundbooth CS4 v2.0.1. In an independent study in 30 healthy women (mean age = 23.66 years, SD = 3.37), we obtained valence and arousal rating of each vocalization. We used visual analogue rating scales, ranging from 0 (*very unpleasant/negative*) to 1 (*very pleasant/positive*) for valence and from 0 (*not arousing at all*) to 1 (*very arousing*) for arousal. This confirmed that positive and negative vocalizations were perceived as more arousing compared with neutral ones (all $p <$ .001), and negative vocalizations were nominally more arousing than positive ones ($p <$ .01). Neutral vocalizations were rated as more pleasant than negative ones ($p <$ .001) and less pleasant than positive vocalizations ($p <$ .001, Bonferroni-corrected).

Image Acquisition

Structural and functional images were acquired with a 3-T Magnetom Trio scanner (Siemens Medical Systems) using a 32-channel head coil. An anatomical scan was obtained with a combined MPRAGE and GRAPPA sequence (192 slices, voxel size = 1.0 mm^3, repetition time [TR] = 2300 msec, echo time [TE] = 3.03 msec, field of view [FOV] = 256 mm, flip angle = 8°). Functional scans were acquired with a multiecho EPI sequence sensitive to the

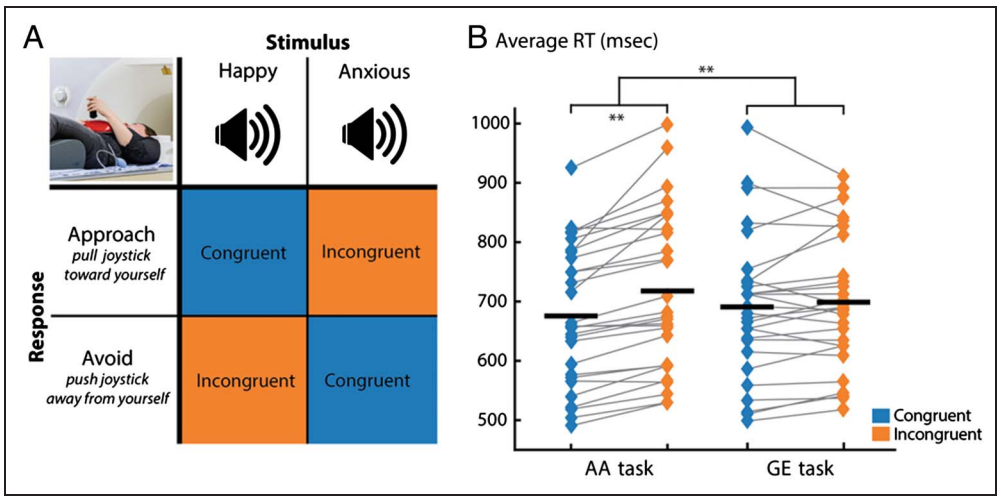

Figure 1. (A) In the auditory AA task, participants were instructed to either approach happy and avoid anxious voices (congruent) or to approach anxious and avoid happy voices (incongruent). In the control GE task (not shown), the same auditory stimuli were presented, but approaching and avoiding movements were based on stimulus gender. (B) Slower responses in incongruent versus congruent trials in the AA task, but not in the GE task. Black lines represent the mean. **$p <$ .001.

BOLD contrast: 36 slices, voxel size = 3.3 × 3.3 × 3.0 mm, TR = 2320 msec, TE_1 = 9.3 msec, TE_2 = 20.9 msec, TE_3 = 32 msec; TE_4 = 44 msec, FOV = 212 mm, flip angle = 90°).

Salivary Measurements

Saliva collection and analysis followed similar procedures as described by Tyborowska et al. (2016) and Volman et al. (2016). Participants abstained from caffeine and alcohol; minimized physical exercise; did not smoke more than five cigarettes on the testing day; and refrained from food, cigarettes, and drinks (except for water) at least 1 hr before the start of the experiment. Saliva samples were collected by passive drooling of 2 mL into Salicap containers (IBL), which were immediately stored at −24°C. Testosterone levels were assessed using a competitive chemiluminescence immunoassay with a sensitivity of 0.0025 ng/ml, and cortisol concentrations were assessed using a chemiluminescence immunoassay with a sensitivity of 0.16 ng/mL.

Data Analysis

Behavioral Analysis

Behavioral data were analyzed using MATLAB 2014B (the MathWorks, Inc.) and SPSS Statistics Version 21.0. Onset of joystick movement was reconstructed based on the joystick displacement measures for each trial and used to calculate RTs, defined as time between stimulus presentation and joystick movement onset (Tyborowska et al., 2016; Volman, Toni, et al., 2011). Errors consisted of incorrect responses (i.e., movement in the wrong direction) and misses (i.e., no response given within the allotted time). Trial blocks with an error rate at or above chance level were excluded from all analyses. Mean RTs were calculated for each task condition, excluding errors and trials with extreme RTs (100 msec < RT < 1500 msec, and RT > 3 *SD*s from the individual mean). We investigated normal distribution of the data and checked for outliers (|*Z*-score| > 3.29). Cortisol levels were log-transformed to accommodate normal distribution. One outlier on accuracy in one GE task condition was removed from the analyses on accuracy. Repeated-measures ANOVAs were conducted on RTs and accuracy separately, with within-subject factors Task (AA/GE), Valence (happy/anxious), and Movement (approach/avoid). In line with previous work using visual affective stimuli (Volman et al., 2016; Volman, Toni, et al., 2011), we included standardized testosterone and cortisol levels as covariates to account for individual differences in emotional action control. The α level was set at .05.

fMRI Preprocessing and Single-Subject Analysis

fMRI data were analyzed following Tyborowska et al. (2016) and implemented in SPM12 (www.fil.ion.ucl.uk/spm). The first 10 volumes of each fMRI run were discarded to allow for T1 equilibration. The four echoes were realigned and combined into a single time series using an optimized echo-weighing method. Preprocessing further involved slice time correction, spatial coregistration to the mean of the functional images, normalization to standard Montreal Neurological Institute (MNI) space, and smoothing with an 8-mm FWHM kernel. At the first level, task regressors describing the stimulus onset and response duration of the four task conditions (approach-happy, approach-anxious, avoid-happy, avoid-anxious) were convolved with the canonical hemodynamic response function for each task separately. Additional regressors included misses and on-screen information (instructions and feedback), residual head movement (original, squared, cubic, first-order and second-order derivatives of the realignment parameters) and three time courses of signal intensities in white matter, CSF, and the portion of the brain image outside the skull (Lund, Nørgaard, Rostrup, Rowe, & Paulson, 2005). The fMRI time series were high-pass filtered (cutoff 128 sec), and the first-order autoregressive model (AR1) was used to correct for temporal autocorrelation.

fMRI Second-Level Analysis

General AA task effects (task > baseline) were investigated in a random-effects multiple regression analysis, using one combined contrast image of all AA task conditions. For the main analysis, a random-effects multiple regression analysis was conducted with contrast images of the four conditions (approach-happy, approach-anxious, avoid-happy, avoid-anxious) per task. Standardized testosterone and cortisol values were added as task- and condition-specific covariates. Finally, 28 subject-specific regressors were added to control for overall between-subject effects. Following previous work (Tyborowska et al., 2016; Volman, Toni, et al., 2011; Roelofs et al., 2009), we tested activation differences for incongruent (approach-anxious, avoid-happy) versus congruent (approach-happy, avoid-anxious) trials in the AA task (congruency effect). We additionally tested whether these congruency effects were stronger in the AA task compared with the GE task by masking the AA task congruency effect with the tasks interaction effect (AA [incongruent > congruent] > GE [incongruent > congruent]).

General task effects (task > baseline) were investigated at the whole-brain peak-level $p_{FWE} < .05$, allowing for spatial inference in large clusters (Woo, Krishnan, & Wager, 2014). Congruency effects were investigated both at the whole-brain level and within a priori defined volumes of interest (VOIs): the bilateral aPFC and amygdala. Following previous work (Volman et al., 2016), the aPFC VOI was functionally defined based on previous AA task results with visual affective stimuli (8-mm spheres on MNI *xyz* = −30, 58, 2; 32, 54, 8; Volman, Toni, et al., 2011). The amygdala VOI was anatomically defined based on the 50% Harvard–Oxford probability atlas. Whole-brain

congruency effects were inferred at the cluster-level, family-wise error (FWE)-corrected for multiple comparisons ($p_{FWE} < .05$), with an initial cluster-forming threshold of $p < .001$. Inferences for the VOIs were made at the peak level (small volume-corrected [SVC] $p_{FWE} < .05$). Anatomical probabilistic atlases implemented in the SPM Anatomy Toolbox (Eickhoff et al., 2005) were used for anatomical inference of activations.

Conjunction With Visual AA Task

We conducted a between-studies conjunction analysis using fMRI data from a visual AA task acquired in a large independent sample of 353 healthy participants (268 males; Kaldewaij et al., 2019b). The visual AA task was part of a baseline measurement in a large prospective study investigating neurobiological mechanisms underlying the development and maintenance of trauma-related psychopathology in police recruits (see Koch et al., 2017, for details). All participants were between 18 and 45 years of age (mean age = 24.46 years, *SD* = 5.19 years) and did not have any current psychiatric or neurological disorders, (history of) endocrine or neurological treatment, and current drug or alcohol abuse and did not use psychotropic medication. The study was approved by the Institutional Review Board Nijmegen and conducted in accordance with the Declaration of Helsinki.

During the visual AA task, participants were required to make approaching and avoiding movements in response to happy and angry faces, again resulting in congruent (approach-happy, avoid-angry) and incongruent (approach-angry, avoid-happy) conditions. During the scanning session, participants first performed a short training session (duration = 3 min), followed by the visual AA task (duration = 12 min). The visual AA task consisted of eight blocks of 12 trials (interblock interval = 21–24 sec; intertrial interval = 2–4 sec), including four congruent (approach-happy, avoid-angry) and four incongruent (approach-angry, avoid-happy) blocks. Blocks were presented in alternating order, and the first block type was counterbalanced between participants. The visual stimuli were happy and angry facial expressions from 36 models (18 male models) obtained from multiple databases (Lundqvist, Flykt, & Ohman, 1998; Martinez & Benavente, 1998; Matsumoto & Ekman, 1988; Ekman & Friesen, 1975). See Tyborowska et al. (2016) for further details regarding the task.

MRI data were obtained with a 3-T Siemens Magnetom Prisma scanner (Siemens Medical Solution), using a 32-channel head coil. Structural T1-weighted images were acquired with a combined MPRAGE and GRAPPA sequence (192 slices, voxel size = 1.0 mm^3, TR = 2300 msec, TE = 3.03 msec, FOV = 256 mm, flip angle = 8°). Functional images were obtained with an ascending dual-echo EPI sequence sensitive to the BOLD contrast: 37 slices, voxel size = 3.3 × 3.3 × 3.0 mm, TR = 1740 msec, TE_1 = 11 msec, TE_2 = 25 msec, FOV = 212 mm, flip angle = 90°.

fMRI data analysis followed similar procedures as the auditory AA task (see above). A random-effects multiple regression analysis was conducted with contrast images of the effects of interest (approach-happy, approach-angry, avoid-happy, avoid-angry). Log-transformed testosterone and log-transformed cortisol values were standardized and added as condition-specific covariates. Finally, subject-specific regressors were added to control for overall between-subject effects. Congruency effects (incongruent vs. congruent trials) were investigated both at the whole-brain cluster level ($p_{FWE} < .05$, cluster-forming threshold $p < .001$) and within the a priori defined VOIs: the bilateral aPFC and amygdala (SVC $p_{FWE} < .05$). Conjunction of spatial activation in the auditory and visual AA tasks was investigated using the *Conjunction Null* analysis in SPM, both within the aPFC VOI (SVC $p_{FWE} < .05$) and at the whole-brain cluster level ($p_{FWE} < .05$, cluster-forming threshold $p < .001$, uncorrected). Differences in neural activity between the auditory and visual AA tasks were investigated by testing for an interaction effect between task versions (Auditory AAT [incongruent > congruent] > Visual AAT [incongruent > congruent]).

Functional Connectivity Analysis—Auditory AA Task

Given our findings of posterior insula activity during emotional control toward affective vocalizations (see Results) and its known role in auditory affective processing vocalizations (Bestelmeyer et al., 2017), we investigated interregional connectivity of the posterior insula with the anterior and ventromedial pFC (vmPFC) during incongruent versus congruent actions. We conducted a psychophysiological analysis (Friston et al., 1997) with the posterior insula seed (8-mm sphere around the task effect peak voxel: MNI *xyz* = 40, −10, −4). Subject-specific contrast images were generated describing the interaction between the time courses of the seed and of the incongruent versus congruent conditions. These contrast images were used in multiple regression analyses, with standardized testosterone and cortisol as covariates. Inferences were made at the whole-brain cluster level ($p_{FWE} < .05$, cluster-forming threshold $p < .001$ uncorrected) and within the functionally defined aPFC VOI (SVC $p_{FWE} < .05$).

RESULTS

Data and results of this paper are available from the Donders Institute for Brain, Cognition and Behaviour repository at http://hdl.handle.net/11633/di.dccn.DSC_3011143.01_768.

Behavioral Results—Auditory AA Task

Participants performed both tasks accurately, with higher performance on the auditory AA Task (95% correct), compared with the GE task (88% correct; task main effect: $F(1, 24) = 48.02$, $p < .001$, $\omega_p^2 = .64$). Importantly, we found a Task (AA/GE) × Valence (happy/anxious) ×

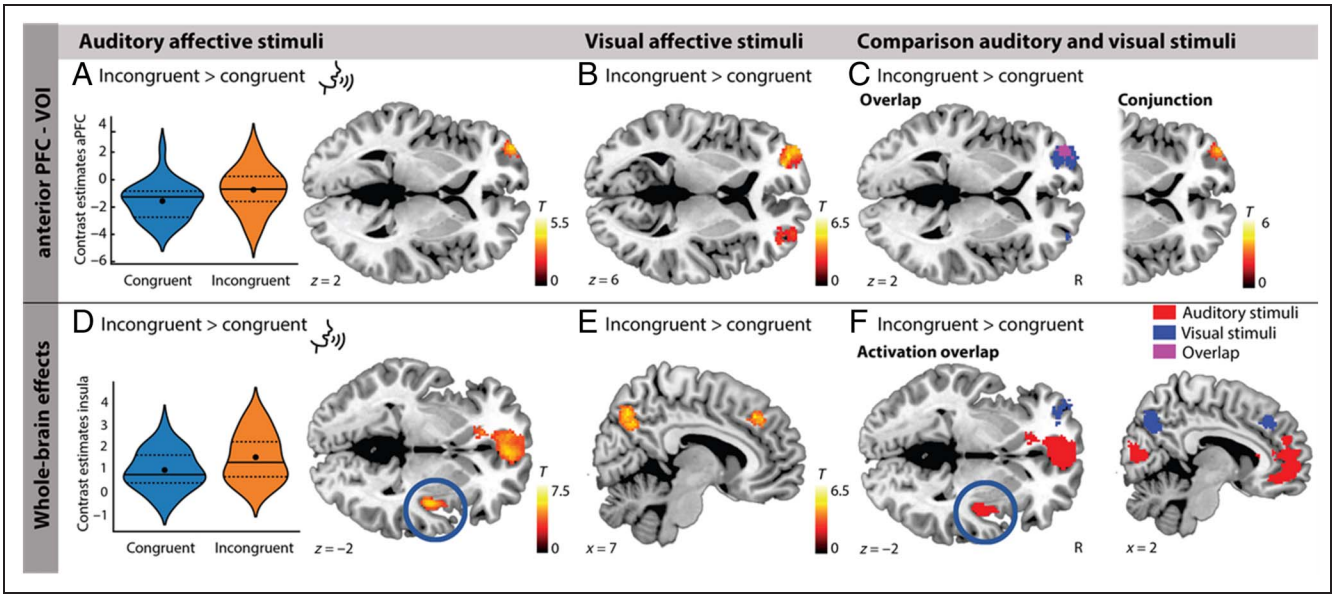

Figure 2. Increased activity in the aPFC during emotional action control toward (A) auditory and (B) visual affective stimuli, and (C) activation overlap and conjunction results for the aPFC VOI. Whole-brain activity during emotional action control in response to (D) auditory and (E) visual affective stimuli, and (F) activation overlap between both tasks. Violin plots show the mean (black dot), median (solid line), and interquartile range (dashed lines) of extracted contrast estimates in the aPFC and posterior insula (blue circle) in arbitrary units. aPFC results shown at $p < .01$ and whole-brain results shown at $p < .001$ for display purposes.

Movement (approach/avoid) interaction effect for RTs, $F(1, 25) = 18.61$, $p < .001$, $\omega_p^2 = .39$ (Figure 1B). When investigating each task separately, we observed a congruency effect in the AA task (Valence × Movement interaction: $F(1, 25) = 36.46$, $p < .001$, $\omega_p^2 = .57$), due to slower responses during affect-incongruent compared with affect-congruent actions. No congruency effect was observed in the GE task ($p = .266$). This indicates behavioral costs in RTs during affect-incongruent responses based on explicit evaluations of affective vocalizations. Cortisol and testosterone did not moderate these congruency effects. For accuracy, no significant congruency effects were observed (AA task $p = .062$, GE task $p = .199$). Therefore, potential differences in neural congruency effects between both tasks cannot be explained by condition-specific differences in task accuracy. Taken together, these results indicate behavioral costs in RTs when participants are required to override their automatic action tendencies in response to explicit evaluation of affective vocalizations.

fMRI Results—Auditory AA Task

General task effects (task > baseline) were found in the bilateral primary auditory cortex (left MNI $xyz = -58, -10, 6$; right MNI $xyz = 56, -20, -10$), left putamen (MNI $xyz = -28, 6, -2$), left motor cortex (MNI $xyz = -32, -28, 68$), cerebellum (MNI $xyz = 4, -64, -14$), and left primary somatosensory cortex (MNI $xyz = -56, -18, 46$; all $p_{FWE} < .05$, whole brain-corrected). Additionally, bilateral amygdala activity (left MNI $xyz = -22, -6, -14$; right MNI $xyz = 18, -10, -16$) was observed during task performance (SVC $p_{FWE} < .05$). Follow-up analyses showed that bilateral amygdala activity was not significantly different in response to negative compared with positive affective vocalization (anxious > happy and happy > anxious: all SVC $p_{FWE} > .729$).

Replicating previous findings on emotional action control using "visual" affective stimuli (Tyborowska et al., 2016; Volman et al., 2016; Volman, Toni, et al., 2011; Roelofs et al., 2009), we observed a congruency effect in the left aPFC in response to affective "vocalizations." Left aPFC activity was increased during incongruent (approach-anxious, avoid-happy) compared with congruent (approach-happy, avoid-anxious) actions (MNI $xyz = -38, 58, 2$; SVC $p_{FWE} = .010$; Figure 2A; see Table 1 for all congruency effects). Comparable but subthreshold congruency effects were observed in the right aPFC (MNI $xyz = 30, 52, 14$). Extending previous findings, we found right posterior insula activity during incongruent compared with congruent responses (MNI $xyz = 40, -10, -4$; $p_{FWE} = .006$), predominantly located in dysgranular region Id1 (Kurth et al., 2010). Additionally, vmPFC activity was observed during incongruent (vs. congruent) responses (MNI $xyz = 2, 52, -2$; $p_{FWE} < .001$), with local maxima in the middle orbital gyrus, superior medial gyrus, and ACC (Figure 2D). These congruency effects were not significantly modulated by salivary testosterone or cortisol (all $p_{FWE} > .05$).

Decreased activation during emotional action control (incongruent < congruent) was observed in the thalamic pulvinar nucleus (MNI $xyz = 6, -30, 2$; $p_{FWE} < .001$). Furthermore, pulvinar activity was significantly modulated by testosterone: Participants with relatively higher testosterone levels showed more thalamic activity during

Table 1. Activation Clusters and Connectivity Results—Auditory AA Task

Anatomical Region	*Side*	*Cluster Size*	*x*	*y*	*z*	*p*	*t Statistic*
Incongruent > congruent							
Anterior prefrontal cortex[a]	L	68	−38	58	2	.010	3.82
Inferior temporal gyrus	R	499	46	−2	−32	<.001	5.36
Posterior insula, area Id1	R	365	40	−10	−4	.006	5.16
vmPFC/anterior cingulate cortex	L	2268	2	52	−2	<.001	5.12
Cerebellum, Lobule V	R	221	−16	−40	−10	.013	5.10
Visual cortex, calcarine gyrus	R	385	4	−78	10	.001	4.49
Congruent > Incongruent							
Thalamus (pulvinar nucleus)	R	522	6	−30	2	<.001	5.29
	L[b]	–	−10	−28	12	–	5.24
Testosterone modulation–thalamus	R	656	10	−22	2	<.001	5.24
Cortisol modulation–amygdala[a]	L	68	−26	−8	−12	.009	3.86
Negative functional connectivity (posterior insula seed) incongruent > congruent							
Anterior prefrontal cortex/frontal pole	R	574	24	48	6	<.001	5.82
Putamen	R	312	28	4	−2	.002	6.32
Inferior frontal gyrus	L	314	−56	18	14	.002	5.55
Cerebellum	L	282	−16	−64	−36	.003	5.02
Middle temporal gyrus	R	175	52	−40	0	.032	4.68

p Values are FWE-corrected at the cluster level for whole-brain effects (initial cluster-forming threshold $p < .001$) and at the voxel level for the VOIs (bilateral aPFC and amygdala). L = left hemisphere; R = right hemisphere. Coordinates are given in MNI stereotaxic space.

[a]Small volume-corrected.

[b]Local maximum in same cluster in contralateral hemisphere.

congruent responses. Despite showing robust task-related responses, the amygdala was not significantly influenced by demands of emotional action control. However, individuals with relatively higher cortisol showed relatively increased left amygdala activity during congruent responses.

In the GE task, we observed no differences between incongruent (approach-angry, avoid-happy) compared with congruent (approach-happy, avoid-angry) actions (all $p_{FWE} > .05$). Moreover, all AA task congruency effects remained significant after masking with the Task × Valence × Movement interaction effect. Thus, the observed neural congruency effects were significantly stronger when based on explicit (AA task) compared with implicit (GE task) affective evaluations.

Conjunction With Visual AA Task

To test whether the observed neural control network is independent from the modality of the affective stimuli, we conducted a between-studies conjunction analysis using visual AA task fMRI data. At the behavioral level, we observed the expected congruency effects: participants responded slower and made more errors during incongruent versus congruent actions (all $p < .001$). During incongruent (vs. congruent) responses to affective visual stimuli, increased activity was found in the bilateral aPFC (left MNI $xyz = -30, 56, 6$; SVC $p_{FWE} = .001$; right MNI $xyz = 34, 48, 12$; SVC $p_{FWE} = .001$; Figure 2B), as well as in the inferior parietal lobule (left MNI $xyz = -34, -54, 40$; right MNI $= 44, -52, 50$), inferior frontal gyrus (MNI $xyz = 48, 28, -20$), precuneus (MNI $xyz = 0, -70, 44$), and frontal gyrus (MNI $xyz = -20, 2, 48$; MNI $xyz = -48, 18, 50$; all $p_{FWE} < .05$ whole brain-corrected; Figure 2E). Critically, a conjunction analysis between congruency effects observed in the auditory and visual AA tasks showed spatial overlap in the left aPFC (MNI $xyz = -38, 58, 2$; SVC $p_{FWE} = .012$, $k = 70$), confirming our hypothesis of supramodal contributions of the aPFC during control over emotional action tendencies (Figure 2C). No significant overlap was found in the rest of the brain (all $p_{FWE} > .05$; Figure 2F). Given potentially confounding demographic differences between samples of the

auditory and visual AA tasks, we selected a matched visual AA task sample consisting of females with middle to high education (n = 81). We again observed left aPFC activity during affect-incongruent responses in this matched sample (MNI xyz = −28, 54, 8; SVC p_{FWE} = .031). Taken together, these results confirm our hypothesis of supramodal contributions of the aPFC during control over emotional action tendencies. Congruency effects in the posterior insula and vmPFC were observed only in the auditory version of the AA task. We found a significant tasks interaction effect (Auditory AAT [incongruent > congruent] > Visual AAT [incongruent > congruent]) in the posterior insula (MNI xyz = 48, 2, 2; p_{FWE} < .001, which included local maxima at the auditory AA task peak coordinates: MNI xyz = 42, −14, −6), indicating higher posterior insula activity in the auditory compared with the visual AA task. Similarly, a significant tasks interaction effect in the medial pFC (MNI xyz = 4, 52, 22; p_{FWE} < .001, again with local maxima at the auditory AA task peak coordinates: MNI xyz = 0, 54, 2) indicated greater medial pFC activity during emotional control in response to affective vocalizations compared with emotional faces. These findings were replicated in the matched visual AA task sample. This suggests that these regions support a modality-dependent form of emotional control, in line with their known involvement in affective processing of voice stimuli with motivational significance (Bestelmeyer et al., 2017).

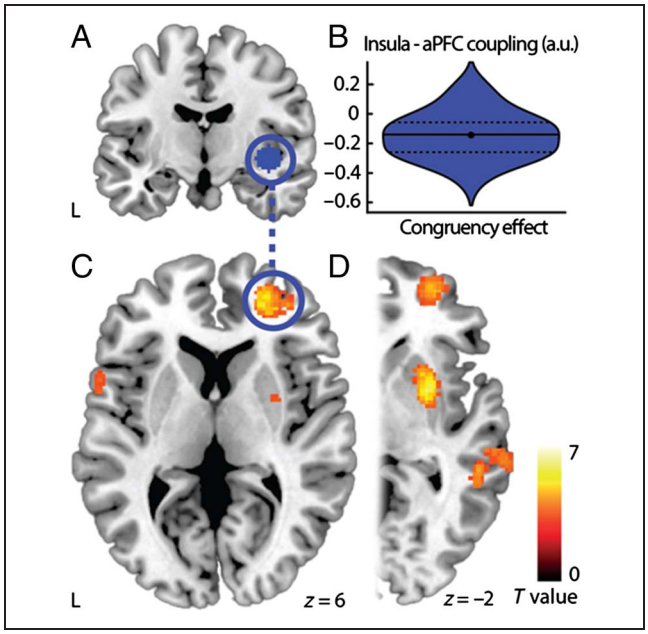

Figure 3. Negative functional connectivity during emotional action control (incongruent > congruent responses) between (A) the posterior insula seed, (B, C) the right aPFC, and (D) putamen and middle temporal gyrus (shown at p < .001 for display purposes). (B) The violin plot shows the mean (black dot), median (solid line), and interquartile range (dashed lines) of extracted contrast estimates of the negative insula–aPFC coupling during emotional action control in arbitrary units (a.u.).

Functional Connectivity—Auditory AA Task

We investigated interregional connectivity of the posterior insula (seed) with the (anterior) pFC during control of auditory-evoked emotional responses. The psychophysiological analysis showed significant incongruency-driven negative connectivity with several brain regions, including the right putamen, left inferior frontal gyrus, cerebellum, and middle temporal gyrus (Table 1). Most critically, the right posterior insula showed negative effective connectivity during emotional action control at the right lateral frontal pole (MNI xyz = 24, 48, 6; p_{FWE} < .001; Figure 3). Confirmatory analysis with our functionally defined aPFC mask confirmed that this effect was located in the right aPFC VOI (MNI xyz = 26, 52, 6; SVC p_{FWE} = .001) and in the left aPFC at subthreshold levels (MNI xyz = −28, 54, 0). These congruency effects were independent of salivary testosterone and cortisol levels (all p_{FWE} >.05). No task-related functional connectivity was found between the posterior insula seed and vmPFC. Taken together, we observed negative functional posterior insula–aPFC connectivity during control over emotional actions towards affective vocalizations, that is, when automatic action tendencies needed to be overridden.

DISCUSSION

This study characterizes a neural circuit for controlling automatic responses elicited by human affective vocalizations, consisting of both modality-independent and modality-specific elements. By directly comparing neural control over emotional action tendencies evoked by auditory and visual affective stimuli, we show that the aPFC controls social–emotional actions in a supramodal manner, that is, irrespectively of the sensory modality of the stimuli. Contrastingly, the posterior insula is preferentially involved during control responses evoked by auditory affect, showing negative functional connectivity with the aPFC during emotional control.

Previous studies using various methodologies (e.g., TMS, fMRI, and MEG) have consistently observed aPFC involvement during control of emotional actions elicited by visual affective stimuli (Bramson et al., 2018; Kaldewaij, Koch, Volman, Toni, & Roelofs, 2016; Tyborowska et al., 2016; Volman, Roelofs, et al., 2011; Volman, Toni, et al., 2011). This type of emotional control differs substantially from control required to resolve emotional conflict at a stimulus level, such as conflicts between emotion and color in emotional Stroop tasks (Williams, Mathews, & MacLeod, 1996; MacLeod, 1991), or between a negative and desired positive interpretation of a visual scene in cognitive reappraisal studies (Etkin et al., 2015). In contrast, control over emotional action tendencies captures the interaction between the emotional valence of a stimulus and an action (Bramson et al., 2018; Roelofs et al., 2009). Control over this interaction may not be accomplished by simply suppressing the emotional action tendency. As

overriding automatic action tendencies may have aversive consequences (e.g., approaching an anxiously screaming individual may put yourself in danger), considering potential alternative actions is required to enable rapid switching to the best alternative option when needed (i.e., avoiding the situation when danger is imminent; Koch et al., 2018). The supramodal character of aPFC contributions to emotional control fits with observations that this area is not directly connected with primary sensory cortices (Ramnani & Owen, 2004) and that it supports metacognitive processes, including the representation of alternative courses of actions to those currently pursued (Mansouri et al., 2017; Koechlin, 2016; Boorman et al., 2009; Koechlin & Hyafil, 2007). The aPFC could contribute to emotional control by implementing abstract goals while controlling immediate action tendencies (Bramson et al., 2018; Koch et al., 2018), possibly by simultaneously monitoring evidence in favor of alternative actions (Mansouri et al., 2017; Koechlin, 2016; Boorman et al., 2009). Our findings introduce a novel element to the functional anatomy of emotion regulation (Morawetz et al., 2017; Etkin et al., 2015; Ochsner, Silvers, & Buhle, 2012). Existing models have focused on differentiating the contribution of dorsolateral and ventrolateral prefrontal cortices to emotional processing of visual material (Morawetz et al., 2017; Etkin et al., 2015). The contribution of the aPFC to emotional control, as well as its supramodal nature, has been largely ignored, despite growing suggestions from coordinate-based meta-analyses of cognitive emotion regulation studies (Koch et al., 2018; Morawetz et al., 2017; Kalisch, 2009).

Besides supramodal aPFC contributions, control over action tendencies evoked by affective vocalizations relies on modality-specific cortical regions: the posterior insula and the vmPFC. Both regions have been implicated in processing emotional sounds (Frühholz et al., 2016), including valence and arousal of affective vocalizations (Bestelmeyer et al., 2017). The vmPFC is additionally involved in regulating emotional behavior (Frühholz et al., 2016), such as fear extinction recall (Milad et al., 2007; Phelps, Delgado, Nearing, & LeDoux, 2004) and cognitive emotion regulation (Diekhof, Geier, Falkai, & Gruber, 2011; Hartley & Phelps, 2010). The posterior insula supports processing of somatosensory and auditory stimuli with motivational significance (Chang et al., 2013), including affective instrumental and voice sounds (Sachs, Habibi, Damasio, & Kaplan, 2018), human voices compared with environmental sounds (Schirmer et al., 2012), and affective vocalizations with high valence and arousal (Bestelmeyer et al., 2017). In humans, direct anatomical connections exist between the posterior insula and auditory cortex, as well as between the posterior insula and aPFC (Ghaziri et al., 2017). This fits with our observation of negative functional connectivity between the posterior insula and aPFC during control toward auditory affective stimuli: The posterior insula may process the motivational salience of auditory affect, which is being downregulated by the aPFC when emotional control is required. This interpretation assigns a rostrocaudal direction in the control-related changes in functional connectivity between the aPFC and posterior insula. This speculation is supported by previous studies showing prefrontal control over auditory processing (Mitchell, Morey, Inan, & Belger, 2005; Knight, Scabini, & Woods, 1989), as well as aPFC modulations of gamma-band power in sensorimotor areas during emotional action control with visual affective stimuli (Bramson et al., 2018). Future interference studies or electrophysiological recordings could test whether the aPFC plays a causal role in modulating posterior insula responses to affective vocalizations when emotional responses need to be controlled.

The primary auditory cortex and amygdala respond to affective vocalizations to a similar extent for actions either congruent or incongruent to auditory-evoked action tendencies. However, previous fMRI studies showed altered amygdala activity, as well as negative aPFC–amygdala functional connectivity during emotional action control using visual affective stimuli (Volman et al., 2013, 2016). It has been suggested that amygdala involvement in unimodal affective voice processing is fairly modest (Schirmer & Adolphs, 2017), which is corroborated by recent meta-analytic evidence showing less amygdala activation during explicit evaluation of emotional expressions in voices compared with faces (Dricu & Frühholz, 2016). Possibly, less amygdala down-regulation was required when overriding automatic action tendencies elicited by affective vocalizations compared with those elicited by affective visual stimuli. Our findings suggest supramodal aPFC contributions during emotional action control over modality-sensitive areas signaling motivational significance, such as the amygdala for visual stimuli (Volman et al., 2013) and the posterior insula for auditory affective stimuli.

Some limitations should be considered when evaluating these findings. First, only female participants were included in the auditory AA task study, eliminating potential confounding effects of sex differences (Cahill, 2006), but also limiting the generalizability of our findings. Nevertheless, we still observed aPFC activity during emotional action control in male and female subsamples of the visual AA task. This observation is in line with previous studies showing aPFC activity during emotional action control with visual affective stimuli in males (Radke et al., 2017; Volman et al., 2013, 2016; Volman, Toni, et al., 2011) and females (Bertsch et al., 2018; Radke et al., 2015). Furthermore, we observed left aPFC activity during the auditory AA task, but functional connectivity between the right posterior insula and right aPFC. Previous studies showed that aPFC activity and connectivity were not consistently lateralized during emotional control toward affective visual stimuli, and lateralization changed as a function of statistical thresholding (Bertsch et al., 2018; Volman et al., 2016; Roelofs et al., 2009). This suggestion was recently confirmed by a meta-analysis showing bilateral aPFC activation across visual AA tasks (Koch et al.,

2018), and it is in line with the current observations of subthreshold right aPFC task activity and left aPFC functional connectivity during emotional action control in the auditory AA task. Finally, the auditory and visual AA tasks were performed by different participants, excluding the possibility that the supramodal aPFC effects are in fact carryover effects of previous task performance. However, it remains to be investigated whether the aPFC shows similar neural patterns across sensory modalities within the same participants, for example, using multivariate cross-classification (Kaplan, Man, & Greening, 2015). We cannot rule out the possibility that differences in neural activity between both task versions may have been influenced by differences in samples and study procedures, rather than differences in sensory modality, although a control analysis with a matched sample replicated the current findings.

In conclusion, we demonstrated supramodal contributions of the aPFC to emotional control of automatic responses elicited by auditory and visual affective stimuli. When controlling automatic actions toward affective vocalizations, the aPFC modulates modality-specific responses in the posterior insula, possibly by downregulating the motivational salience of affective vocalizations. These findings open the way for future studies investigating supramodal emotional control in psychopathologies characterized with emotional dysregulations, such as social anxiety, borderline personality disorder, and psychopathy (Bertsch et al., 2018; Volman et al., 2016; Roelofs et al., 2010).

Acknowledgments

This work was supported by the Netherlands Organization for Scientific Research (VIDI grant number 452-09-006, awarded to Christian J. Fiebach), funding the auditory AA task study and author A. G. This work was further supported by the European Research Council (starting grant number ERC_StG2012_313749, awarded to K. R.) and the Netherlands Organization for Scientific Research (VICI grant number 453-12-001, awarded to K. R.), supporting the visual AA task study and authors S. B. J. K., R. K., and K. R. We thank all our participants for their participation, as well as our current and former colleagues of the "Police-in-Action" project for their valuable help in participant recruitment and data acquisition of the visual AA task study. Voice symbol in Figure 1 was by Gregor Cresnar from the Noun Project.

Reprint requests should be sent to Saskia B. J. Koch, Donders Centre for Cognitive Neuroimaging, Kapittelweg 29, 6525 EN Nijmegen, The Netherlands, or via e-mail: s.koch@donders.ru.nl.

REFERENCES

Belin, P., Fillion-Bilodeau, S., & Gosselin, F. (2008). The Montreal affective voices: A validated set of nonverbal affect bursts for research on auditory affective processing. *Behavior Research Methods*, *40*, 531–539.

Bertsch, K., Roelofs, K., Roch, P. J., Ma, B., Hensel, S., Herpertz, S. C., et al. (2018). Neural correlates of emotional action control in anger-prone women with borderline personality disorder. *Journal of Psychiatry & Neuroscience*, *43*, 161–170.

Bestelmeyer, P. E., Kotz, S. A., & Belin, P. (2017). Effects of emotional valence and arousal on the voice perception network. *Social Cognitive and Affective Neuroscience*, *12*, 1351–1358.

Bestelmeyer, P. E., Maurage, P., Rouger, J., Latinus, M., & Belin, P. (2014). Adaptation to vocal expressions reveals multistep perception of auditory emotion. *Journal of Neuroscience*, *34*, 8098–8105.

Bludau, S., Eickhoff, S. B., Mohlberg, H., Caspers, S., Laird, A. R., Fox, P. T., et al. (2014). Cytoarchitecture, probability maps and functions of the human frontal pole. *Neuroimage*, *93*, 260–275.

Boorman, E. D., Behrens, T. E., Woolrich, M. W., & Rushworth, M. F. (2009). How green is the grass on the other side? Frontopolar cortex and the evidence in favor of alternative courses of action. *Neuron*, *62*, 733–743.

Braga, R. M., Hellyer, P. J., Wise, R. J., & Leech, R. (2017). Auditory and visual connectivity gradients in frontoparietal cortex. *Human Brain Mapping*, *38*, 255–270.

Bramson, B., Jensen, O., Toni, I., & Roelofs, K. (2018). Cortical oscillatory mechanisms supporting the control of human social–emotional actions. *Journal of Neuroscience*, *38*, 5739–5749.

Cahill, L. (2006). Why sex matters for neuroscience. *Nature Reviews Neuroscience*, *7*, 477–484.

Chang, L. J., Yarkoni, T., Khaw, M. W., & Sanfey, A. G. (2013). Decoding the role of the insula in human cognition: Functional parcellation and large-scale reverse inference. *Cerebral Cortex*, *23*, 739–749.

Chen, M., & Bargh, J. A. (1999). Consequences of automatic evaluation: Immediate behavioral predispositions to approach or avoid the stimulus. *Personality and Social Psychology Bulletin*, *25*, 215–224.

Cheney, D. L., & Seyfarth, R. M. (2018). Flexible usage and social function in primate vocalizations. *Proceedings of the National Academy of Sciences, U.S.A.*, *115*, 1974–1979.

Diekhof, E. K., Geier, K., Falkai, P., & Gruber, O. (2011). Fear is only as deep as the mind allows: A coordinate-based meta-analysis of neuroimaging studies on the regulation of negative affect. *Neuroimage*, *58*, 275–285.

Dricu, M., & Frühholz, S. (2016). Perceiving emotional expressions in others: Activation likelihood estimation meta-analyses of explicit evaluation, passive perception and incidental perception of emotions. *Neuroscience & Biobehavioral Reviews*, *71*, 810–828.

Eder, A. B., & Rothermund, K. (2008). When do motor behaviors (mis)match affective stimuli? An evaluative coding view of approach and avoidance reactions. *Journal of Experimental Psychology: General*, *137*, 262–281.

Eickhoff, S. B., Stephan, K. E., Mohlberg, H., Grefkes, C., Fink, G. R., Amunts, K., et al. (2005). A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. *Neuroimage*, *25*, 1325–1335.

Ekman, P., & Friesen, W. (1975). *Pictures of facial affect*. Palo Alto, CA: Consulting Psychologists Press.

Etkin, A., Büchel, C., & Gross, J. J. (2015). The neural bases of emotion regulation. *Nature Reviews Neuroscience*, *16*, 693–700.

Frijda, N. H. (1986). *The emotions*. Cambridge: Cambridge University Press.

Friston, K., Buechel, C., Fink, G. R., Morris, J., Rolls, E., & Dolan, R. (1997). Psychophysiological and modulatory interactions in neuroimaging. *Neuroimage*, *6*, 218–229.

Frühholz, S., Trost, W., & Grandjean, D. (2014). The role of the medial temporal limbic system in processing emotions in voice and music. *Progress in Neurobiology*, *123*, 1–17.

Frühholz, S., Trost, W., & Kotz, S. A. (2016). The sound of emotions—Towards a unifying neural network perspective of affective sound processing. *Neuroscience & Biobehavioral Reviews*, *68*, 96–110.
Ghaziri, J., Tucholka, A., Girard, G., Houde, J.-C., Boucher, O., Gilbert, G., et al. (2017). The corticocortical structural connectivity of the human insula. *Cerebral Cortex*, *27*, 1216–1228.
Hartley, C. A., & Phelps, E. A. (2010). Changing fear: The neurocircuitry of emotion regulation. *Neuropsychopharmacology*, *35*, 136–146.
Heuer, K., Rinck, M., & Becker, E. S. (2007). Avoidance of emotional facial expressions in social anxiety: The approach–avoidance task. *Behaviour Research and Therapy*, *45*, 2990–3001.
James, W. (1884). II. What is an emotion? *Mind*, *os-IX*, 188–205.
Kaldewaij, R., Koch, S. B. J., Volman, I., Toni, I., & Roelofs, K. (2016). On the control of social approach–avoidance behavior: Neural and endocrine mechanisms. *Current Topics in Behavioral Neurosciences*, *30*, 275–293.
Kaldewaij, R., Koch, S. B. J., Zhang, W., Hashemi, M. M., Klumpers, F., & Roelofs, K. (2019a). Frontal control over automatic emotional action tendencies predicts acute stress responsivity. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *4*, 975–983.
Kaldewaij, R., Koch, S. B. J., Zhang, W., Hashemi, M. M., Klumpers, F., & Roelofs, K. (2019b). High endogenous testosterone levels are associated with diminished neural emotional control in aggressive police recruits. *Psychological Science*, *30*, 11611–11173.
Kalisch, R. (2009). The functional neuroanatomy of reappraisal: Time matters. *Neuroscience & Biobehavioral Reviews*, *33*, 1215–1226.
Kaplan, J. T., Man, K., & Greening, S. G. (2015). Multivariate cross-classification: Applying machine learning techniques to characterize abstraction in neural representations. *Frontiers in Human Neuroscience*, *9*, 151.
Knight, R. T., Scabini, D., & Woods, D. L. (1989). Prefrontal cortex gating of auditory transmission in humans. *Brain Research*, *504*, 338–342.
Koch, S. B. J., Klumpers, F., Zhang, W., Hashemi, M. M., Kaldewaij, R., van Ast, V. A., et al. (2017). The role of automatic defensive responses in the development of posttraumatic stress symptoms in police recruits: Protocol of a prospective study. *European Journal of Psychotraumatology*, *8*, 1412226.
Koch, S. B. J., Mars, R. B., Toni, I., & Roelofs, K. (2018). Emotional control, reappraised. *Neuroscience & Biobehavioral Reviews*, *95*, 528–534.
Koechlin, E. (2016). Prefrontal executive function and adaptive behavior in complex environments. *Current Opinion in Neurobiology*, *37*, 1–6.
Koechlin, E., & Hyafil, A. (2007). Anterior prefrontal function and the limits of human decision-making. *Science*, *318*, 594–598.
Kurth, F., Eickhoff, S. B., Schleicher, A., Hoemke, L., Zilles, K., & Amunts, K. (2010). Cytoarchitecture and probabilistic maps of the human posterior insular cortex. *Cerebral Cortex*, *20*, 1448–1461.
Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (1990). Emotion, attention, and the startle reflex. *Psychological Review*, *97*, 377–395.
LeDoux, J. (2012). Rethinking the emotional brain. *Neuron*, *73*, 653–676.
Lund, T. E., Nørgaard, M. D., Rostrup, E., Rowe, J. B., & Paulson, O. B. (2005). Motion or activity: Their role in intra- and inter-subject variation in fMRI. *Neuroimage*, *26*, 960–964.
Lundqvist, D., Flykt, A., & Ohman, A. (1998). The Karolinska directed emotional faces (KDEF). CD ROM from Department of Clinical Neuroscience, Psychology section, Karolinska Institutet.
MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*, 163–203.
Mansouri, F. A., Koechlin, E., Rosa, M. G. P., & Buckley, M. J. (2017). Managing competing goals—A key role for the frontopolar cortex. *Nature Reviews Neuroscience*, *18*, 645–657.
Mars, R. B., Jbabdi, S., Sallet, J., O'Reilly, J. X., Croxson, P. L., Olivier, E., et al. (2011). Diffusion-weighted imaging tractography-based parcellation of the human parietal cortex and comparison with human and macaque resting-state functional connectivity. *Journal of Neuroscience*, *31*, 4087–4100.
Martinez, A., & Benavente, R. (1998). The AR face database. CVC Technical Report. No. 24. Barcelona, Spain: Centre de Visioper Computador, Universitat Autonoma de Barcelona.
Matsumoto, D., & Ekman, P. (1988). *Japanese and Caucasian facial expressions of emotion and neutral faces*. San Francisco: University of California.
Mayer, A., Schwiedrzik, C. M., Wibral, M., Singer, W., & Melloni, L. (2016). Expecting to see a letter: Alpha oscillations as carriers of top–down sensory predictions. *Cerebral Cortex*, *26*, 3146–3160.
Milad, M. R., Wright, C. I., Orr, S. P., Pitman, R. K., Quirk, G. J., & Rauch, S. L. (2007). Recall of fear extinction in humans activates the ventromedial prefrontal cortex and hippocampus in concert. *Biological Psychiatry*, *62*, 446–454.
Mitchell, T. V., Morey, R. A., Inan, S., & Belger, A. (2005). Functional magnetic resonance imaging measure of automatic and controlled auditory processing. *NeuroReport*, *16*, 457–461.
Morawetz, C., Bode, S., Baudewig, J., Jacobs, A. M., & Heekeren, H. R. (2016). Neural representation of emotion regulation goals. *Human Brain Mapping*, *37*, 600–620.
Morawetz, C., Bode, S., Derntl, B., & Heekeren, H. R. (2017). The effect of strategies, goals and stimulus material on the neural mechanisms of emotion regulation: A meta-analysis of fMRI studies. *Neuroscience & Biobehavioral Reviews*, *72*, 111–128.
Neubert, F. X., Mars, R. B., Thomas, A. G., Sallet, J., & Rushworth, M. F. (2014). Comparison of human ventral frontal cortex areas for cognitive control and language with areas in monkey frontal cortex. *Neuron*, *81*, 700–713.
Ochsner, K. N., & Gross, J. J. (2005). The cognitive control of emotion. *Trends in Cognitive Sciences*, *9*, 242–249.
Ochsner, K. N., Silvers, J. A., & Buhle, J. T. (2012). Functional imaging studies of emotion regulation: A synthetic review and evolving model of the cognitive control of emotion. *Annals of the New York Academy of Sciences*, *1251*, E1–E24.
Pannese, A., Grandjean, D., & Frühholz, S. (2015). Subcortical processing in auditory communication. *Hearing Research*, *328*, 67–77.
Phelps, E. A., Delgado, M. R., Nearing, K. I., & LeDoux, J. E. (2004). Extinction learning in humans: Role of the amygdala and vmPFC. *Neuron*, *43*, 897–905.
Radke, S., Volman, I., Kokal, I., Roelofs, K., de Bruijn, E. R. A., & Toni, I. (2017). Oxytocin reduces amygdala responses during threat approach. *Psychoneuroendocrinology*, *79*, 160–166.
Radke, S., Volman, I., Mehta, P., van Son, V., Enter, D., Sanfey, A., et al. (2015). Testosterone biases the amygdala toward social threat approach. *Science Advances*, *1*, e1400074.
Ramnani, N., & Owen, A. M. (2004). Anterior prefrontal cortex: Insights into function from anatomy and neuroimaging. *Nature Reviews Neuroscience*, *5*, 184–194.
Roelofs, K., Elzinga, B. M., & Rotteveel, M. (2005). The effects of stress-induced cortisol responses on approach–avoidance behavior. *Psychoneuroendocrinology*, *30*, 665–677.

Roelofs, K., Minelli, A., Mars, R. B., van Peer, J., & Toni, I. (2009). On the neural control of social emotional behavior. *Social Cognitive and Affective Neuroscience*, *4*, 50–58.

Roelofs, K., Putman, P., Schouten, S., Lange, W.-G., Volman, I., & Rinck, M. (2010). Gaze direction differentially affects avoidance tendencies to happy and angry faces in socially anxious individuals. *Behaviour Research and Therapy*, *48*, 290–294.

Sachs, M. E., Habibi, A., Damasio, A., & Kaplan, J. T. (2018). Decoding the neural signatures of emotions expressed through sound. *Neuroimage*, *174*, 1–10.

Schirmer, A., & Adolphs, R. (2017). Emotion perception from face, voice, and touch: Comparisons and convergence. *Trends in Cognitive Sciences*, *21*, 216–228.

Schirmer, A., Fox, P. M., & Grandjean, D. (2012). On the spatial organization of sound processing in the human temporal lobe: A meta-analysis. *Neuroimage*, *63*, 137–147.

Tyborowska, A., Volman, I., Smeekens, S., Toni, I., & Roelofs, K. (2016). Testosterone during puberty shifts emotional control from pulvinar to anterior prefrontal cortex. *Journal of Neuroscience*, *36*, 6156–6164.

Volman, I., Roelofs, K., Koch, S., Verhagen, L., & Toni, I. (2011). Anterior prefrontal cortex inhibition impairs control over social emotional actions. *Current Biology*, *21*, 1766–1770.

Volman, I., Toni, I., Verhagen, L., & Roelofs, K. (2011). Endogenous testosterone modulates prefrontal-amygdala connectivity during social emotional behavior. *Cerebral Cortex*, *21*, 2282–2290.

Volman, I., Verhagen, L., den Ouden, H. E. M., Fernandez, G., Rijpkema, M., Franke, B., et al. (2013). Reduced serotonin transporter availability decreases prefrontal control of the amygdala. *Journal of Neuroscience*, *33*, 8974–8979.

Volman, I., von Borries, A. K. L., Hendrik Bulten, B., Jan Verkes, R., Toni, I., & Roelofs, K. (2016). Testosterone modulates altered prefrontal control of emotional actions in psychopathic offenders. *eNeuro*, *3*, 1–12.

Williams, J. M., Mathews, A., & MacLeod, C. (1996). The emotional Stroop task and psychopathology. *Psychological Bulletin*, *120*, 3–24.

Woo, C. W., Krishnan, A., & Wager, T. D. (2014). Cluster-extent based thresholding in fMRI analyses: Pitfalls and recommendations. *Neuroimage*, *91*, 412–419.

Zhang, Y., Zhou, W., Wang, S., Zhou, Q., Wang, H., Zhang, B., et al. (2018). The roles of subdivisions of human insula in emotion perception and auditory processing. *Cerebral Cortex*, *29*, 517–528.