A brain mechanism for facilitation of insight by positive affect

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Abstract

Previous research has shown that people solve insight or creative problems better when in a positive mood (assessed or induced), though the precise mechanisms and neural substrates of this facilitation remain unclear. We assessed mood and personality variables in 79 participants before they attempted to solve problems that can be solved either by an insight or analytic strategy. Participants higher in positive mood solved more problems, and specifically more with insight, compared to participants lower in positive mood. Functional magnetic resonance imaging (fMRI) was performed on 27 of the participants while they solved problems. Positive mood (and to a lesser extent and in the opposite direction, anxiety) was associated with changes in brain activity during a preparatory interval preceding each solved problem; modulation of preparatory activity in several areas biased people to solve either with insight or analytically. Analyses examined whether (a) positive mood modulated activity in brain areas showing responsivity during preparation; (b) positive mood modulated activity in areas showing stronger activity for insight than noninsight trials either during preparation or solution; and (c) insight effects occurred in areas that showed mood-related effects during preparation. Across three analyses, the anterior cingulate cortex (ACC) showed sensitivity to both mood and insight, demonstrating that positive mood alters preparatory activity in ACC, biasing participants to engage in processing conducive to insight solving. This result suggests that positive mood enhances insight, at least in part, by modulating attention and cognitive control mechanisms via the ACC, perhaps enhancing sensitivity to detect non-prepotent solution candidates.

INTRODUCTION

This paper investigates the neural basis of one way that affect modulates cognition. Specifically, we report changes in brain activity, as measured with functional magnetic resonance imaging (fMRI), that occur as affect modulates problem-solving strategies. People can solve problems through methodical, analytic processing, through insight, or through some mix of both (for recent reviews: Bowden et al., 2005; Gilhooly & Murphy, 2005). These two strategies, or (sets of) processes can co-occur, overlap, and interact, yet they are phenomenologically, behaviorally, and neurologically distinct, as described below. It has previously been demonstrated that positive affect (PA) specifically facilitates people's ability to solve creative or "insight problems," i.e., problems that are more often solved with insight (Isen et al., 1987; Estrada, Isen, & Young, 1994; Isen, 1999 a,b; Rowe et al., 2007; Amabile, 2005). Therefore, observing brain activity associated with shifts of problem solving approaches in different affective states provides fertile ground for examining the neural mechanisms of emotion-cognition interactions. Here, we show that distinct affect states change actual cognitive organization to modulate problem-solving processes beyond the well-documented mood-memory congruency effect (Teasdale & Fogarty, 1979).

The distinction between insight and analytic solving has been anecdotally recognized for millennia, and has been the subject of scientific inquiry for nearly a century (e.g., Duncker, 1945; Kohler, 1917; Maier, 1930). A plethora of behavioral evidence details how these two solving processes differ. Analytic processing involves deliberate application of strategies and operations to gradually approach solution. Insight, which is considered a type of creative cognition, is the process through which people suddenly and unexpectedly achieve solution through processes that are not consciously reportable. Insight solutions tend to involve conceptual reorganization, often occurring after solvers overcome an impasse in their solving effort, and are suddenly able to recognize distant or atypical relations between problem elements that had previously eluded them (Gilhooly & Murphy, 2005; Metcalfe, 1986; Metcalfe & Wiebe, 1987; Smith & Kounios, 1996; Schooler et al., 1993; Schooler & Melcher, 1995; Weisberg, 1994). When solution is achieved, these factors combine to create a unique phenomenological experience, termed the Aha! or Eureka! moment.

PA has been shown to facilitate insight and creative problem solving across a broad range of settings (Isen et al., 1987; Ashby, Isen, & Turken, M., 1999; Estrada, Isen & Young, 1997; Isen, 1999b; Rowe et al., 2007). One description of this effect is that PA enhances cognitive flexibility in various settings, such as in classifying material (Isen & Daubman, 1984), in negotiation tasks (Carnevale & Isen, 1986), in medical diagnoses (Estrada et al., 1994) and in creative problem solving tasks (Isen et al., 1984; Isen et al., 1985). Various explanations have been proposed to explain this facilitation (also see Discussion). Briefly, one hypothesis is that PA promotes a more global scope of attention (Gasper & Clore, 2002; Bolte, 2003), enhancing access to distant or unusual associations (Isen et al, 1985; Federmeier, 2001; Friedman et al., 2003), which facilitates creative solutions to classic insight problems such as Duncker's candle task (Isen et al., 1987) and improves performance (Isen et al., 1987; Rowe et al., 2007) on the Remote Associates Test (Mednick, 1962). Another hypothesis is that PA enhances switching *between* global and local attentional modes (Bauman & Kuhl, 2005) or between strategies (Dreisbach & Goschke, 2004); or, similarly, that it enhances selection of different perspectives (Ashby et al., 1999).

In contrast, negative affect states such as anxiety and depression have been associated with deficits in attentional and cognitive control mechanisms (Mayberg et al., 1999; Bishop et al., 2004), often inducing a narrow scope of attention (Easterbrook, 1959). Therefore, anxiety in particular should impede cognitive flexibility, problem restructuring, and insight solving.

This study extends the existing literature in two ways. First, we examine not just the facility in solving a particular type of problem, but how mood modulates *which strategy*, insight or analytic, is

preferred (or successful). Second, we measure brain activity as people solve these problems, to observe the neural mechanisms of insight problem solving that are modulated by mood.

Insight and analytic problem solving are associated with different patterns of brain activity, measured with both fMRI and electroencephalography (EEG), both at the moment people achieve solution (Jung-Beeman et al., 2004) and as people prepare for each new problem (Kounios et al., 2006). For one thing, the right hemisphere, generally, seems to make stronger contributions as people process insight problems and recognize their solutions (Beeman & Bowden, 2000; Bowden & Beeman, 1998; Bowden & Jung-Beeman, 2003a). More specifically, compared to solving problems without insight, solving with insight involves stronger activity in right temporal regions thought to be important for integrating distant semantic associations (Jung-Beeman et al., 2004). Additional brain regions showed similar but weaker "insight effects" in the earlier study, but manifest strong effects in the current study; these include: anterior cingulate, posterior cingulate cortex (PCC), parahippocampal cortex (PHC), right superior frontal gyrus (SFG) and right inferior parietal lobe (IPL).

Additionally, during a brief preparation period prior to the presentation of each problem, various brain regions are more active prior to problems solved with insight than prior to problems solved without insight (Kounios et al., 2006). That is, different patterns of brain activity are conducive to solving the subsequent problem with insight versus analytic processing. The distinguishing areas include bilateral temporal areas involved with semantic processing, posterior cingulate cortex putatively involved in attention, and anterior cingulate cortex thought to be important for cognitive control. Thus, each of these areas represents a reasonable candidate for affect-induced modulation of insight problem solving. The left temporal cortex is more adept at preparing to retrieve many close prepotent associations, while activity in the right temporal cortex enhances the readiness to pursue weaker associations (Jung-Beeman, 2005). On the other hand, the posterior cingulate is thought to be involved in visuospatial expectancy (Small et al., 2003) and the anterior cingulate is more likely to be involved in cognitive control, and possibly in switching between solution candidates (or other thought processes), which is likely an important component of insight.

Anterior Cingulate and Insight Processes

We have demonstrated that the rostral portion of the dorsal anterior cingulate cortex (dACC (BA 9, 24, 32)) showed a sustained increase in neural activity during the preparatory interval before participants actually see problems, and stronger ACC activity occurs prior to trials solved with insight than those solved more analytically (Kounios et al., 2006).

We hypothesized that insights would involve greater cognitive control and restructuring processes, and that the dorsal anterior cingulate cortex would be involved in the shift and selection of a new solution path. In tasks involving response competition, cognitive control is thought to be important for the monitoring of competing responses (Macdonald et al., 2000; van Veen et al., 2001; Weissman et al., 2003), in overcoming prepotent responses when strategic processes were less engaged and conflict high (Carter et al., 2000), and in shifting attention (Davis et al., 2005; Dreisbach & Goschke, 2004; Kondo et al., 2004). Such cognitive control mechanisms could be critical for insight because they enable problem solvers to detect competing solution candidates, rely less on dominant associations or strategies, and/or enable shifting attention from a prepotent but irrelevant association to the less potent, but correct, association. This could be an important component of what insight researchers variously term cognitive restructuring and flexibility, or "breaking set" and "overcoming functional fixedness."

Anterior Cingulate, Positive Affect and Insight

One possible mechanism by which PA could facilitate insight is through cognitive restructuring processes. PA is likely to facilitate insight by increasing a person's ability to switch and select alternative cognitive perspectives (Baumann & Kuhl, 2005; Isen, 1999b; Dreisbach & Goschke,

2004), reducing perseveration on one particular solution candidate or solving approach, thus increasing the probability of engaging in various cognitive restructuring processes. We propose that PA could modulate activity in the ACC (Lane et al., 1998) to make it more open to detecting competing (weak) activations, biasing a shift toward insight solutions. The modulated ACC activity might facilitate one or a combination of mechanisms such as: switching between global and local processing modes of attention (Baumann & Kuhl, 2005); switching from irrelevant to relevant solving strategies, and/or selecting the correct solution (Dreisbach & Goschke, 2004).

The ACC appears to be a particularly promising site for interactions between cognitive processes and affect states. Besides its involvement in modulating cognitive processes via attention shifting, conflict detection, response competition and/or selection mechanisms (Bush et al., 2000; Badre & Wagner, 2004; Dreher et al., 2003; Ruff et al., 2001; Kerns et al., 2004; Botvinick et al., 2004), the ACC also appears to be involved in emotional processes (Bush et al., 2000; Drevets et al., 1998; Whalen et al., 1998; Mayberg et al., 1999). Functional neuroimaging studies show overlapping activation patterns within the ACC between cognitive and affective tasks (Fichtenholtz et al., 2004; Papez, 1937; Lane et al., Teasdale, 1999). Electrophysiological studies have identified a population of dorsal ACC neurons that show increased activity to high versus low-conflict Stroop tasks, including those with emotional valence (Davis et al., 2005). Moreover, cytoarchitectonic studies suggest the involvement of specialized spindle cells of Brodmann Area 24 that integrate cognitive input with emotional overtones (Nimchinsky et al., 1999).

Given the ACC's involvement in cognitive control and emotional processes, and our prior evidence that activity in the ACC prior to solving problems is associated with solution strategy, we predict that affect states will modulate ACC activation, and thereby influence insight (versus analytic) solving processes. Specifically, we hypothesize that PA states will increase activity in the ACC before the actual problem onset, biasing the solver toward cognitive processing that is relatively conducive to insight.

Hemispheric Asymmetries, Affect, and Insight

Another possibility can be derived from the following considerations: 1) Right hemisphere (RH) processing seems to make strong contributions to insight solving overall (Bowden & Beeman, 1998; Jung-Beeman et al., 2004); 2) RH semantic processing activates or maintains activation of a broader set of semantic associations than does LH semantic processing (Beeman et al., 1994; Chiarello et al, 1991; Faust et al., 2007), and these broad associations seem very relevant for solving with insight; 3) Positive mood seems to broaden the overall pattern of semantic associations (Federmeier et al., 2001; Isen 1985); 4) Global or broad attention is associated with RH visual processing, creative problem solving (Ansburg & Hill, 2003), and positive mood (Gasper & Clore, 2002; Rowe et al., 2007); and 5) inducing an approach regulatory focus (with low arousal) increases measures of relative RH activation, as well as facilitating creative problem solving (Friedman & Forster, 2005) . Thus, it remains hypothetically possible that PA will directly increase overall activity in the right hemisphere, specifically in the right superior temporal gyrus (STG), which is, cytoarchitectonically more suited than the left STG at integrating distant semantic associates via coarse semantic coding (for review, Jung-Beeman, 2005). However, such an effect might seem to contradict some established associations between positive mood (or approach focus) and leftward asymmetries in electroencephalographic activity (Davidson, 1992; Tomarken et al., 1992; Herrington et al., 2005). Moreover, to us, it seems intuitively more likely that a global characteristic like positive mood would either modulate all semantic processing (in both hemispheres) to broaden the scope of semantic associations, or, more likely, to modulate attention or cognitive control mechanisms that make solvers better able to detect (and utilize) remote associations that are only weakly active (perhaps, mostly due to RH semantic processing).

Experiment

Insight typically occurs when people initially focus on an incorrect but dominant association (e.g., in Figure 1, *ache* can form compounds with tooth and heart, but not potato), and need to overcome this impasse and switch to the correct solving strategy to be able to reach a sudden (Aha!) understanding of the solution (Bowden & Jung-Beeman, 2003a, & Jung-Beeman et al., 2004). In many studies of insight solving, problems have typically been classified a priori, as either "insight problems" or as "noninsight problems" (Weisberg, 1994); but because any problem can be solved through insight, through straightforward (incremental, strategic) problem solving, or through a combination of both (Bowden et al., 2005) the a priori "insight" classification is not definitive.

We exploit this feature by asking participants to report directly which strategy they used predominantly to achieve solutions, in order to directly contrast trials that lead to insight solutions versus those that lead to noninsight solutions. This enables us to examine insight versus noninsight processing while holding task and stimulus type constant. Participants were presented with a large set of Compound Remote Associate (CRA) problems (Bowden & Jung-Beeman, 2003b). Similar problems (Mednick, 1962) are often used as "insight problems" or for creative problem solving (Isen, 1987; 1999a), and the ability to solve them correlates with the ability to solve other classic insight problems (Duncker, 1945; Maier, 1930). However, they can be solved either analytically or with insight (Bowden & Jung-Beeman, 2003a; review: Bowden et al., 2005). The type of processing involved in successfully solving these problems varies across trials (Jung-Beeman et al., 2004; Kounios et al., 2006) and across individuals (Kounios et al., 2008), making this paradigm a strong candidate for investigating how affect can, in a general (rather than in only a mood-consistent way), modulate higher level cognition. Specifically, we examine the brain basis of how PA and anxiety modulate solving strategy, tipping the balance of processes toward insight or analytic strategies.

Mood state (including positive and negative affect, and anxiety) and personality measures, gathered prior to the experimental session, were related to performance and neuroimaging measures. For the participants who underwent fMRI scanning, we identified brain regions involved in various aspects of problem solving, and correlated the signal change in these regions with the mood and personality indices, as well as identifying areas that showed contrast in the brain activity during problem preparation between high- and low-positive mood individuals.

METHODS

Participants and Procedure

All 79 participants were neurologically healthy, right-handed and native speakers of English. After giving informed consent, all participants completed mood state inventories for PA and negative affect (PANAS), state anxiety (STAI), and a variety of other personality inventories measuring more stable individual traits (Behavioral Inhibition Scale-Behavioral Activation Scale, the Neuroticism subscale for the Big 5 Personality Mini-Markers, and the Magical Ideation Scale as an indicator of schizotypy). The mood state inventories (PANAS and STAI), given to all participants just before they performed the CRA task, measured the extent that participants were currently experiencing a positive (PANAS) or anxious mood (STAI). We examined correlations between all mood and personality scores and various problem solving measures (solving rate and proportion of problems solved with insight), as well as fMRI signal change.

Following these questionnaires, 52 participants performed the problem-solving task outside the scanner, providing only behavioral data, and 30 participants performed the problem-solving task in the scanner. Data from 3 participants were excluded – due to poor fMRI signal in two of the participants and due to one participant providing only two analytic responses.

Problem solving paradigm

   We measured insight and analytical solving of 135 CRA problems (Bowden & Jung-Beeman, 2003b), adapted from a test of creative cognition (Mednick, 1962). For each problem, participants see three problem words (tooth, potato, heart), and must generate a solution (sweet) that can form a compound word or phrase with each problem word (sweet tooth, sweet potato, sweetheart). The solution word can precede or follow each problem word. Like most problems (even classic "insight problems"), these problems can be solved either with insight, or through more methodical or analytical processes. We relied on participants' trial by trial judgments to determine the type of processing that led to each solution. This method has reliably shown consistent differences in behavior (Beeman & Bowden, 2000; Bowden & Beeman, 1998; Bowden & Jung-Beeman, 2003a) and in brain activity (Jung-Beeman et al., 2004; Kounios et al., 2006, 2008). For instance, in our prior EEG study, the neural processes biasing the sudden (Aha!) that led up to an insight solution, were associated with increased neural activity (less alpha power) peaking over mid-frontal cortex and bilateral temporal cortices for insight versus analytical preparatory processes (Kounios et al., 2006). Using a different population sample and methodology, fMRI signal corroborated the EEG findings, specifically isolating the ACC as the medial frontal region that revealed increased neural activity for insight versus noninsight preparatory processing, and also showed increased activity within the bilateral temporal cortical areas revealed during EEG (Kounios et al., 2006). In another study, about a third of a second prior to the insight solution button press, a burst of EEG gamma activity in the right anterior superior temporal gyrus (aSTG) corresponded to the increase in fMRI solution-related signal within the same region (Jung-Beeman et al., 2004). This RH activation likely reflects the processing and integration of a broad range of semantic associations leading to solution (Beeman et al., 1994; Bowden & Jung-Beeman, 1998, 2003a; Jung-Beeman et al., 2004).

   Prior to the current experiment, participants received instructions to make insight/noninsight judgments, emphasizing that they should respond "insight" if they achieved solution suddenly and surprisingly, possibly by switching their train of thought just prior to solution, and that as soon as they thought of the solution candidate, they were instantly confident it was the solution. In contrast, they should respond "noninsight" if they achieved solution incrementally, or by some analytical strategy, e.g., by strategically retrieving candidates and testing them out.

   Each trial began with a fixation cross that remained on the screen for a variable rest period (from 0, 2, 4, 6, or 8 sec, randomized across all trials), during which participants prepared for the next trial (Fig.1). Such variable delays were used to jitter the events and optimize deconvolution of the fMRI signal from successive events. After this preparation period, the three problem words (tooth, potato, heart) were presented on the screen (horizontally centered, just above, at, and just below central fixation), and persisted until participants solved the problem, or a 15s time limit was reached. Participants attempted to produce a single solution word (sweet) that could form a compound word with each of the problem words. If participants solved the problem, they made a bimanual button press by pressing the 2 outer buttons with a finger on each hand when they arrived at the solution; after a variable (0-8s) delay, a solution prompt appeared, and participants verbalized the solution. After another variable delay (0-8s), an insight prompt ("Insight?") appeared. To control for motor response differences between insight and analytic ratings, participants pressed the two outer buttons with a finger on each hand if they had reached the solution with an insight; or, they pressed the two inner buttons if they had reached the solution through analytic noninsight means. After the insight/analytical solution rating, or after 15s elapsed on unsolved trials, the next preparation period began.

Image acquisition

Thirty fMRI participants performed the CRA task during scanning, which for all participants occurred in the same Siemens Trio (3 Tesla) scanner and eight channel head coil, with the same scanning protocol, at Northwestern's Center for Advanced MRI. Head motion was restricted with plastic calipers built into the coil and a vacuum pillow. The functional imaging sequence was optimized for detection of the BOLD effect (Ogawa et al., 1992) including local shimming and 8 sec of scanning prior to data collection to allow the MR signal to reach equilibrium. Functional imaging used a gradient echo echo-planar sequence (TR = 2 sec for 38 3-mm slices, TE = 20 msec, matrix size 64x64 in 220-mm field of view). Participants solved problems during four scans of 10 min 20 s and a final fifth scan that was truncated when participants finished solving problems. Each functional scan was synchronized with the onset of the first problem in that block of trials; timing of subsequent trials was response-dependent, and not synchronized with image acquisition.   Anatomical high-resolution images were acquired in the same plane, with T1-weighted images parallel to the ACPC plane.

Image analysis

Functional and anatomical images were co-registered through time, spatially smoothed with a 7.5 mm Gaussian kernel, and fit to a common template. Within each run, voxels were eliminated if the signal magnitude changed more than 20% across successive TRs, or if the mean signal level was below a noise threshold. Functional data were transformed (Collins et al. 1994) to a standard stereotaxic atlas (Talairach and Tournoux 1988) with a voxel size of 2.5 mm^3. The data were analyzed using general linear model analysis, as implemented in AFNI (Ward, "http://afni.nimh.nih.gov/afni"), that extracted average estimated responses to each trial-type, correcting for linear drift and removing signal changes correlated with head motion, as well as signal attributed to other temporally adjacent events to ensure that signal could be isolated to the event of interest. For example, when extracting signal related to preparation events, we included in the analysis: the preceding insight ratings, the subsequent problem onsets, and the subsequent solutions, to factor out signal more closely tied to those events than to the preparation event. Signal was estimated for all time points (TRs 0-10) within the same model, without regard to any presumed hemodynamic response function.

The primary focus of this report was fMRI signal, hence brain activity, corresponding to the preparation intervals. We examined changes in BOLD signal following the onset of this preparation period in three ways:

(A) Areas that turned on, i.e., changed their activity, during preparation. We examined overall responsivity corresponding to the preparation interval, manifested as a rise and fall of BOLD signal from onset of the preparation period to peak response and back down to baseline. Specifically, for every voxel, signal corresponding to the peak of the preparation period (TRs 4, 5, & 6 following onset of preparation period; for comparison, there was a peak signal in motor cortex at TR 3, corresponding to the button press from the insight-rating preceding the preparation period) was contrasted with signal corresponding to the points preceding and following the preparation period (TRs 1, 9, & 10). We identified regions of signal change that were consistent across all 27 participants, with a significance threshold combining t values (p < .005) and cluster size (at least 1500 mm^3 in volume). The dorsal anterior cingulate cortex (dACC), posterior cingulate cortex (PCC), and the right angular gyrus (AG) clusters exceeded the above criteria, increasing preparatory activity. Of all these statistically reliable clusters (functionally defined ROIs), the dACC and the right AG were the only two ROIs where preparatory responsivity strongly correlated with positive mood across all 27 participants.

Because *any* changes (up or down) in activity could be meaningful, to be thorough we also examined areas that exhibited deactivation, i.e., a fall and rise of signal corresponding to the

preparation interval. The left and right Inferior Frontal Gyrus (IFG) showed systematic preparatory deactivation in which the mean signal for the expected preparatory peak hemodynamic signal (i.e. TRs 4, 5, 6), was significantly lower than the mean baseline signal (i.e. the first TR and last two TRs). Neither of these areas exhibited correlations between signal change and mood.

   (B) Areas that showed insight-specific activity during preparation or solution. Peak preparatory signal specific to insight trials was calculated by comparing the difference between insight and analytic preparation events for each participant by extracting the mean signal within the 3 TRs (TRs 4,5,6) corresponding to the expected preparatory hemodynamic peak. For comparison, the preceding insight-rating button press elicited peak signal in motor cortex at 4 sec, just prior to the preparation onset peak signal (6 sec) for each participant. Similarly, peak insight solution related signal was calculated by examining differences between insight and analytic solution events for each participant by examining the mean signal within the 3 TRs (TRs 3,4,5 – we chose an early time window to minimize contamination from post-solution activity) corresponding to the expected peak signal leading up to the solution point (see Figure 9 for comparison). The subsequent button press elicited peak signal in motor cortex (10 sec) at the solution point. The significance threshold combined cluster-size and t-values for each voxel within a cluster (set at least 500 mm^3 in volume) in which each voxel was reliably different across participants, [t (26) = [3.09], p < 0.005 uncorrected], for insight versus noninsight preparation, and for insight versus noninsight solutions]. The ACC, PCC, left STG, and right MTG ROI clusters exceeded these criteria, manifesting stronger preparatory peak signal for insight versus analytical trials. Several regions showed stronger peak signal for insight versus analytical solutions including: ACC, PCC, right parahippocampal gyrus (PHC), left MTG, right MTG, right Inferior Parietal Lobe (IPL), and right Superior Frontal Gyrus (SFG).

   We then extracted the mean preparatory hemodynamic responsivity signal for each participant, as described by (A), within the regions that showed an insight effect at preparation, and within the regions that showed an insight effect at solution, as described above. We correlated this preparatory responsivity within these "insight" regions with positive mood (PA-NA) and anxiety (STAI) scores. Of all the ROIs defined by the insight effect that corresponded to the time window at preparation and the time window leading up to the solution point, only the ACC ROI manifested strong correlations between overall preparatory signal change and positive mood.

   (C) Areas that showed mood differences in activity during preparation. To examine how individual differences in affect state influenced successful preparation preceding solved trials, a whole-brain analysis identified regions in which the 8 participants highest in PA showed different signal during preparation (as described in A) than did the 8 participants lowest in PA. The dorsal ACC (dACC), ventral ACC (vACC) and PCC all exceeded significance criteria, t(14) = 3.32, p=.005, v > 500mm^3), all showing stronger preparatory activation for participants high in PA than for participants low in PA.

   The functional overlap, illustrated in a convergence map, between all the 3 analyses occurred only within the dorsal ACC at (-2, 42, 22). The analysis with the least stringent significance threshold corresponded to a p < .005, combined with a cluster size of at least 500mm^3. Thus, the functional overlap between all three analyses, manifesting activation only within the dACC, suggests a much lower probability of a type I error.

   In a final set of analyses, we examined whether insight effects (stronger peak signal for insight than for noninsight trials, across all 27 participants) occurred in any of the ROIs defined by the positive mood preparatory effect (C). We contrasted peak fMRI signal for insight versus noninsight preparation periods (defined above), as well as insight versus noninsight solutions (at the TRs corresponding to the last 2 sec of processing prior to solutions). Within these ROIs, consistently stronger signal for insight than for analytic preparatory events occurred only within the dACC. Similarly, within these mood-sensitive ROIs, stronger signal for insight than for analytic solutions

occurred only in the dACC. None of the mood-sensitive ROIs showed stronger signal for analytic than insight trials, at preparation or solution. Insight versus analytic signal was not enhanced by positive mood at any other time points (all p > .2).

RESULTS

Behavioral measures

Participants correctly solved 41.0% (sd=11.4) of the problems, and identified 50.8% (sd = 16.3) of their solutions as insight (mean response time= 6.57 sec, sd= 1.31) and 46.8% (sd= 16.2) of their solutions as analytic/ without insight (mean response time= 7.35sec, sd= 1.23). Of trials with responses, 3.96 % (sd= 2.52) were errors. Participants solved problems faster with insight than they did analytically (t (78) = [3.60], p <.001).

We examined how affect, assessed by a variety of state, trait and personality questionnaires, related to problem solving behavior. The range of scores on the affective scales was somewhat limited. In particular, only 5 out of 79 participants had a score higher than 20 on the Negative Affect (NA) scale, which ranges from 10-50. However, some participants had a high score on both the PA and NA scales, consistent with the assertion that the PA and NA scales are orthogonal (Watson & Tellegen, 1988). How should we compare the mood of a person scoring high on PA and NA with the mood of a person scoring high on PA but low on NA? Although results were as strong (sometimes stronger) if we used strict PA scores, we took into account NA scores by using PA-NA as an index of positive mood.

Consistent with prior studies, positive mood modulated solving rates: the top third most positive (PA-NA) participants (mean PA-NA score= 24.0, sd 3.77, see Table 1) solved more problems (mean solved: 60.0; mean solution response time: 6.66 sec) than did the bottom third, or least positive mood participants (mean PA-NA score= 5.35; mean solved: 51.3; mean solution response time: 7.19 sec), (t (50) = [2.24], p < .05).

Positive mood was also related to which type of strategy, by self-report, led to solutions. As predicted, the number of insights differed significantly across the three levels of positive mood [F(2,76) = 7.364, p = .001]. By contrast, the number of problems solved analytically, i.e., without insight, did not differ [F(2,76) = 1.485, p = .233]. Therefore, positive mood specifically facilitated insights, but did not change the rate of analytical solutions (Figure 3A). Specifically, the highest positive mood participants solved more problems with insight (mean insights= 34.5; mean insight response time= 6.12 sec) than did the lowest positive mood participants (mean insights= 21.9; mean insight response time= 7.31 sec) (t (50) = [3.96], p<.0005). Overall, a regression analysis (partialing out all other mood and personality variables) showed that positive mood (PA-NA) was directly correlated with insight solving (r (77) = .40, p<.005) (Figure 2).

Anxiety had the opposite effect (see Figure 3B) where the third of participants highest in anxiety (mean STAI score: 42.1, sd 3.77) solved fewer problems with insight (mean insights: 24.1; mean insight response time: 6.12 sec) than did the third of participants (t(50)= [2.75], p < .01) lowest in anxiety (mean STAI score: 24.7; mean insights: 33.1; mean insight response time: 7.31 sec), and anxiety was inversely correlated with solving with insight (r (77) = -.34, p<.005) (Figure 2). However, anxiety did not have a reliable effect on overall solving rates (top versus bottom third, t(50) = [1.277], p = .207). Anxiety enhanced the proportion of solutions achieved analytically without insight (t(50)= [2.189], p = .033) but did not reliably change the raw number of analytical solutions (t(50) = [1.235], p = .222).

Imaging measures

We conducted 3 analyses to examine the neural basis of the interaction between positive mood and insight solving. In these analyses, we showed that PA modulates participants' pre-problem preparatory brain states to specifically facilitate insight solutions by enhancing signal within the rostral region of the dorsal ACC (see convergence map in Figure 7). These preparatory brain states were assessed by examining fMRI signal corresponding to the variable 0-8 seconds rest between the end of one trial and the beginning of the next 3-word problem, while participants fixate on a centrally located cross and prepare for the next problem (Kounios et al., 2006).

(A) Do brain regions showing signal change at preparation show mood effects?

As described in the Methods, we first identified regions of interest (ROIs) that showed changes in neural activity across all preparatory periods preceding trials that participants subsequently solved (Figure 4, Table 2). Across all participants, we then examined whether this preparatory activity correlated with PA, anxiety, solving rates, or solving strategy (solving with insight or noninsight). This analysis enabled us to investigate if certain regions that "turned on" at preparation were modulated by positive mood and anxiety states.

As illustrated by Table 2A, three areas showed increased activation during preparation: dACC, posterior cingulate cortex (PCC), and the right angular gyrus (AG). In two of these regions, as positive mood increased across all 27 participants, so did the amount of preparatory activity: in the ACC ($r(25) = 0.41$, $p < .05$, see Figure 4C); and in the right AG ($r(25) = 0.40$, $p < .05$). Preparatory activity in the rostral dACC also inversely correlated with anxiety, but this correlation was not statistically reliable ($r(25) = -0.34$, $p = .08$, Table 2). Preparatory activity in the PCC showed a mild but non-significant positive correlation with overall proportion of problems solved ($r(25) = .36$, $p = .06$, Table 2), but no correlation with positive mood.

Hypothetically, *deactivations* could be equally important to increases in activation. So, for completeness, we performed the same analyses looking at areas that deactivated during preparation. Two areas showed systematic deactivation compared to baseline: the left and right Inferior Frontal Gyri (IFG). This deactivation during preparation was negatively correlated with the overall proportion of problem solved, (left IFG: $r(25) = -.40$, $p < .05$; right IFG: $r(25) = -.50$, $p < .05$) (Table 2) but did not correlate with any mood variables (p's $> .20$). This analysis (A), therefore, demonstrates that among the ROIs showing changes in neural activity at preparation, only the dorsal ACC and right AG increased activation with positive mood.

Does brain activity at preparation predict brain activity at solution?

We examined whether preparatory brain activity predicted overall solution brain activity, and whether this preparatory activity then correlated with mood in regions showing specific insight effects. As mentioned above, the areas showing overall increased responsivity at preparation included the dACC, PCC and right AG. Each of these areas, therefore, represents a good candidate for preparatory activity predicting overall solution related activity. In order to examine where preparatory activity predicted overall solution-related activity, we identified regions that showed solution related responsivity, similar to the way we defined preparatory ROIs as described by analysis (A). For instance, we defined solution-related ROIs, by subtracting the mean signal across the 3TRs corresponding to baseline solution-related signal (TRs 1,6,7) from the mean signal across the 3 TRs (TRs 3,4,5) corresponding to peak signal leading up to the solution (see Figure 9 for comparison). These solution-related functional ROIs would, therefore, indicate regions of the brain that "turned on" upon arriving at solution. We then looked back at preparatory responsivity within these solution-active ROIs. We found that as preparatory activity increased, so did solution related responsivity, within one region only: the region of the dorsal ACC. This analysis demonstrates that preparatory activity within the dorsal ACC predicted overall solving activity.

(B) Do brain regions showing insight specific activity at either preparation or solution correlate with mood?

We next examined whether preparatory activity correlated with mood in regions identified as showing insight-specific processing [see Methods (B)]. We identified ROIs that showed an "insight effect," i.e., stronger peak signal for insight versus analytical processes, either during preparation (Kounios et al., 2006) or leading up to solution (as in Jung-Beeman et al., 2004). Within these "insight effect" regions, we examined whether overall preparatory responsivity (from preparation onset to peak response and back down to baseline) was modulated by positive mood states.

Regions that showed this "insight effect" at preparation – stronger signal during preparation preceding problems that were eventually solved with insight than during preparation preceding analytic solutions – included the ACC, the PCC and the right and left MTG (Table 2C), as previously described (Kounios et al., 2006). Within these ROIs, positive mood correlated (across all 27 participants) with preparatory responsivity only in the ACC (r (25) = 0.40, p <.05, Table 2C). This preparatory activity in the ACC also inversely correlated with anxiety (r (25) = -0.40, p <.05). Moreover, the peak of this preparatory activity in ACC correlated with the overall proportion of problems solved (r (25) = 0.37, p = .05). Positive mood did not correlate with preparatory activity observed in other areas showing insight effects during preparation (PCC: r (25) = 0.23, p = .27); left MTG: r (25) = 0.22, p = .27; right MTG: r (25) = -0.16, p = .42).

We next examined whether positive mood modulated preparatory activity in areas that showed an "insight effect" at *solution* (see Figure 9). We identified several regions showing insight effects at solution, i.e., stronger signal for insight solutions than for noninsight solutions. These ROIs included the right anterior STG, ACC, PCC, right PHC, bilateral MTG (stronger in right than left), right SFG, and the right IPL (Table 2D). These data, with more participants and better imaging protocols, match well with earlier results showing smaller effects, but in the same general regions, with right anterior STG again showing the largest effect (Jung-Beeman et al., 2004). Within all these ROIs showing insight effects at solution, preparatory activity correlated with positive mood only within the ACC (r (25) = 0.45, p <.05, see Figure 5, Table 2D). Again, ACC preparatory activity negatively correlated with anxiety (r (25) = -0.44, p <.05), while preparatory peak signal positively correlated with the overall proportion of problems solved (r (25) = 0.37, p = .05).

(C) Are brain regions showing positive mood effects during preparation involved in solving with insight?

In the above analyses, we identified ROIs by overall preparatory responsivity (A) and by insight effects (B), and then found that preparatory activity within the ACC ROIs specifically consistently correlated with positive mood across all participants. Analysis (C) does the converse, first identifying ROIs that show mood effects in preparation for all trials, then determining whether an insight effect (stronger signal prior to insight solutions than prior to noninsight solutions) occurred within these ROIs. The positive mood preparatory effect indicated which brain regions manifest increased preparatory responsivity, across all trials, for the 8 participants highest in positive mood compared with the 8 participants lowest in positive mood, regardless of whether the hemodynamic response demonstrated a rise and fall of signal (Figure 6).[1] For instance, some areas showed decreasing activity during preparation (left and right IFG), but more rapid decreases in Low Positive Mood than in High Positive Mood participants. The ACC and the PCC showed more preparatory responsivity for the eight participants highest versus the eight participants lowest in positive mood.

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[1] Although the top third of participants would technically be 9 participants, matching PA scores made it impossible to use more than eight participants on either end of the distribution

In the ACC region showing a mood group effect across all trials (specifically, the rostral portion of the dorsal ACC, see Figure 6), the preparation signal was stronger, across all participants, preceding problems subsequently solved with insight than preceding problems subsequently solved analytically (t(26)=[2.3], p = .03) (see Figure 8). In contrast, the PCC region that showed stronger preparation signal for the high positive than for the low positive participants did not show any insight effect during preparation (t < 1.0). We then tested whether these same regions (showing mood effects during preparation) showed insight effects leading up to solution. Indeed, across all participants, there was stronger fMRI signal for insight solutions than for noninsight solutions in the dorsal ACC (t(26)= [3.97], p < .0005, see Figure 9), the ventral ACC (t(26)= [3.8], p < .001), and the PCC (t(26)= [3.8], p < .001). These effects were not due to making the insight rating at the end of each trial, as there were no effects within any of these ROIs on the BOLD signal corresponding to the insight rating button press, (all t's < 1.2).

Thus, some brain areas – particularly the ACC – in which positive mood modulated activity during the preparation for upcoming trials, do seem especially involved in processing that leads to insight solutions. The functional overlap of areas showing both mood and insight effects is illustrated in a convergence map (Figure 7), which shows that only the rostral portion of the dACC manifests the mood-insight correspondence in all three analyses described above.

DISCUSSION

Participants higher in positive mood showed different patterns of brain activity during preparation periods preceding each solved problem, and solved more problems overall, compared to participants lower in positive mood. The mood related facilitation in solving was limited to solving with insight, as high positive mood participants solved many more problems with insight, and somewhat fewer without insight, compared to the low positive mood participants. The results reported above used PA-NA scores as an index of positive mood, and are maintained or stronger when using PA alone as the index of positive mood. In regression analyses with all mood and personality measures, PA yielded a nominally stronger correlation with insight % (r (77) = .41, p < .0005) than did PA-NA (r (77) = .40, p < .0005). Furthermore, the same pattern of HRF peaks and group differences were attained if PA was used rather than PA-NA. However, some participants scored high on both PA and NA (consistent with prior literature claiming PA and NA scores on the PANAS inventory are orthogonal, e.g. Watson & Tellegen, 1988), so it is unclear whether they should be considered high in positive mood. Therefore, we decided to consistently use PA minus NA scores throughout all the analyses.

Interestingly, as positive mood seemed to be increasing overall solving productivity, as well as shifting the type of processing employed to specifically facilitate insight solving, anxiety had somewhat the opposite effect, decreasing insight solutions, but not affecting solving performance as reliably or as consistently as positive mood.

The experimental paradigm relies on retrospective self-report measures to categorize solutions as insight versus noninsight. It is thus important to note that positive mood affected not just whether participants reported insight, but also their overall ability to solve problems (higher positive mood participants actually solved more of these problems, and all the "extra" solutions were reported to be with insight). Thus, mood affects solving behavior.

This trial-by-trial reporting method does not assume participants solve problems with insight based on a priori categorization of the problems. (Our own pilot research shows that for solving classic insight problems, participants report "insight" solutions about 65% of the time, report "analytic" solutions 25% of the time, and the remaining 10% of the time report "other" solutions when they solve without insight and without analytic methods). Even if we did rely on relatively

more 'objective' measures such as GSR measures or warmth ratings, we would still have more confidence in self-report measures. For instance, if a participant reports to have had an insight but shows gradual continuous changes in warmth ratings as he/she progresses toward the solution, rather than the sudden discontinuous jump associated with insights upon reaching the solution, we would still have more trust in the participant's self report assessment rather than warmth ratings.

Moreover, in prior studies, participants manifest different patterns of behavior and neural activity when they report solving (or recognizing solutions) with insight compared to when they report solving without insight. E.g., recognizing solutions with insight occurs faster, and with more priming of solutions (suggesting semantic activation of the solution prior to solving) than recognizing solutions without insight (e.g., Bowden & Beeman, 2003a).

Within the current study, the different solution categories were associated with qualitatively distinct patterns of brain activation preceding solution (see Fig. 9), including differently shaped hemodynamic response functions; yet there were no consistent differences at the point of insight judgments. This suggests the decisions were based on some differences in prior processing leading up to solutions, rather than posthoc decisions

Also, the high positive mood group and the low positive group both showed identical solution latency patterns (in this experiment, slightly faster insight than noninsight solutions), and parallel hemodynamic responses in fMRI signal within each category (insight vs. noninsight), suggesting that high and low positive mood participants used roughly the same processes and decision-making criteria for identifying insight and noninsight solutions.

Besides affecting behavior, positive mood also correlated with brain activity as people prepared for each new problem (in the task-free preparation interval). Specifically, we examined brain regions that changed activity during this preparation period; regions that showed insight effects (more activity during insight than noninsight trials) during this preparation period; and regions that showed insight effects at solution. Across all these analyses, only dACC consistently showed brain activity during this (resting) preparation interval that increased as positive mood increased (see Table 2, Figure 7). The corollary was also true: the ACC region that was more responsive (showed greater increase of fMRI signal corresponding to the preparatory period) in highly positive than in less positive participants also showed insight effects across all participants (Figures 8, 9). All these affect-related effects occurred despite a somewhat limited range of variability in affect (particularly in terms of negative affect).

Thus, we have strongly demonstrated that positive mood is reliably associated with preparatory states that increase responsivity in the rostral dACC, and that this modulation is associated with processing that leads to insight solutions. We are not arguing that the activation in the ACC represents a neural correlate of positive mood, or that positive mood states induce insight. We are concluding that positive mood is one factor that enhances activity in the rostral dACC, and that this mediates the shift toward insight solutions.

The precise mechanism by which positive mood facilitates insights through correspondingly modulating cognitive control processes within the ACC is not entirely obvious. Cognitive control is itself a multifaceted concept, involving the recruitment of frontal regions – including the dorsal ACC, but also DLPFC, particularly in the LH – implicated in the detection of competing responses, overcoming prepotent response tendencies, and switching attention to select the correct response (Weissman et al, 2003; Carter et al, 2000; Kondo et al., 2004; Weissman et al., 2004; Hedden & Gabrieli, 2006). ACC, specifically, has been implicated in several processes, such as error detection (Carter et al., 1998) or conflict monitoring (Botvinick et al., 2004; Kerns et al., 2004; Weissman et al., 2003).

We did not examine conflict monitoring in our study per se, and this study was not designed to tease apart the exact role of ACC in cognitive control. However, we favor a view by which the ACC

is involved in monitoring not just conflict, but a variety of competing responses, such as multiple associations or strategies involved in solving problems. One way of putting it is that the ACC sets a parameter of detecting such competing activations, that allows either task shielding (ignoring other stimuli or thoughts to remain focused) or task switching (detecting competing stimuli, so that other components of cognitive control networks can switch attention to them; see Dreisbach & Goschke, 2004). One mechanism by which PA facilitates insight is by increasing this parameter for detecting multiple competing associations, which provides the solver a better chance of suddenly switching attention to the correct solution (or to solution-related information), thus facilitating insights. In line with our 'competing activation' hypothesis, we think that PA enhances insights by possibly enhancing the detection of semantic associations (Rowe et al, 2007) facilitating shorter solution RTs, which would also partly explain why insight trials tended to be slightly faster than noninsight trials. In contrast, if insights only involved greater conflict monitoring, we would predict longer RTs for insight versus noninsight trials in our task.

PA previously has been linked to modulation of cognitive control processes to enhance cognitive flexibility, at the expense of perseveration or maintained focus (Dreisbach & Goschke, 2004). Further, prior theoretical explanations have attributed increases in cognitive flexibility to the effect of PA at enhancing phasic dopaminergic activity in the ACC and the prefrontal cortex (Ashby et al., 1999; 2002), consistent with other models of dopamine's effect on cognitive control (e.g., Braver et al., 1999, Daw et al., 2006).

When people encounter a problem to solve (or any input to understand), they frequently engage multiple possible solving mechanisms. However, under various circumstances, different mechanisms are favored – due to individual states or traits, or due to the problem itself (which is why some problems are more likely to be solved with insight, and others more analytically; Ansburg & Hill, 2003; Oelling & Knoblich, 2003; Bowden et al., 2005). PA likely shifts the balance of which mechanisms will be most effective. As noted in the introduction, solving problems with insight requires cognitive flexibility (hence cognitive control), because it benefits from "cognitive restructuring" of the problem, enabling the solver to pursue a new strategy or a new set of associations. Several putative mechanisms could explain (in whole or in part) how PA enhances such flexibility. It may alter the selection process through which information enters working memory (Ashby et al, 1999; 2002); it may tip the balance toward a more global focus of attention (Gasper & Clore, 2002), or a broader attention to both external visual space and internal conceptual space (Rowe et al, 2007) allowing more problem elements to simultaneously influence solution efforts; it may facilitate switching between different modes of attention (Baumann & Kuhl, 2005; Kondo et al., 2004), or switching from irrelevant to relevant solving strategies (Dreisbach & Goschke, 2004). These putative mechanisms may overlap, or may work in combination. The bottom line is that solvers appear to be better able to switch from pursuing a dominant but errant set of associations to a solution-relevant set.

Note that such a proposal does not mean that PA facilitates solutions by directly enhancing access to a broader range of semantic associations, e.g., by increasing RH semantic processing. Recall that another hypothetical mechanism by which positive mood could facilitate insight would be through enhanced RH processing, given the demonstrated importance of RH semantic processing for processing a broad set of semantic associations (Beeman et al., 1994; Chiarello et al., 1998) generally, and for insight solutions specifically (Bowden & Beeman, 1998; Jung-Beeman et al., 2004). Several pieces of evidence suggest that PA could enhance relative RH activation. First, PA increases sensitivity to a larger range of semantic associations (Fredrickson et al., 2005; Federmeier et al., 2001) which, as noted, is characteristic of RH semantic processing. Second, induced positive mood increases a global focus of attention (Gasper & Clore, 2002), which is usually associated with RH visual attention, whereas a local focus of attention is associated with LH processing. Third,

inducing an approach regulatory focus (which is often associated with PA) enhances both overall RH activation, as measured by a line-bisection task, and creativity (e.g., Friedman & Forster, 2005). Finally, compared to people who solve anagrams analytically, people who solve with insight show increased brain activity at rest in mostly right-lateralized regions, according to resting state EEG (Kounios et al., 2008). However, a great deal of research using frontal asymmetries during resting-state EEG associates LH activity with PA or approach regulatory focus, (e.g., Sutton & Davidson, 1997). Further, effects that shift processing towards biases that are associated with one or the other hemisphere could occur due to modulation of medial attention or cognitive control related processes.

Regardless, in the current experiment, PA did correlate with signal change during the preparation period in one lateral (rather than midline) cortical region, the angular gyrus of the RH; however, this area did not show other mood-related effects, nor did it show an "insight effect" (stronger activity for insight than noninsight trials) at either solution or the preparation period. Rather than simply increasing RH semantic processing, it appears that PA heightens solvers' sensitivity to solution-relevant processing, which may often occur within the RH semantic processing network (Jung-Beeman, 2005), working in co-operation with cognitive control processes in the frontal cortex to make the switch to converge to the correct solution. Still, it remains possible that a wider range of assessed (or induced) PA would reveal enhanced RH relative activation associated with a high positive mood.

There are several potential alternative explanations that can be considered and rejected. First, one might wonder whether positive mood did not alter the processing that led to solution, but instead simply affected participants' willingness to label a solution as "insight." This is unlikely, as we mentioned earlier, because participants higher in positive mood actually solved more problems than participants lower in positive mood – they solved more with insight, and almost equally as many without insight as the lower positive mood group. Moreover, the high and low positive mood subgroups showed similar solution reaction times for insight versus noninsight solutions (for both groups, slightly faster insight than noninsight solutions). Furthermore, both subgroups showed nearly identical hemodynamic responses for insight solutions and likewise for noninsight solutions; that is, the solution types differed, but the groups did not, suggesting that both groups used the same processes for solutions they labeled as insight.

Given that insight solutions were (in this study) faster than noninsight solutions, the possibility arises that participants higher in positive mood were more likely to adopt simpler decision heuristics before responding that they achieved solution. For instance, positive mood has been suggested to the use of "satisficing", rather than optimizing solving strategy (Kaufmann & Vosburg., 1997), or even suggested to be related to reduced overall cognitive capacity (Mackie & Worth., 1989). However, such a strategy should lead to more premature and incorrect responses, i.e., trials on which participants press the button indicating solution, but then give an incorrect response. Yet high and low positive mood participants gave equally few incorrect responses (p>.20); indeed, in other studies, participants who demonstrate a preference to solve without insight are more likely to make incorrect responses (Kounios et al., 2008).

Another possibility to consider is that PA enhances all neural activity (or perhaps enhances hemodynamic response, such as caffeine does), and that the PA-associated enhancements during preparation only occur in ACC because that is the primary area showing increased signal during that epoch. However, we observed no PA-related enhancement of signal change in brain areas showing large responses corresponding to either problem onset or solution (e.g., the insight effect in right aSTG was no bigger in high positive mood than in low positive mood participants).

Given that the "Aha!" experience has an affective component, we also considered the possibility that differences during the preparation period were remnants of activity from the preceding trial. Immediately before the preparation period, participants made their insight versus noninsight rating

of the prior trial (if it was solved). However, hemodynamic responses directly related to these ratings did not differ depending on the type of rating made (no reliable clusters of activation were observed). The enhanced activation of dACC also did not relate to whether the prior trial was solved at all, so it was not a form of increased attention in response to failure or error evaluation on the prior trial (Bush et al., 2000).

The difference between insight preparation and noninsight preparation cannot be attributed to simple lack of attention, because we analyzed only preparation periods preceding problems that were solved, not solved versus unsolved problems. Moreover, the mood-related difference in preparation activity within the dorsal ACC was not attributable to increased arousal (Critchley et al., 2005), because if anything it was inversely related to anxiety. If increased arousal drove the effect then it should be stronger in high-, rather than low-anxiety participants. Indeed, given the inverse relation between positive mood and anxiety, it's possible that some effects discussed here could be attributable to lack of anxiety (Beversdorf et al., 1999; Beversdorf et al., 2002), rather than presence of positive mood. However, all behavioral and neuroimaging measures correlated more consistently with increasing positive mood than with decreasing anxiety, whereas few of the effects correlated with the anxiety measure. Further, the effects of PA have been shown to be distinct from "affectless arousal" (Isen et al., 1987). If anything, arousal is thought to impede creativity, facilitating a narrow range of attention and perseveration on the prepotent response, thereby inhibiting overall cognitive flexibility (Easterbrook, 1959; Kischka et al., 1996; Martindale, 1995).

Finally, others have noted increased activation during what they term the default state of attention in MPFC (including dorsal ACC) and PCC (Raichle et al., 2001). It is at least possible that mood-associated changes in ACC in the current study reflect modulation of a default state network. However, we have no assessment of such default activation in the current study, so it would be a leap to make solid claims one way or the other.

Whether default state or task-related preparation, positive mood enhances activity within dACC in a manner conducive to solving with insight. This modulation may promote a more global (Gasper & Clore, 2002) or diffuse focus of attention, which has previously been linked to improved insight or creative problem solving (Ansburg & Hill, 2003; Rowe et al., 2007). Thus, we believe that one mechanism by which positive mood facilitates the shift toward an insight is by modulating ACC activity, at both the preparation and solution time periods, in a manner that enhances the detection of multiple competing associations. Therefore, a solver focused on an incorrect association (or solution path) is better "prepared" to detect and switch attention to the correct association; if this attention suddenly brings the correct solution into awareness, the solver experiences an "Aha!"

CONCLUSIONS

We examined the relation between various mood states (including positive mood and anxiety) and personality measures, assessed prior to the experiment, and brain activity immediately preceding and during problem solving. We found that positive mood enhanced overall solving for these insight-like verbal problems, and particularly increased the likelihood of solving them with insight. We demonstrated that these effects were related to brain activity in the ACC during the preparation interval prior to each trial. Specifically, activity increased in the ACC more for high-positive than for low-positive mood participants. The ACC was the only region showing sensitivity to multiple measures of this mood-insight association, providing strong evidence that positive mood states alter preparatory activity in the ACC biasing participants to engage in problem processing that is conducive to solving with insight. These results have important implications for neural accounts of both general analytic problem solving, and creative insight solving. Previous research has demonstrated that positive mood broadens the scope of attention to both external visual space and

internal conceptual space (Rowe et al., 2007). The current work illustrates a neural basis for this modulation of problem solving by positive mood. Further, it suggests that positive mood enhances insight and creative problem solving, at least in part, by modulating attentional and cognitive control mechanisms within the ACC to allow more sensitivity to detect competing solution candidates.

Acknowledgements

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Table 1. Behavior: Positive Mood Enhances Solving Performance and Solving with Insight while Anxiety Inhibits Solving with Insight

Out of 135 problems	Average Solved Number	Average Insight Number	Average Noninsight Number	Solve %	Insight %	Non Insight %
All 79 Participants	55.3	28.1	25.9	41.0	50.8	46.8
High Positive Mood Participants	60.0 *	34.5 ***	24.9	44.4 *	57.5 ***	41.5 ***
Low Positive Mood Participants	51.3	21.9	29.0	38.0	42.7	56.5
High Anxious Participants	52.3	24.1 **	27.1	38.7	46.1 **	51.8 *
Low Anxious Participants	57.1	33.1	23.5	42.3	57.9	41.2

For all 79 participants tested, mean number of overall solutions, solutions with insight, and analytical noninsight solutions are given for each participant group (n = 26), high vs. low positive mood was calculated using PA-NA scores from the PANAS inventory; high vs. low anxiety scores from the STAI inventory (*p < .05, **p < .01 ***p < .0005). Solved percentages were calculated out of 135 trials; insight and analytical percentages were calculated out of the total solved number.

Table 2. Neuroimaging**:** Positive Mood States Predict Increased Preparatory Activity in the ACC to Enhance Solving with Insight

Structure	Correlations			Brod. Areas	Volume (mm)	Center Coord.			Mean % sig	Max % sig	Mean t	Max t
	Pos. Mood	Anxiety	Solve %			X	Y	Z				
A. Preparatory activity												
L. IFG	0.22	-0.24	**-0.40***	9, 6	4375	-42	3	26	-0.07	-0.11	6.6	9.1
R. IFG	0.2	-0.26	**-0.50***	6	3219	47	-13	41	-0.06	-0.1	5.5	7
ACC	**0.41***	-0.34	0.27	9, 32	1562	1	47	13	0.1	0.15	5.5	6.5
PCC	0.29	-0.32	0.36	31,23	6641	-1	-48	33	0.05	0.1	3.5	4.4
R. AG	**0.40***	-0.22	**0.41***	40	6031	47	-60	39	0.07	0.1	3.4	4.2
B. High Pos. Mood Preparatory State > Low Pos. Mood Preparatory State												
D ACC	**0.50***	**-0.44***	0.20	32, 9	3188	0	36	21	0.08	0.12	3.8	5.3
v. ACC	**0.44***	**-0.47***	0.21	24	938	-10	26	0	0.07	0.09	4	6.2
PCC	**0.40***	-0.34	-0.23	31, 30	875	6	-44	25	0.05	0.1	3.8	4.6
C. Insight Preparation > Analytical Preparation												
PCC	0.23	-0.28	0.10	31	6641	-24	-10	-10	0.07	0.09	3.5	4.4
ACC	**0.40***	**-0.40***	**0.37***	32	1047	-3	43	5	0.08	0.1	3.5	4.4
L p.M/STG	0.22	**-0.41***	0.21	22, 19, 39	797	50	59	1	0.08	0.07	3.4	4.2
R.p.M/STG	-0.16	-0.15	-0.10	39, 37	562	46	69	24	0.07	0.07	3.4	4.2
D. Insight Solution > Analytical Solution												
R M/STG	0.27	**-0.38***	0.02	21, 22	2156	57	-33	2	0.08	0.1	4	4.8
PCC	0.27	-0.24	0.26	31	2047	2	-42	34	0.08	0.12	4	4.9
R. PHC	-0.05	-0.01	-0.01	34	1984	20	-11	-13	0.08	0.12	3.8	5.6
ACC	**0.45***	**-0.44***	**0.37***	24, 32	1984	-4	36	3	0.09	0.13	3.4	4.1
L. M/STG	0.22	0.18	0.25	21	1516	-59	-19	-5	0.05	0.1	3.4	4
R. SFG	0.18	-0.27	0.30	9	1234	8	51	28	0.09	0.11	3.4	4.2
R. IPL	0.24	-0.16	0.08	40	703	55	-39	38	0.06	0.07	3.4	4.1

Each value in the correlations section is a correlation value of either positive mood (PA-NA), anxiety (STAI) or overall solving proportion with activity in the corresponding cluster that represents the signal difference between the contrasted conditions as a percent of average signal within the cluster (*p < .05). (A) shows ROIs identifying significant signal change within the 3 TRs corresponding to the expected peak preparatory signal (i.e. TRs starting at 6 sec through 12 sec) compared to the 1st and last 2 TRs, corresponding to the baseline preparation signal. (B) shows the positive mood preparatory ROIs with increased fMRI preparatory activity for the top 8 participants highest in Positive Mood than the bottom 8 participants lowest in positive mood (C) shows ROIs with stronger fMRI peak signal for insight preparation than for analytical noninsight preparation (D) shows ROIs with stronger fMRI signal within the 3 TRs corresponding to the expected peak signal just prior to insight solutions than for analytical solutions. No clusters showed the opposite effect at this strict threshold.

Figure Captions

Figure 1. Sequence of events within a trial of the Compound Remote Associate (CRA) task. Each trial began with a central fixation cross, signaling the onset of the preparation interval, which lasted for a variable 0-8s, after which the problem was presented. Participants pressed the response buttons bimanually if/when they achieved solution, then verbalized the solution at the Solution prompt, and then reported whether they solved the trial with or without insight at the Insight prompt. The intervals between these events were jittered for a variable 0-8s.

Figure 2. Scatter plots for all 79 participants indicating the relation between percent of solutions achieved by insight and (A) positive mood (PA-NA); and (B) anxiety (STAI), both presented in standardized z scores for illustration purposes, with regression lines and values obtained from multiple regression including all mood and personality measures.

Figure 3. Subgroups of participants by high-, medium-, and low- positive mood (A) and Anxiety (B) scores, illustrating the number of correct solutions achieved with and without insight.

Figure 4. (A) The regions of interest (ROI) within the dorsal ACC (see Table 2 for co-ordinates) showing strongly increased signal (p<.0001), across all 27 participants, corresponding to the preparation interval, superimposed on the averaged normalized structural image of all participants. Brain images show (left to right) axial, sagittal and coronal images (with left hemisphere on left of axial and coronal images). (B) The average signal change across this dACC region, for the 20 seconds following onset of the preparation interval (which lasted 0-8 sec). (C) Scatterplot illustrating the correlation between positive mood and increased preparatory activity in this dACC region (peak-baseline) across all 27 participants.

Figure 5. (A) The ROI within the rostral ACC showing stronger signal for insight (p <.001) than for noninsight solutions (as in Jung-Beeman et al., 2004), across all 27 participants. Brain images show (left to right) axial, sagittal and coronal images (with left hemisphere on left of axial and coronal images). (B) Scatterplot illustrating the correlation between positive mood and increased preparatory activity (peak-baseline) in this rostral ACC region showing an insight solution effect, across all 27 participants.

Figure 6. All ROIs showing stronger signal change (peak-baseline) corresponding to the preparation interval for high positive mood than for low positive mood participants (p<.005). Reliable clusters include dorsal and ventral ACC, as well as PCC. (No reliable clusters showed the reverse, i.e., stronger signal for low positive mood participants).

Figure 7. Convergence map, showing all voxels within each of the three types of analyses: Voxels showing reliable signal change (peak-baseline) corresponding to preparation (blue); voxels showing both preparation activity and insight solution effects (green); voxels showing both preparation activity and stronger preparation signal in high- than in low-positive mood participants (purple); and voxels showing all three effects (black).

Figure 8. Insight preparation effect in mood sensitive ROI: Average percent signal change over time, corresponding to the preparation interval across all voxels in the ROI showing a reliable mood effect (stronger preparation activity in the high- than in the low-positive mood participants). The blue line shows signal change for preparation prior to problems solved with insight, pink shows preparation signal prior to problems solved without insight, and the green line shows the difference,

which was near-constant throughout the epoch. The green shaded region (i.e. TRs starting at 6 sec through TR ending at 12 sec), showing stronger signal for insight versus noninsight preparation (* p < .05) corresponds to the peak signal for the preparation period. For comparison, the preceding button press elicited peak signal in the motor cortex (M1) at 4sec, which corresponded to the insight rating button press from the prior trial.

Figure 9. Insight solution effect in mood sensitive ROI: Average percent signal change over time, corresponding to the solution interval (i.e., 0 sec corresponds to a solution event 2 seconds prior to the solution button press), across all voxels in the ROI showing a reliable mood effect at preparation. The blue line shows signal change prior to problems solved with insight, pink shows signal change prior to problems solved without insight, and the green line shows the difference, which was near-constant throughout the epoch. The green shaded region (TR starting at 4 sec through TR ending at 10 sec) showing greater solution-related signal (* p < .0005) for insight versus noninsight trials, corresponds to the peak signal leading up to the solution. For comparison, the subsequent solution button press elicited peak signal in the motor cortex (M1) at 10 sec (i.e., 8 seconds following the button press).
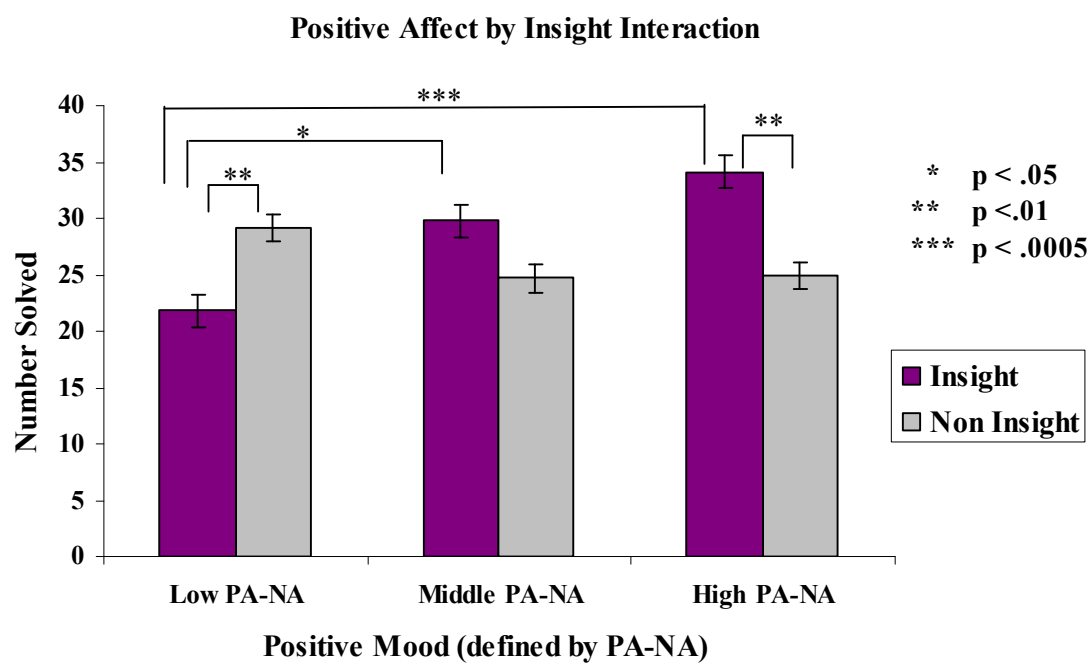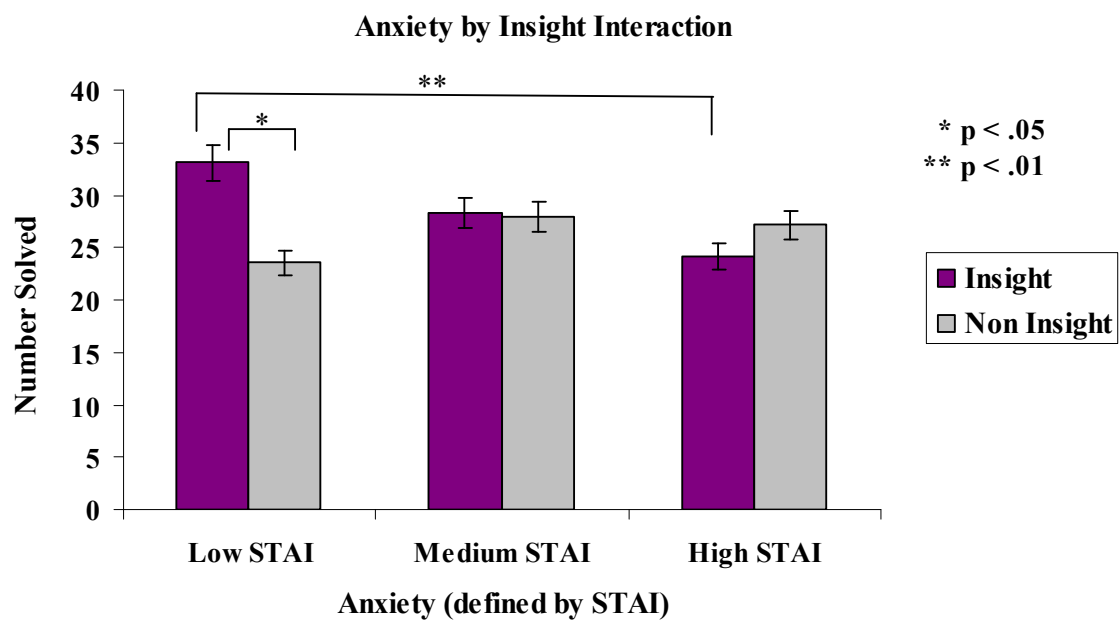
Figure 1.

Figure 2.

Positive Mood and % Insight

Anxiety and % Insight

Figure 3.

A.

Positive Affect by Insight Interaction

*   p < .05
**   p <.01
*** p < .0005

B.

Anxiety by Insight Interaction

* p < .05
** p < .01

Figure 4.

A.

B.

C.

Figure 5.

A.

Insight solution effect in ACC

B.

r = 0.45, p < .05

% signal change

Positive Mood (PA-NA)
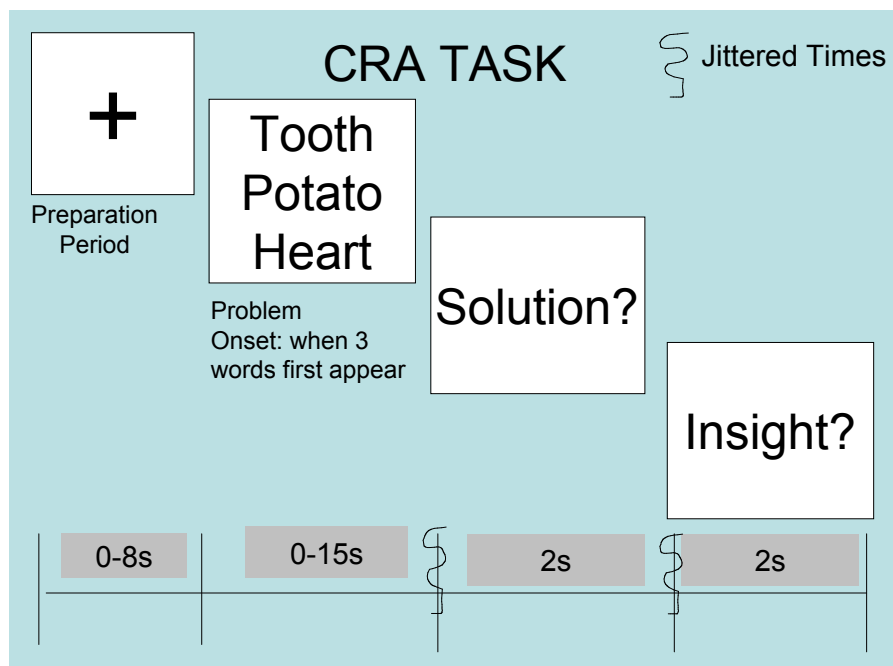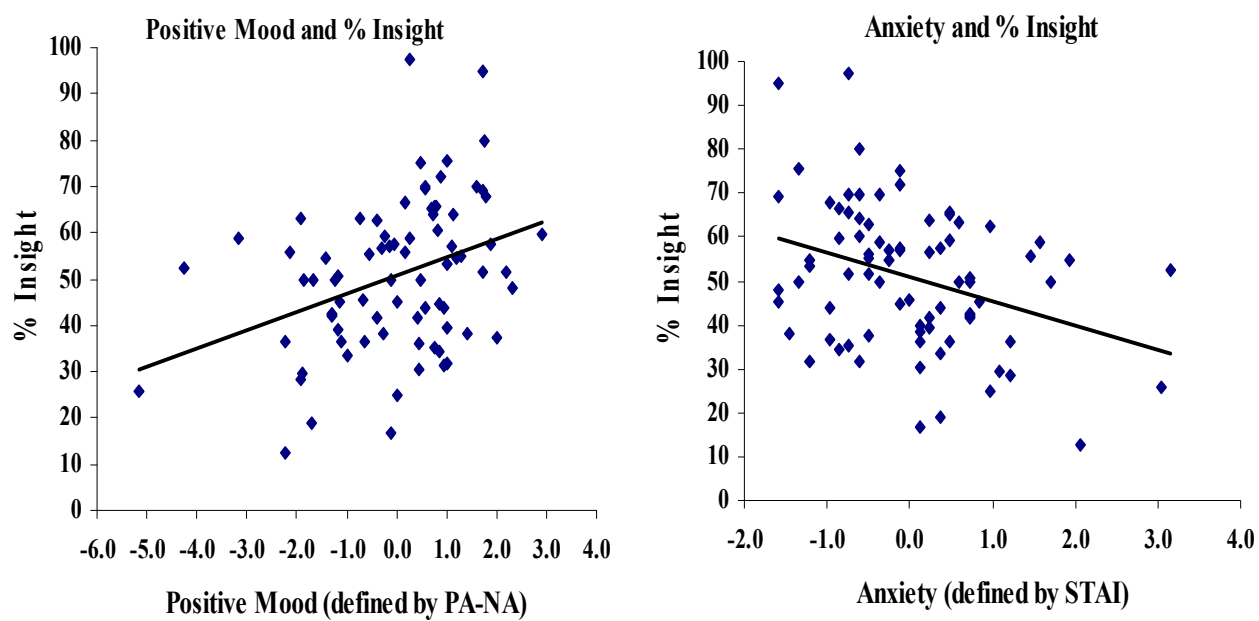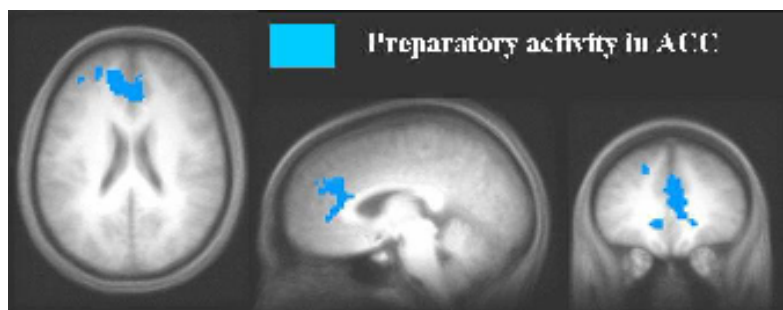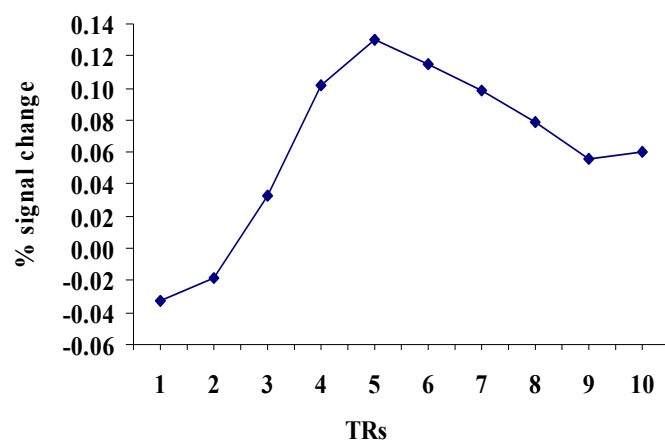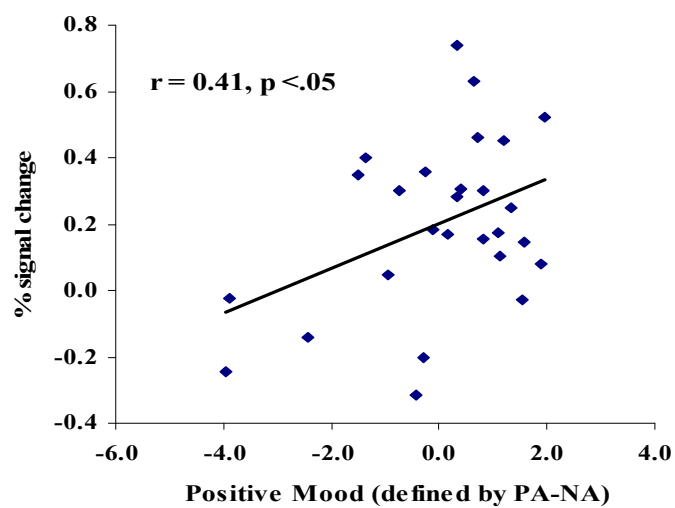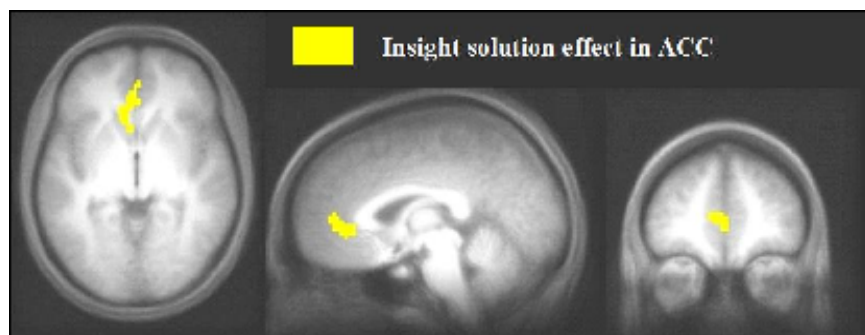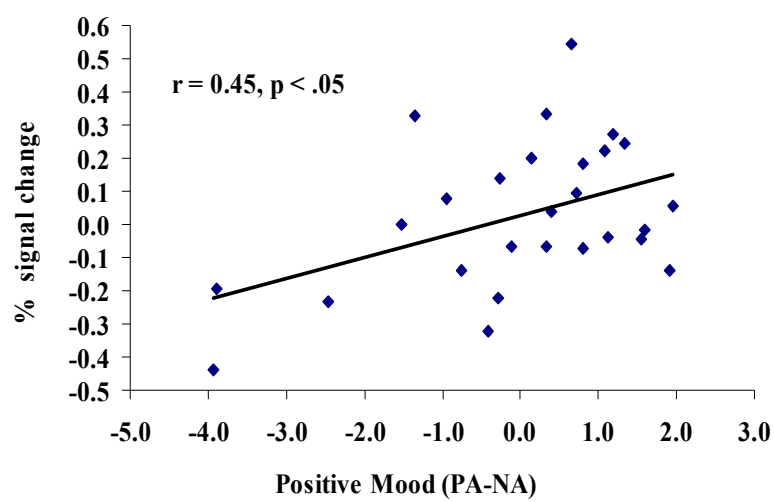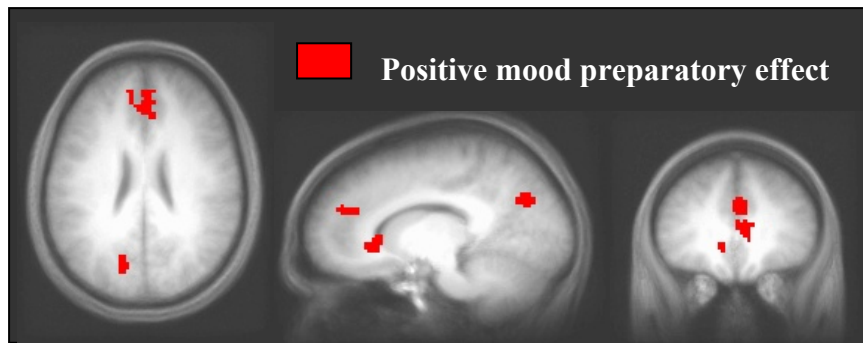
Figure 6.

Figure 7.

Figure 8.

Figure 9.