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Evaluating ambivalence: social-cognitive and affective brain regions associated with ambivalent decision-making

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Ambivalence is a state of inconsistency that is often experienced as affectively aversive. In this functional magnetic resonance imaging study, we investigated the role of cognitive and social-affective processes in the experience of ambivalence and coping with its negative consequences. We examined participants' brain activity during the dichotomous evaluation (pro *vs* contra) of pretested ambivalent (e.g. alcohol), positive (e.g. happiness) and negative (e.g. genocide) word stimuli. We manipulated evaluation relevance by varying the probability of evaluation consequences, under the hypothesis that ambivalence is experienced as more negative when outcomes are relevant. When making ambivalent evaluations, more activity was found in the anterior cingulate cortex, the insula, the temporal parietal junction (TPJ) and the posterior cingulate cortex (PCC)/precuneus, for both high and low evaluation relevance. After statistically conservative corrections, activity in the TPJ and PCC/precuneus was negatively correlated with experienced ambivalence after scanning, as measured by Priester and Petty's felt ambivalence scale (1996). The findings show that cognitive and social-affective brain areas are involved in the experience of ambivalence. However, these networks are differently associated with subsequent reduction of ambivalence, thus highlighting the importance of understanding both cognitive and affective processes involved in ambivalent decision-making.

Keywords: ambivalence; decision-making; fMRI; coping behavior; social-affective network

INTRODUCTION

Ambivalence, defined as the coexistence of opposing attitudinal positions, is a state that violates humans' motivation to be consistent in ones' thoughts, feelings and behaviors (Festinger, 1964; Kaplan, 1972; Brinol and Petty, 2005; Proulx *et al.*, 2012). Ambivalence is experienced in a broad range of situations, stretching from intimate relationships to broader societal issues, such as abortion or the use of nuclear energy. Ambivalent attitudes are cognitively complex (Cacioppo *et al.*, 1997), can lead to the experience of conflicting emotions (e.g. Hass *et al.*, 1992; Newby-Clark *et al.*, 2002), and are thus often experienced as aversive when making high stake decisions (van Harreveld *et al.*, 2009a; for an overview, see van Harreveld *et al.*, 2009b). In this imaging study we were interested in these cognitive and affective components of ambivalence, and investigated how coping processes aimed at ambivalence reduction are associated with brain activation during the evaluation of ambivalent stimuli.

Prior neuroscientific studies focused primarily on the cognitive aspects of ambivalent attitudes (viz. Cunningham *et al.*, 2003; Cunningham *et al.*, 2004; Jung *et al.*, 2008). Cunningham and colleagues (2003) observed that evaluating ambivalent famous names (e.g. Bill Clinton) elicits increased activity in the ventrolateral prefrontal cortex, especially when these names were evaluated on their conflicting evaluative dimension (good *vs* bad) relative to when they were classified into non-evaluative categories (e.g. past *vs* present). These findings were thought to indicate more effortful information processing for ambivalent concepts (Cunningham and others 2003). In a following study, Cunningham *et al.* (2004) provided additional evidence for the cognitive complexity of ambivalent attitudes by showing that evaluating ambivalent, socially relevant concepts (e.g. immigration) on the evaluative good–bad dimension was positively correlated with activity in areas that are activated during tasks requiring cognitive control, including the anterior cingulate cortex (ACC). This correlation was not found when the ambivalent concepts were evaluated on a non-evaluative dimension. The latter finding was interpreted in terms of ambivalence being a state of conflict requiring additional processing and control (see also Botvinick *et al.*, 2001; Kerns *et al.*, 2004).

Despite the progress that has been made in unraveling brain regions involved in cognitive processing of ambivalence, no prior studies examined neural correlates of the affective components of ambivalence. This is surprising, as research repeatedly showed that ambivalent attitudes present an inconsistency among attitude components that can be experienced as aversive (e.g. van Harreveld *et al.*, 2009b). For example, it has been demonstrated that ambivalence elicits more negative affect when one has to commit to one side of one's attitude compared with when one can stay uncommitted (van Harreveld *et al.*, 2009a). This is especially the case when the decision has consequences for the decision-maker. For example, van Harreveld and colleagues (2009a) provided participants with either univalent or ambivalent information and subsequently asked them to write an article on this topic. Participants receiving ambivalent information were either forced to form a univalent judgment on the topic or they were allowed to express an uncommitted, mixed attitude. Ambivalent individuals who had to give a univalent evaluation of the topic experienced more physiological arousal as measured by electrodermal activity and reported higher negative affect. Prior studies demonstrated that the experience of negative emotional states in general and the generation of physiological arousal is associated with elevated activity in several brain regions, including the insula (Critchley *et al.*, 2000; Phan *et al.*, 2004; Critchley, 2005), a limbic forebrain area thought to serve as a hub for the integration of affective and cognitive processes (Craig, 2009) and that contributes to the subjective experience of emotions (Mériau *et al.*, 2009). Critchley *et al.* (2000) showed, for example, that spontaneous fluctuations of physiological arousal measured by electrodermal activity during a card game with faked feedback were correlated with activation changes in the anterior insula. Given that ambivalence is associated with negative affect and physiological arousal, these findings suggest that ambivalence is associated with enhanced activity in the insula.

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Second, attitudinal ambivalence is thought to be a social-cognitive process given that attitudes fulfill an essential social function. According to Lieberman (2007), attitudes describe and form our social identities. This social nature of attitudes becomes apparent when looking at the influence others can have on our attitudes. Experiencing discrepancy between one's attitude and the attitude of close others (e.g. family, friends), for example, can increase one's ambivalence toward an attitude topic (Priester and Petty, 2001). We believe social cognition to be especially important when an unequivocal evaluative decision has to be made by committing to one side of the attitude. For example, consulting close others can decrease ambivalence when their opinions guide individuals to make the right decision (cf. Ohlen *et al.*, 2006). Mentalizing about, retrieving, integrating and processing information from various sources including beliefs about one's social environment is thus an essential part of attitude formation and decision-making processes (cf. Ajzen, 1991). A common network underlying these social cognitive processes includes the medial PFC and posterior cingulate cortex (PCC), temporal lobes and the temporo-parietal junction (TPJ) (the 'social brain network'; Adolphs, 2009; Rilling and Sanfey, 2011). Specifically the TPJ and PCC, two regions that are functionally connected, are both engaged in situations that require the integration of information through mentalizing and self-projection, i.e. the act of thinking about different future outcomes and referencing these alternative outcomes to oneself (Buckner and Carroll, 2006; Saxe, 2010; Mars *et al.*, 2012). As such, we hypothesized ambivalent decision-making to be associated with increased activation in the social brain network, including the PCC and TPJ.

In this study, we examined the cognitive and social-affective components of ambivalent decision-making, self-reported ambivalence and behavior aimed at coping with the negative affect ambivalence elicits. Participants made evaluative for-against judgments about pretested ambivalent or univalent (positive or negative) word stimuli that are personally or socially important (e.g. globalization, happiness, terrorism). An intricate component of the design was the extent to which the judgment was relevant as ambivalence needs to be interpreted as meaningful in order to elicit negative affect (cf. van Harreveld *et al.*, 2009b). Ambivalence was made meaningful by manipulating the probability of negative consequences of judgments about the attitude topics using a between-subject design. The negative consequences of judgments were related to monetary loss for all participants. However, dependent on between-subject condition, participants were instructed that it was either very probable (high evaluation consequences) or less probable (low evaluation consequences) that making a wrong judgment would have negative consequences. The amount of money participants lost when reaching the threshold of allowed wrong judgments was equally high for all participants. After scanning, experienced ambivalence about the attitude topics was measured by Priester and Petty's (1996) felt ambivalence scale. Additionally, individuals could compensate for uncertainty about their judgments by buying so-called jokers that neutralized one possibly wrong evaluation each. This served as a behavioral measure of uncertainty compensation.

We expected to replicate previous findings showing greater activity in ventrolateral PFC and ACC during ambivalent decision-making (Cunningham *et al.*, 2004). Additionally, we anticipated greater engagement of a social-affective network during judgments about ambivalent compared to univalent topics. This network includes the insula, reflecting the emotional intensity of the judgment situation (Singer *et al.*, 2009), as well as the TPJ and PCC, pointing toward the role social-cognitive processes take in the induction and reduction of the negative experience of ambivalence (cf. Ohlen *et al.*, 2006). Finally, we expected greater activation in these networks during ambivalent decision-making when evaluations were more relevant, thus, when the probability of negative consequences of a wrong evaluation was high.

To shed more light on the relation between brain regions involved in ambivalence-processing and subsequent coping behavior, we related brain activity in ACC, insula, TPJ and PCC during ambivalent decision-making to the self-report and behavioral measures after scanning. We predicted that greater activity in these areas during ambivalence would be related to more uncertainty-compensating behavior and a less intense experience of ambivalence.

METHODS

Participants

Forty-three students of Leiden University in the Netherlands, (24 female and 21 male) in the age range 18–25 years (mean = 21, s.d. = 1.89) participated in the study in exchange for course credit or an equivalent monetary compensation. Two additional participants were excluded from the analyses because of technical problems with the obtained images or because they indicated not having followed experimental instructions. Participants were randomly assigned to either the high evaluation consequences ($N = 21$) or the low evaluation consequences condition ($N = 22$).

Prior to the study, all participants completed a checklist to make sure they were eligible to take part in an magnetic resonance imaging (MRI) study. All procedures were approved by the medical ethical committee of the Leiden University Medical Center and participants gave informed consent for the study. Anatomical scans were examined by a radiologist in line with the University's policies; no anomalies were found.

Design and procedure

In the scanner, participants were presented with a total of 60 concepts, of which 30 had been rated as ambivalent (e.g. organ donation), 15 as positive (e.g. summer) and 15 as negative (e.g. child labor) in an earlier pilot study with other participants ($N = 53$). Participants' task was to judge each concept upon whether they were 'for' or 'against' by pressing one of two buttons with their right hand. The decision category ('for'; 'against') corresponding to the button press was counterbalanced, so that half of the participants saw the option 'for' on the left side of the screen, while the other half saw it on the right side of the screen.

Items were displayed in four sets of 15 concepts each. Each set consisted of concepts of the same valence, so that two sets comprised univalent concepts and two contained only ambivalent concepts. A blocked stimulus presentation (which was analyzed with an event-related design, see below) was used to simplify participants' reference in the behavioral postmeasure (see below for more information). Importantly, participants were not instructed about the valence of the concepts displayed in the sets, so that they did not expect concepts to be of positive, negative or ambivalent valence when doing the task. To control for the number of left and right button presses, positive and negative concepts were combined in sets of univalent trials. Possible differences between positive and negative trials were tested in subsequent analyses. The order within all sets was randomized and the order across sets was counterbalanced in a way that two consecutive sets were of different valence (ambivalence *vs* univalence).

Stimulus presentation lasted until participants made a response. A fixation cross preceded each trial which created a jittered interstimulus interval (min. = 4000 ms, max. = 6600 ms). After participants made a choice, a black screen was presented for 2500 ms before the next trial started (see Figure 1b).

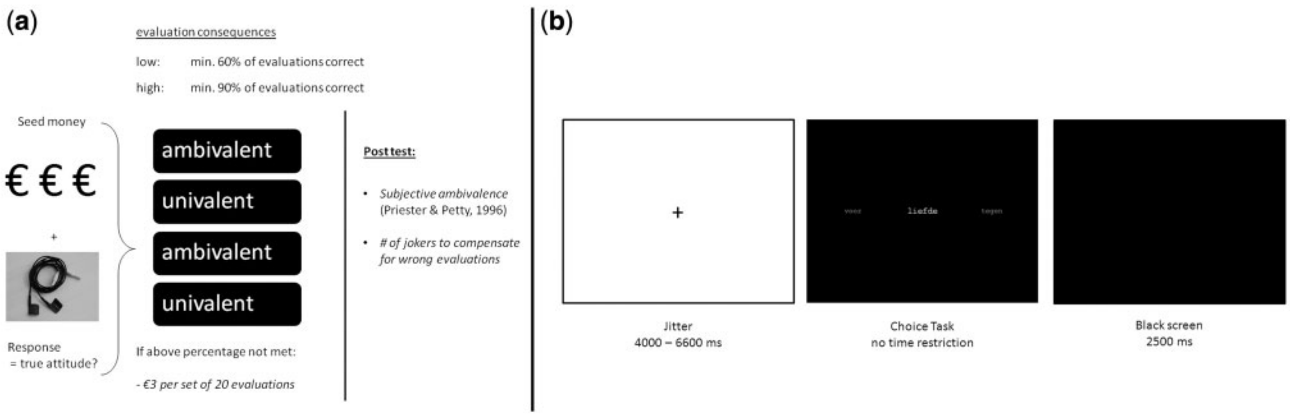

Fig. 1 Display of (**a**) Design of the study. (**b**) Timing sequence of a trial of the scanner task.

Evaluation consequences

To test the effect of evaluation relevance, evaluation consequences were manipulated between-participants. We told all participants that we could determine their 'true' attitudes about each of the presented topics by measuring their physiological response (EDA) corresponding to their explicit evaluations. Dependent on evaluation consequence condition, we varied the number of times they were allowed to make an 'incorrect' judgment in the following way. All participants were told that they could earn up to €12 on top of the participant compensation dependent on their performance on the evaluation task during scanning. It was explained that the task includes judging a number of topics by categorizing them into 'for' or 'against' according to their opinion. Prior to scanning, an electrode was placed on the palm of participants' left hand, which measured their EDA. Unbeknown to participants, in reality EDA was not measured during the study and the cover story merely served as a way to have people think that we could judge their responses. Participants were told that measuring EDA was a common way of testing whether someone reports the truth (i.e. a bogus lie-detector). In reality, there were neither right nor wrong evaluations nor were we able to tell whether participants' evaluation reflected their 'true' attitude.

After having been placed inside the scanner, participants in both conditions were instructed to respond as honestly as possible during the evaluation task. In the high evaluation consequences condition, participants were instructed that their data would only be useful if their judgment matched their 'true attitude' on more than 90% of the evaluations. This instruction aimed at making each evaluation trial more important. In the low evaluation relevance condition, the percentage of 'necessary correct answers' was 60%, thus decreasing the pressure to be correct on each judgment. Participants in both conditions were told that they would lose €3 of their seed capital per set of judgments that exceeded the percentage of 'allowed wrong answers'.

To familiarize themselves with the task, participants went through four test trials by categorizing two ambivalent and two univalent concepts before the experimental trials (see Figure 1a for a schematic overview of the design).

Subjective ambivalence and coping behavior

To test post-decisional ambivalence and coping with uncertainty about one's judgment, two post tests were administered immediately after the scanning session. First, participants rated each previously evaluated subject on Priester and Petty's subjective ambivalence scale (1996). This measure consists of three items based on the tripartite model of attitudes (e.g. Ostrom, 1969) and assesses the affective, cognitive and behavioral components of the ambivalent attitude. The three items were anchored with 'Toward this topic I...' *have completely one-sided feelings, feel no conflict*, and *feel no indecision* (0) and *have mixed feelings, feel maximum conflict* and *maximum indecision* (100). Responses were given using a slider ($\alpha = 0.94$).

In order to prevent participants from forming an opinion about the topics before entering the scanner, subjective ambivalence was only assessed outside the scanner after the experiment. We relied on the aforementioned pretest of a different group of participants for the selection of appropriate stimuli.

Second, we used a behavioral measure to assess participants' coping with uncertainty about the dichotomous evaluations they had made. As part of the experiment, participants were instructed that they were only allowed to give a prespecified number of wrong answers (10% or 40%), otherwise it would cost them up to €3 per set of evaluations exceeding this percentage. Participants were given the possibility to buy 'jokers' to compensate for evaluations they were uncertain about. Jokers cost €0.50 which was taken out of their seed capital and compensated one 'wrong' evaluation per specified set of 15 evaluations. For example, buying two jokers would allow for three instead of one 'error' in the high evaluation consequences condition. Participants did not specify the particular judgment they were uncertain about, but indicated for which set of evaluations they wanted to buy jokers (1–4).

MRI data acquisition

Scanning was performed with a standard whole-head coil on a 3.0 Tesla Philips Achieva scanner at the Leiden University Medical Center. To limit head motion to a minimum, foam inserts were placed around the head inside the head coil. Using E-Prime, stimuli were projected onto a screen in the magnet bore which participants could see through a mirror attached to the head coil. The evaluation task consisted of one event-related run, lasting approximately 8 min. Functional data were obtained using T2*-weighted echo-planar imaging (EPI). The first two volumes were removed to allow for equilibration of T1 saturation effects (TR = 2.2 s, TE = 30 ms, sequential acquisition, 38 slices of 2.75 mm, field of view 220 mm, 80×80 matrix, in-plane resolution 2.75 mm). A high-resolution 3D T1-FFE scan for anatomical reference was collected (repetition time (TR) = 9.760 ms; echo time (TE) = 4.59 ms, flip angle = 8°, 140 slices, $0.875 \times 0.875 \times 1.2\ mm^3$ voxels, field of view (FOV) = $224 \times 168 \times 177\ mm^3$). After the functional runs, a high-resolution 3D T1-weighted anatomical image was obtained (TR = 9.751 ms, TE = 4.59 ms, flip angle = 8°, 140 slices, 0.875 mm × 0.875 mm × 1.2 mm and FOV = 224.000 × 168.000 × 177.333).

fMRI data analysis

Data preprocessing and analyses were carried out using SPM5 (Wellcome Department of Cognitive Neurology, London). Rigid body motion correction was applied. Movement parameters were below 3 mm for all participants and scans. Functional volumes were spatially normalized to EPI templates. The spatial normalization algorithm applied a 12-parameter affine transformation with a nonlinear transformation involving cosine basis functions, and subsequently resampled the volumes to 3 mm cubic voxels. Templates were based on the MNI305 stereotaxic space (Cocosco *et al.*, 1997), and the Montreal Neurological Institute (MNI) atlas was used to refer to the coordinates. An 8 mm full-width-at-half-maximum isotropic Gaussian kernel was used to spatially smooth the functional volumes. Statistical analyses were carried out on individual participants' data using the general linear model in SPM5.

The data were modeled by a series of events convolved with a hemodynamic response function (HRF). Trials were modeled based on the onset of stimulus presentation, specified as zero-duration events. In a second *post hoc* analysis the data were analyzed with reaction time (RT) as a duration regressor. These results were largely overlapping with the model using zero-duration vectors (Table 1), therefore, the RT model is not further described. The trial functions were used as covariates in a general linear model, along with a basic set of cosine functions to high-pass filter the data. The least-squares parameter estimates of the height of the best-fitting canonical HRF for the different conditions were used in pairwise contrasts. Four main contrast analyses were distinguished. Activity during evaluations of ambivalent topics was contrasted with evaluations of univalent topics (ambivalent > univalent). Second, we compared activity for evaluations of positive concepts with evaluations of negative concepts to see whether univalent evaluations evoke valence-dependent differences in activation (negative > positive, positive > negative). Third, we contrasted ambivalent evaluations with positive evaluations (ambivalent > positive) and with negative evaluations (ambivalent > negative) to examine the role valence plays in ambivalent decision-making. Fourth, group differences were tested using two-sample *t*-tests. Only effects of at least 10 contiguous voxels that exceeded a false discovery (FDR) corrected threshold of $P < 0.05$ are reported. In addition to analyses on the whole-brain level, we further tested for effects of the between-subject factor evaluation relevance in subsequent region-of-interest (ROI) analyses. ROIs were extracted using the Marsbar toolbox for SPM5 (Brett *et al.*, 2002).

RESULTS

Behavioral measures

Behavioral results during scanning

A repeated measures analysis of variance was performed on RTs with topic valence (univalence *vs* ambivalence) as a within-subject factor and evaluation consequences (low *vs* high) as between-subject factor. As predicted, RTs were slower for ambivalent evaluations (mean = 1.88 s, s.d. = 0.55 s) than for evaluations of univalent topics (mean = 1.30 s, s.d. = 0.38 s), $F(1,41) = 122.86$, $P < 0.0001$, $\eta^2 = 0.75$. No effect was found of the between-subject factor evaluation consequence, $F(1,41) = 1.04$, $P =$ ns. An additional repeated measures analysis on the univalent items only revealed faster RTs when judging positive stimuli (mean = 1.21 s, s.d. = 0.38 s) compared with negative stimuli (mean = 1.40 s, s.d. = 0.42 s), $F(1,41) = 21.82$, $P < 0.001$, $\eta^2 = 0.35$. Again, there was no effect of the between-subject factor evaluation consequence, $F(1, 41) = 1.00$, $P =$ ns.

Second, we assessed the distribution of participants' categorization of target stimuli according to stimuli valence. Conform our expectations, positive stimuli were mostly evaluated positively ('for-category'; 98.8%) and negative stimuli were mostly evaluated as negative ('against-category'; 97.4%). Categorization of ambivalent stimuli was mixed, with stimuli being evaluated positively in 69.7% of the cases and negatively in 30.3%.

Table 1 Coordinates of clusters of activation showing significantly more activity during the evaluation of ambivalent than univalent stimuli

Anatomical region	Left/right	*k*	*x*	*y*	*z*	RT model
TPJ	L	197	−45	−66	33	
			−54	−69	24	
			−39	−54	27	
	R	84	57	−66	30	
Insula	L	22	−39	12	9	*
			−45	12	3	*
			−33	9	0	
	R	27	39	15	−3	*
			39	15	−12	
ACC	Ventral	1810	6	51	−6	*
	SFG		−18	42	42	
	dorsal/(pre-)SMA		3	21	45	*
Precuneus/PCC	L	844	−3	−54	15	
			−6	−45	6	
			0	−48	30	*
Central gyrus	L	155	−33	−15	57	*
			−42	−9	54	*
			−39	−27	54	*
Temporal lobe	L	210	−33	−90	−18	*
			−18	−96	−15	*
			−42	−72	−15	*
Temporal gyrus	L	18	−57	−12	−24	
Occipital lobe	R	76	39	−93	−9	*
			24	−99	−3	*
			18	−90	−3	*
Parahippocampal gyrus	R	13	21	−27	−15	

No significant clusters were found for the evaluation of univalent > ambivalent stimuli. Clusters that stayed significant when including RTs as a duration factor are marked with *. All clusters reached an FDR-corrected significance level of $P = 0.05$ and exceeded the minimum threshold of 10 voxels. The coordinates of the maximally activated voxel are given for each cluster. k = number of voxels in the cluster; x, y, z = MNI coordinates.

Behavioral results of the post-fMRI test

Data of four participants (three female) were lost due to technical problems. This was only the case for the behavioral measure of coping with uncertainty; participants' ratings of subjective ambivalence were unaffected.

Subjective ambivalence. A subjective ambivalence score about each topic was calculated by taking the mean of participants' self-reported *conflicting thoughts*, *indecisiveness* and *mixed feelings* about each topic. As expected, participants experienced more subjective ambivalence about the ambivalent topics (mean = 31.08, s.d. = 11.00) than univalent topics (mean = 14.80, s.d. = 13.14), $F(1,41) = 67.63$, $P < 0.001$, $\eta^2 = 62$. There was no main effect of evaluation consequences and no interaction between evaluation consequences and ambivalence (all *P*s = *ns*).

Coping behavior. When given the possibility to buy jokers in order to compensate for possibly wrong judgments made during the judgment task, more jokers were purchased for ambivalent evaluations (mean = 1.87, s.d. = 1.51) than for univalent evaluations (mean = 0.44, s.d. = 0.72), $F(1,37) = 37.82$, $P < 0.001$, $\eta^2 = 0.51$. As expected, participants displayed more uncertainty-compensating behavior for judgments regarding ambivalent than univalent topics. Again, no effect was found of evaluation consequences, $F(1,37) = 1.138$, $P = 0.29$.

The number of jokers purchased to compensate for possibly wrong judgments about ambivalent topics correlated significantly with the amount of subjective ambivalence participants felt about the ambivalent topics, $r = 0.33$, $P = 0.04$, demonstrating that the experience of ambivalence is associated with uncertainty about previous decisions regarding the ambivalent topics. No such correlation was found for univalent topics, $r = 0.17$, $P = ns$.

Neuroimaging results

Whole-brain contrasts

Blood-oxygenation-level dependent (BOLD) signal during ambivalent evaluations was contrasted with the signal during univalent evaluations (ambivalent > univalent). Results revealed that a network of regions was more activated during ambivalent evaluations, including the dorsal ACC extending into the lateral PFC, ventral ACC, insula, TPJ and the precuneus/PCC (Figure 2). No significant activity was found in the reverse contrast (univalent > ambivalent) indicating that univalent decisions did not lead to greater activation than ambivalent decisions.

To control for valence-dependent differences among univalent trials, a contrast analysis was conducted to clarify whether positive and negative evaluations differ in the activation pattern. The contrast negative > positive showed that evaluating negative stimuli resulted in more activity in the insula/IFG as well as the anterior dACC than positive topics (Figure 2). No regions were detected in the reverse contrast (positive > negative).

The contrast ambivalent > positive revealed a pattern of activation that highly overlaps with the network found for the contrast ambivalent > univalent (Figure 2). The ambivalent > negative contrast resulted in a network of activity which partly overlapped with the network detected in the ambivalent > univalent contrast. More activity was found for ambivalent evaluations in the dACC, vACC, TPJ (bilateral) and the precuneus/PCC, but insula activity did not differ significantly between evaluations of ambivalent and negative issues (Figure 2). All significant clusters are reported in Tables 1 and 2 (see also Supplementary Tables S1–S3).

A direct comparison of ambivalent > univalent for the high and the low consequences condition (i.e. a two-sample *t*-test) did not result in any significant activation in either direction. However, it is possible that small differences in activation fail to reveal statistical threshold in whole-brain analyses. Since we had a priori predictions about the activity pattern dependent on evaluation consequences, ROI analyses were conducted.

ROI analyses

ROIs were determined based on the brain areas that distinguished between ambivalence and univalence in decision-making processes (ambivalent > univalent, across all participants). ROI analyses were conducted to test for (a) interaction between ambivalence and evaluation consequence conditions and (b) relations with behavioral and self-reported measures of ambivalence and coping. The following regions were selected based on our a priori hypotheses by drawing a 6 mm sphere around the most active voxel: bilateral insula (MNI 39, 15, −12 and −39, 12, 9), bilateral TPJ (MNI 57, −66, 30 and −45, −66, 33), dorsal ACC (MNI 3, 21, 45), ventral ACC (MNI 6, 51, −6) and the precuneus/PCC (MNI −3, −54, 15) (Supplementary Figure S1).

None of these regions showed significant main or interaction effects with evaluation consequences condition except for the ventral ACC. In this region, a main effect of consequences condition indicated that high evaluation consequences were associated with greater activation compared with evaluations that were less consequential, $F(1,41) = 4.516$, $P = 0.04$, $\eta^2 = 0.10$ (Supplementary Figure S2). No interaction with ambivalence was found.

Correlations neuroimaging and behavior

We conducted correlational analyses to investigate the relationship between neural activity and post-decisional ambivalence and coping as assessed by self-report and behavioral measures. For this analysis, we collapsed across low and high consequences conditions, given that there were no interaction effects in the analyses reported above. This allowed us to test these relations in a large sample.

Several correlations were found for brain activity (ambivalent – fixation) and the experience of ambivalence after decision-making using the same ROIs. We applied stringent Bonferroni corrections ($P < 0.007$), and two correlations remained strongly significant. Activity in the left TPJ was negatively associated with subjective ambivalence experienced about ambivalent topics afterwards (respectively, $r = -0.419$, $P = 0.005$). A similar correlation was found for activity in the precuneus/PCC ($r = -0.448$, $P = 0.003$; see Figure 3). No significant correlations were found for univalent – fixation.

Several other correlations did not survive Bonferroni corrections and were thus not reliably related to subsequent ambivalence, including the correlations with the behavioral measure of coping with uncertainty. We also tested correlations for ambivalent relative to univalent trials. None of these correlations survived Bonferroni correction (all correlations can be found in Tables 3 and 4, see also Supplementary Figures S3 and S4).

DISCUSSION

This study investigated the neural correlates of ambivalent decision-making and coping by asking participants to make forced evaluations of ambivalent and univalent target stimuli with an emphasis on evaluation consequences. The study resulted in three main findings. Consistent with prior research, ambivalent decision-making resulted in dorsal and ventral ACC activation, extending into the dorsal and ventral lateral PFC (Cunningham *et al.*, 2004). Second, ambivalent decision-making engaged a social-affective network including the insula, TPJ and the precuneus/PCC. Third, activation during ambivalent decision-making was negatively correlated with the amount of subjective ambivalence participants experienced about the ambivalent topics afterwards. The discussion is structured along these main findings.

Ambivalence is a state in which positive and negative associations are simultaneously accessible. This inconsistency asks for cognitive control in order to inhibit one reaction and follow through with another (Cunningham *et al.*, 2004) and has been associated with activation in the ACC, frontal pole and orbital frontal cortex (Cunningham *et al.*, 2003; Jung *et al.*, 2008). Our study partly replicates this finding showing greater ACC and lateral PFC activity during ambivalent decision-making compared with univalent decision-making (see also Nomura *et al.*, 2003; Simmons *et al.*, 2006), and thereby confirms the role of the prefrontal cortex in complex decision-making situations (Bunge *et al.*, 2002).

Previous neurological studies have predominantly focused on the cognitive network involved in ambivalence. However, recent studies demonstrated that being confronted with one's ambivalence in decision-making situations leads to negative affect, especially when anticipating consequences of one's decision (van Harreveld *et al.*, 2009a). As

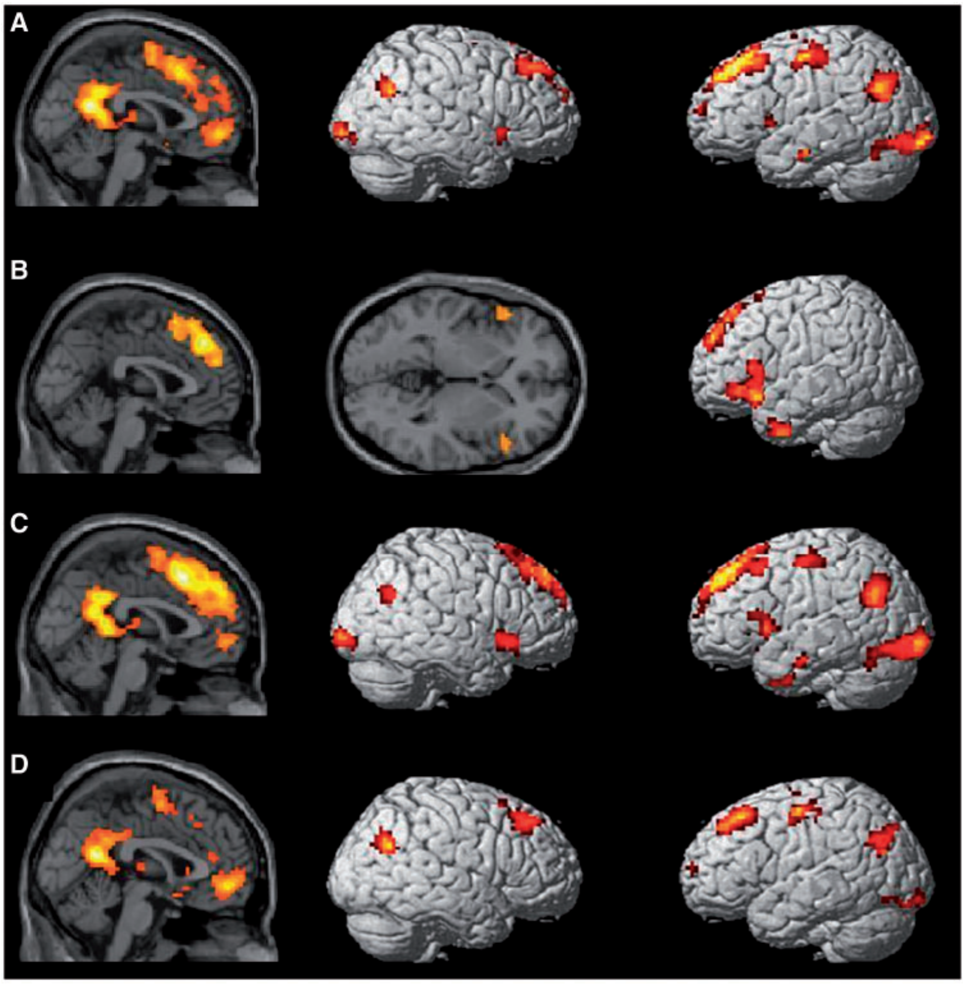

Fig. 2 Whole-brain contrasts: (**A**) ambivalent decision-making > univalent decision-making; (**B**) negative > positive decision-making; (**C**) ambivalent > positive decision-making; (**D**) ambivalent > negative decision-making.

Table 2 Coordinates of clusters of activation showing more activity for evaluation of negative than positive stimuli

Anatomical region	Left/right	*k*	*x*	*y*	*z*
Insula	L	250	−48	39	−9
			−45	21	−12
			−54	21	9
	R	94	48	27	−12
			33	18	−18
			54	24	0
ACC	Dorsal	701	9	42	39
			−3	42	45
			−18	51	30
Temporal lobe	L	63	−45	0	−42
	R	10	24	57	30

No significant clusters of activation were found for the evaluation of positive > negative stimuli. All clusters reached an FDR-corrected significance level of $P = 0.05$ and exceeded the minimum threshold of 10 voxels. The coordinates of the maximally activated voxel are given for each cluster. k = number of voxels in the cluster; x, y, z = MNI coordinates.

expected, this study demonstrated that ambivalent stimuli led to greater activation in a social-affective network including the insula, TPJ and PCC/precuneus in the context of an emphasis on potentially wrong evaluations that could have negative consequences.

It was hypothesized that activity in the insula reflects the negative emotional state individuals experience when confronted with the undesired inconsistency that constitutes ambivalence (e.g. Critchley *et al.*, 2000; Phan *et al.*, 2004; Critchley, 2005). However, no significant difference in insula activity was detected for negative univalent compared to ambivalent trials. These findings suggest that insula activation reflects the negative valence component of ambivalent stimuli instead of the aversive state ambivalence can elicit. This is in line with previous studies, showing greater activity in the insula during the processing of negative words (Straube *et al.*, 2011) and the role of the insula in generating an arousal response (Berntson *et al.*, 2011). It is also in accordance with the notion that ambivalent attitudes are asymmetrical in the sense that they are more dependent on fluctuations in the negative component than in the positive component (Cacioppo *et al.*, 1997). Nevertheless, we believe the consequences of ambivalence can be meaningfully distinguished from those of negativity. Even though not surviving Bonferroni corrections, there was a tendency for insula activity to be related to more coping behavior for ambivalent than negative trials. The arousal response that is reflected in insula activity may thus have a differential effect on behavior depending on whether it is elicited by negative or ambivalent stimuli.

We predicted that ambivalent decision-making would also be associated with activation in the social brain network. Buckner and Carroll (2006) suggested that frontal and medial temporal areas such as the

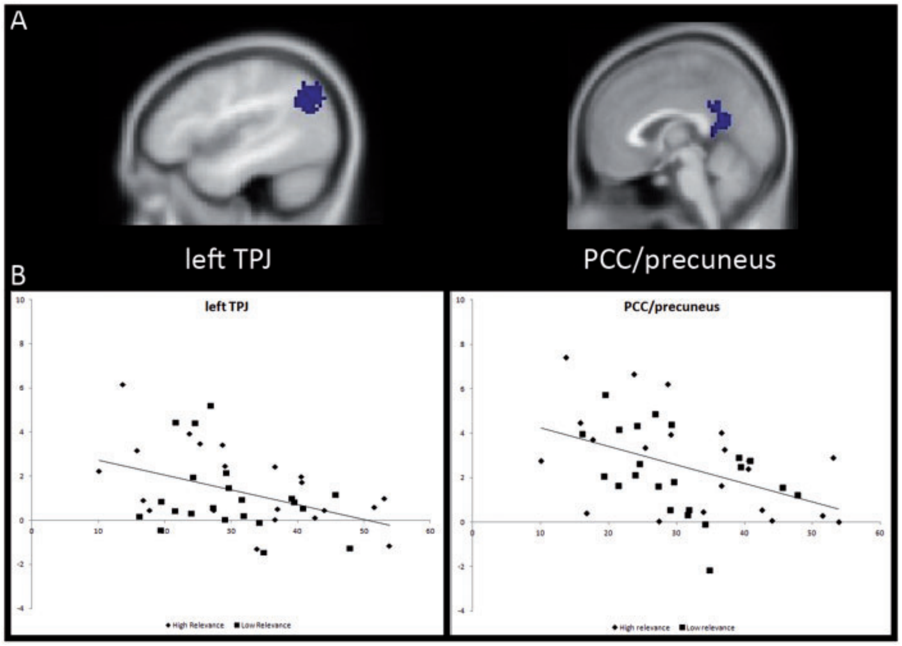

Fig. 3 (**A**) Showing the lTPJ and PCC/precuneus, regions that correlated significantly with experienced ambivalence after decision-making. (**B**) Scatterplot of activity during ambivalent trials (ambivalent-fixation) and experienced ambivalence after decision-making. Left: left TPJ (-45, -66, 3). Right: PCC/precuneus (-3,-54,15). Both correlations survived Bonferroni corrections.

Table 3 Correlations of regions of interest associated with ambivalent decision-making (ambivalent − fixation) and subjective ambivalence and coping behavior after the evaluation task

	Coping behavior ($N = 39$)		Subjective ambivalence ($N = 43$)	
	r	*P*	*r*	*P*
Insula				
Left	0.071	0.667	−0.237	0.125
Right	−0.357*	0.026	−0.137	0.381
TPJ				
Left	−0.113	0.495	−0.419***	0.005
Right	0.037	0.821	0.004	0.978
ACC				
Dorsal	−0.152	0.354	−0.316*	0.039
Ventral	−0.163	0.321	−0.176	0.260
Precuneus/PCC	−0.176	0.284	−0.448***	0.003

$*P < 0.05$, $**P \leq 0.01$, $***P \leq 0.007$; Bonferroni correction: $P = 0.007$.

Table 4 Correlations of regions of interest associated with ambivalent decision-making (ambivalent − univalent) and subjective ambivalence and coping behavior after the evaluation task

	Coping behavior ($N = 39$)		Subjective ambivalence ($N = 43$)	
	r	*p*	*r*	*p*
Insula				
Left	0.398*	0.012	0.116	0.458
Right	0.128	0.436	0.059	0.709
TPJ				
Left	0.047	0.778	−0.069	0.658
Right	0.125	0.447	0.029	0.854
ACC				
Dorsal	0.341*	0.034	0.123	0.430
Ventral	0.247	0.129	0.101	0.517
Precuneus/PCC	0.131	0.428	0.184	0.236

Correlations are based on difference scores of brain activation (ambivalent − univalent) and post-measures (ambivalent − univalent).
$*P < 0.05$, $**P < 0.01$, $***P \leq 0.007$; Bonferroni correction: $P = 0.007$. The correlation between coping behavior and left insula activity remains significant for activity during ambivalent − negative trials ($r = 0.394$, $P = 0.013$).

TPJ and the PCC are specifically engaged by decision-making processes that call for an analysis of oneself in another perspective, time or place (see also Mars *et al.*, 2012). Similarly, the TPJ has repeatedly been related to the *Theory of Mind*, i.e. the ability for metacognition and inferring other people's thoughts (ToM; Fletcher *et al.*, 1995; Gallagher *et al.*, 2000; van Overwalle, 2009), whereas the PCC has been linked to the processing of moral conflicts (Sommer *et al.*, 2010). Both regions may be engaged due to social and situational perspective-taking, in that individuals reflect on the ambivalent topic by looking at their and others' opinion under differing circumstances. The current findings suggest that activity in TPJ and PCC reflects the way individuals attempt to identify and reduce their ambivalence, demonstrated by the negative relation between activity in these regions and subjective ambivalence after the evaluation. Reflecting on one's own attitude in relation to different situations and opinions of relevant others may help individuals to construct a less conflicted attitude. This is in line with the idea that close others are often consulted in complex decision-making processes and that their involvement influences decision outcomes (Ohlen *et al.*, 2006).

Contrary to expectations, the probability of evaluation consequences did not interact with ambivalence. Possibly, participants perceived all judgments as relevant and meaningful independent of the probability of negative consequences of a wrong judgment. Not finding an interaction of ambivalence and the probability of evaluation consequences counters a potential alternative explanation of the observed effects. Even though being forced to make an evaluatively unequivocal decision about an ambivalent topic mirrors many real-life situations (e.g. abortion), the setup of this study might have led participants to feel judged unfairly when having to report their real (mixed) attitude, but not being able to do so. However, a higher probability of evaluation consequences only led to greater activity in the ventral ACC independent of stimulus valence, thus disconfirming this alternative explanation. Compared with the dorsal ACC, the ventral part of the ACC is more affect-oriented since it is functionally connected to other emotion-related areas like the amygdala and anterior insula (Bush *et al.*, 2000; Kanske and Kotz, 2011). This is in line with our findings, in that a higher probability of negative evaluation consequences led to greater emotional relevance of all stimuli independent of stimulus valence as reflected in greater ventral ACC activity.

Taken together, the current results bring us a step closer to understanding the role of cognitive and social-affective networks in the experience of ambivalence and processes aimed at coping with its negative consequences. It was shown that not only a cognitive but also a social-affective network is involved in ambivalent decision-making, including the insula, TPJ and PCC. Activity in both networks dictated the engagement of coping processes as indicated by their correlation with experienced ambivalence after the evaluation and uncertainty-compensating behavior, yet the evidence was considerably stronger for involvement of the social-affective network. These results demonstrate the involvement of the social brain network, including TPJ and PCC, in the processing of ambivalence as well as the initiation of coping processes aimed at ambivalence reduction.

SUPPLEMENTARY DATA

Supplementary data are available at *SCAN* online.

Conflict of Interest

None declared.

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