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Rationality and emotionality: serotonin transporter genotype influences reasoning bias

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Reasoning often occurs under emotionally charged, opinion-laden circumstances. The belief-bias effect indexes the extent to which reasoning is based upon beliefs rather than logical structure. We examined whether emotional content increases this effect, particularly for adults genetically predisposed to be more emotionally reactive. SS/SL_G carriers of the serotonin transporter genotype (5-HTTLPR) were less accurate selectively for evaluating emotional relational reasoning problems with belief-logic conflict relative to L_AL_A carriers. Trait anxiety was positively associated with emotional belief-bias, and the 5-HTTLPR genotype significantly accounted for the variance in this association. Thus, deductive reasoning, a higher cognitive ability, is sensitive to differences in emotionality rooted in serotonin neurotransmitter function.

INTRODUCTION

Humans are not perfectly rational. We display biases leading to errors in reasoning and decision making (Tversky and Kahneman, 1974). One common type of bias in deductive reasoning is when one accepts or rejects a conclusion based on one's knowledge about the world (hereafter termed beliefs) rather than logical validity (Evans *et al.*, 1983). In relational reasoning tasks, one must evaluate whether a conclusion follows logically from the premises, regardless of the believability of the content. For example, given the premises, 'Cars are bigger than motorcycles' and 'Motorcycles are bigger than airplanes', the conclusion 'Cars are bigger than airplanes' is logically valid but unbelievable, as cars are not bigger than airplanes in the real world. Participants tend to be slower or less accurate in accepting unbelievable conclusions as logically valid and also in accepting believable conclusions that are logically invalid (Roberts and Sykes, 2003). Thus, accepting conclusions that are *incongruent* with our beliefs interferes with logical reasoning. Conversely, when the validity and belief of the conclusion are *congruent* (valid, believable or invalid, unbelievable), participants are faster or more accurate in evaluating the conclusion. Reduced performance for incongruent than congruent conclusions, termed the *belief-bias effect*, indexes how much our beliefs interfere with reasoning and has been demonstrated using categorical syllogisms and conditional and relational reasoning problems (Byrne and Tasso, 1999; Goel and Dolan, 2003; Roberts and Sykes, 2003).

In addition to our beliefs, emotion also influences deductive reasoning. Two lines of evidence indicate that manipulation of emotional processing hinders the reasoning process. First, affective state (pre-existing or induced) reduces logical reasoning performance. Patients with anxiety disorders made more errors on a conditional reasoning task (Wason Selection Task) than healthy controls when reasoning with anxiety-provoking material (de Jong *et al.*, 1997). In healthy participants, experimentally inducing negative or positive mood resulted in more errors on the Wason Selection Task than without mood manipulation (Oaksford *et al.*, 1996). Second, affective content (pre-existing or conditioned) reduces reasoning performance relative to neutral content. Given logically identical reasoning problems, participants made more errors when problems comprised emotionally charged statements (e.g. 'If there is danger, then one feels nervous') than neutral statements (e.g. 'If one is in a library, then one sees books') for conditional (Blanchette and Richards, 2004; Blanchette, 2006) and categorical (Lefford, 1946) reasoning problems. Reduced reasoning accuracy was also observed for neutral words associated with negative or positive emotional pictures relative to those associated with neutral pictures (Blanchette and Richards, 2004; Blanchette, 2006). Thus, neutral content with experimentally acquired emotional valence also reduced deductive reasoning performance. Together, these findings indicate that emotional state and content influence logical reasoning.

If emotional processing influences logical reasoning, then individual differences in emotional reactivity ought to influence reasoning performance. One source of individual differences in emotional reactivity is a polymorphism in the promoter region of the serotonin transporter gene (5-HTTLPR) that results in short (S) and long (L) variants. The S allele is linked to lower expression of serotonin transporter mRNA (Hu *et al.*, 2006). Further, the L allele contains an A to G single-nucleotide polymorphism (SNP, rs25531) that influences transcriptional efficiency, rendering the L_G allele functionally similar to the S allele (Hu *et al.*, 2006). Findings of studies comparing S carriers (SS alone or with SL_G) with homozygous L carriers (e.g. LL or L_AL_A) suggest that the S allele is associated with higher emotional reactivity. Specifically, S allele carriers were overrepresented in patients with affective disorders (Caspi *et al.*, 2003), exhibited more depressive and anxiety-related behaviors despite being healthy (Lesch *et al.*, 1996; Gonda *et al.*, 2009) and showed a stronger bias towards emotional content in spatial attention (Beevers *et al.*, 2009) and interference (Koizumi *et al.*, 2010) tasks. Further, the amygdala, a critical brain region underlying emotional behavior, is more responsive to negative stimuli in healthy S carriers (Munafo *et al.*, 2008). Together, these findings indicate that S (and L_G) carriers differ in emotional reactivity from L carriers (and L_A alone). No study has examined whether these allelic differences influence emotional processing in the context of logical reasoning.

We investigated the effect of 5-HTTLPR genotype on belief-bias in relational reasoning problems with and without emotional content. In light of evidence indicating functional similarity between the S and L_G alleles (Hu *et al.*, 2006), we included L_G carriers in the S group as done

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in past work (Armbruster *et al.*, 2009). Other heterozygous carriers (SL_A, L_AL_G) were excluded in order to maximize observed allelic differences (Roiser *et al.*, 2009). We predicted that carriers of the 5-HTTLPR S or L_G alleles (SS, SL_G, L_GL_G) would demonstrate increased belief-bias relative to homozygous carriers of the L_A allele (L_AL_A) during reasoning with emotional, but not non-emotional, content. This prediction is based upon findings of increased sensitivity to negative affective stimuli in S (and L_G) carriers, which ought to make suppression of beliefs with emotional content more difficult relative to L_AL_A carriers. Such a finding would indicate that serotonin-related differences in emotional reactivity influence cognitive control during deductive reasoning. Furthermore, in light of past findings relating the S allele to increased anxiety, we also examined the association between the 5-HTTLPR genotype, trait anxiety and belief-bias for emotional material.

METHODS

Participants

One hundred and sixty-nine Georgetown University undergraduates (65 males) of primarily European descent without history of psychiatric diagnosis or medication, who were native English speakers or fluent by age 10 years, participated for course-credit or payment. Consent was acquired according to Institutional Review Board guidelines. Participants provided a saliva sample that was analysed for 5-HTTLPR and the rs25531 SNP in the serotonin transporter gene (SLC6A4). Genotype frequencies were in Hardy–Weinberg equilibrium ($\chi^2 = 2.45$, $df = 1$, $P > 0.1$). For SLC6A4, after excluding L_AS and L_AL_G genotypes, our final sample included two groups, L_AL_A and SS/SL_G. The L_AL_A group ($N = 41$; 44% males; 85% European descent; age: $M = 19.4$, s.d. = 1.2) did not differ from the SS/SL_G group ($N = 34$; 41% males; 74% European descent; age: $M = 19.1$, s.d. = 1.1) in age ($P > 0.4$), gender ($P > 0.8$) or ethnicity ($P > 0.2$). The SS/SL_G group was composed of SS ($n = 22$) and SL_G ($n = 12$) carriers. No participants had the rare L_GL_G genotype.

Genotyping

Saliva samples (Oragene, Canada) were analyzed for 5-HTTLPR using a two-step process. First, the long (L) and short (S) variants were determined. The repeat polymorphism in the promoter region of the 5-HTT gene was genotyped by PCR as previously described (Lesch *et al.*, 1996) using the following primers at concentrations of 10 μM; forward: 5'-GGCGTTGCCGCTCTGAATGC-3'; reverse: 5'-GAGGGA CTGAGCTG-GACAACCAC-3'. PCR was performed using the AccuPrime™ GC-Rich DNA polymerase system (Invitrogen) with the following PCR program: 95°C for 10 min, followed by 35 cycles of 95°C for 30 s, 65°C for 30 s and 72°C for 1 min. A final extension time of 72°C for 10 min was performed after the 35 cycles were complete. The PCR products were then run out on a 2% agarose gel stained with ethidium bromide. The amplification yielded distinct bands at 484 bp (S allele = 14 copies of repeat) and 528 bp (L allele = 16 copies of repeat), which were distinguished by a 100 bp DNA ladder run on the same gel. Second, the L_A and L_G variants were determined for the rs25531 SNP, present only on the long allele. Genotyping for rs25531 was performed by digesting the PCR products generated from the 5-HTTLPR PCR reactions with the restriction enzyme MspI (New England BioLabs). Specifically, 10 μl restriction digestion reactions were performed by combining 8 μl of the 5-HTTLPR PCR product, 1 μl of 10× NEBuffer 4 and 1 μl of MspI (concentration = 100 000 U/ml) and incubating the reactions for 2 h at 37°C followed by heat inactivation of the enzyme at 80°C for 20 min. The substitution of the G for A in the SNP produces an additional MspI recognition site (CCGG) on the long allele of the 5-HTTLPR PCR product. Genotypes were determined by running the digested PCR products out on a 2% agarose gel stained with ethidium bromide. Samples with two copies of the A allele for rs25531 showed a band at 340 bp (as well as bands at 127 and 62 bp due to multiple MspI recognition sites on the 5-HTTLPR PCR product), while samples with two copies of the G allele for rs25531 had additional digestion of the 340 bp product, yielding bands at 166 and 174 bp (as well as bands at 127 and 62 bp). Samples that were heterozygous for rs25531 showed a combination of these two band patterns.

Table 1 Experimental conditions and example stimuli

Trial type	Emotional	Non-emotional
Congruent	Cockroaches are smaller than snakes. Cockroaches are bigger than maggots. Snakes are bigger than maggots? (Valid, Believable); 24 trials	Adults are younger than children. Adults are older than infants. Children are older than infants? (Valid, Believable); 24 trials
Incongruent	Tobacco is more poisonous than venom. Tobacco is less poisonous than mucus. Venom is less poisonous than mucus? (Valid, Unbelievable); 24 trials	Trees are taller than flowers. Trees are shorter than grass. Flowers are shorter than grass? (Valid, Unbelievable); 24 trials

Stimulus materials

Stimuli consisted of 96 three-term relational reasoning problems (e.g. A > B, B > C, therefore A > C) that varied by emotion and congruency (Table 1). Words for the reasoning problems were selected from the Affective Norms for English Words database [ANEW; (Bradley and Lang, 1999)], which provides ratings for arousal and valence on a 10-point scale. Emotional problems contained primarily negative (<4 = negative, 84.7%, >7 = positive valence, 15.3%) and highly arousing (>3.5; mean: 5.9) words, whereas non-emotional problems contained words that were neither positive nor negative (4–7 valence) and low in arousal (<5.5; mean: 4.2).

Problems also varied on belief-logic congruency. For congruent problems, the validity of the conclusion was in accordance with semantic beliefs (*valid*, *believable* and *invalid*, *unbelievable*). For incongruent problems, the validity of the conclusion was in conflict with semantic beliefs (*valid*, *unbelievable* and *invalid*, *believable*). The 96 logic problems varied by Emotional content (emotional, non-emotional) and Congruency (congruent, incongruent), creating four conditions, 24 problems each: Emotional Congruent, Emotional Incongruent, Non-emotional Congruent and Non-emotional Incongruent. Conditions were equated for conclusion believability (12 believable, 12 unbelievable), validity (12 valid, 12 invalid), determinacy (18 determinate, 6 indeterminate) and content type (13 non-living, 6 living, 5 abstract).

Procedure

Practice

Following task description and explanation of the task (what constitutes a logical conclusion), participants completed 14 practice problems where they determined if the conclusion followed logically from the premises by basing the decision on logical form and not on the factual truth or falsity of the conclusion. Participants were given unlimited time and were asked to re-think the problem if they made errors and to correct the error until all problems were correctly solved.

Reasoning task

Problems were presented on a computer screen in pre-determined random order held constant across participants. Participants were

instructed to press the 'F' key if a problem was 'logical' and 'J' key if it was 'not logical', as quickly as possible. Premise 1 appeared on the screen for 3 s, followed by Premise 2 below it for 3 s, and then the conclusion below it, after which all three remained on the screen for 6 s. Participants had 6 s to respond, and the next problem appeared immediately after their response or after the 6 s. No feedback was provided.

Belief questionnaire

The questionnaire measured whether the participant's beliefs matched those of the experimenters. Forty-eight conclusions (half believable, half unbelievable) were selected randomly, including 12 problems from each of the four experimental conditions. Participants were asked to mark each conclusion as 'True', 'False' or 'Don't Know', based on their own knowledge.

Working memory

Participants completed a verbal *N*-back task, consisting of six alternating 1.2-min blocks of two- and three-back conditions ('low' and 'high' working memory load, respectively). Each block comprised 24 trials preceded by an instruction screen stating the type of trial in the block, for example, '2-back' or '3-back'. For all conditions, one letter was presented on the screen at a time (for 0.5 s followed by a 2.5-s inter-trial interval), and the participant was instructed to press a button with their right index finger on the keyboard when the letter on the screen was the same as the one presented *n* trials previously. In the two-back condition, participants were instructed to press the button if the letter was the same as 2 before it (e.g. 'R' then 'L' then 'R'); in the three-back condition, participants were instructed to press the button if the letter was the same as 3 before it (e.g. 'M' then 'K' then 'P' then 'M'). The number of target responses was identical across trial conditions. Stimuli comprised consonants only; vowels were omitted to prevent encoding series of letters as pronounceable strings.

Trait anxiety

Participants completed the STAI (Spielberger *et al.*, 1983), a self-report measure of state and trait anxiety. Scores of trait but not state anxiety were used in further analysis in order to examine the influence of a stable rather than situational characteristic of emotionality.

RESULTS

Belief questionnaire

For each participant, responses were coded based upon the match with the experimenter as agree (true/false by both), disagree (true/false mismatch between the two) or uncertain ('don't know'). Mean agreement was high, disagreement and uncertainly low and independent *t*-tests revealed no genotype differences. Mean percentage of 'agree' responses was emotional: congruent (L_AL_A: $M = 94.1\%$, s.d. $= 7.2$; SS/SL_G: $M = 92.1\%$, s.d. $= 8.6$; $P > 0.2$) incongruent (L_AL_A: $M = 92.9\%$, s.d. $= 6.7$; SS/SL_G: $M = 92.8\%$, s.d. $= 5.0$; $P > 0.9$); non-emotional: congruent (L_AL_A: $M = 94.3\%$, s.d. $= 6.9$; SS/SL_G: $M = 93.0\%$, s.d. $= 6.4$; $P > 0.3$) incongruent (L_AL_A: $M = 92.9\%$, s.d. $= 6.3$; SS/SL_G: $M = 91.4\%$, s.d. $= 7.3$; $P > 0.3$). Since average disagreement (2.4%) and uncertainty (4.5%) across conditions was extremely low, mean percentage of disagreement (L_AL_A: $M = 2.4\%$, s.d. $= 1.6$; SS/SL_G: $M = 2.6\%$, s.d. $= 1.8$; $P > 0.5$) and uncertainty (L_AL_A: $M = 4.2\%$, s.d. $= 2.8$; SS/SL_G: $M = 4.8\%$, s.d. $= 2.9$; $P > 0.3$) were collapsed across conditions.

Table 2 Mean (s.d.) accuracy and reaction time for relational reasoning problems with emotional and non-emotional content in SS/SL_G and L_AL_A carriers

	Short (SS/SL_G; $N = 34$)	Long (L_AL_A; $N = 41$)
Accuracy		
Emotional		
Congruent	85.57% (10.31)	85.88% (10.19)
Incongruent	73.93% (14.01)	80.74% (10.82)
Non-emotional		
Congruent	85.06% (11.54)	88.27% (8.19)
Incongruent	77.94% (12.59)	80.67% (10.75)
Reaction time		
Emotional		
Congruent	2482 ms (718)	2411 ms (572)
Incongruent	2850 ms (584)	2700 ms (468)
Non-emotional		
Congruent	2586 ms (546)	2447 ms (528)
Incongruent	2785 ms (588)	2676 ms (521)

Reasoning task

A response was scored as 'correct' if it was consistent with the logical validity of the problem and 'incorrect' if it was not consistent with logical validity or if there was no response within 6 s ('timed-out'; $M = 7\%$ of problems). For each participant, mean accuracy (% correct) and mean reaction time (ms) for correct responses were computed for congruent and incongruent problems with and without emotional content (Table 2). Mixed ANOVAs with genotype (SS/SL_G *vs* L_AL_A) as a between-subject factor and congruency (congruent *vs* incongruent) and emotion (emotional *vs* non-emotional content) as within-subjects factors were computed separately for accuracy and reaction time. Controlling for ethnicity and for working memory performance (3-back accuracy) did not change the significance of any reported results.

Accuracy

A main effect of congruency [$F(1, 73) = 65.99$, $P < 0.001$, $\eta^2 = 0.47$] indicated a significant belief-bias effect as participants were more accurate for belief-logic congruent ($M = 86.19\%$, s.d. $= 8.77$) than incongruent ($M = 78.32\%$, s.d. $= 10.83$) problems. While no other main effects or two-way interactions reached significance (Ps > 0.10), the genotype × congruency × emotion interaction was significant [$F(1, 73) = 6.28$, $P = 0.014$, $\eta^2 = 0.08$]. Planned comparisons testing for group differences indicated that accuracy was lower in SS/SL_G ($M = 73.93\%$, s.d. $= 14.01$) relative to L_AL_A ($M = 80.74\%$, s.d. $= 10.82$) participants, only for problems in the emotional incongruent condition [$t(73) = 2.37$, $P = 0.020$]; genotype groups did not differ in other conditions (P's > 0.20). Further, planned comparisons showed that each genotype group exhibited belief-bias (congruent > incongruent) for both emotional (SS/SL_G: $t(33) = 6.31$, $P < 0.001$; L_AL_A: $t(40) = 3.240$, $P < 0.001$) and non-emotional (SS/SL_G: $t(33) = 3.71$, $P = 0.001$; L_AL_A: $t(40) = 5.30$, $P = 0.002$) conditions.

As expected based on the three-way interaction, a genotype × emotion ANOVA on the amount of belief bias (Congruent minus Incongruent) revealed an interaction [$F(1, 73) = 6.28$, $P = 0.014$, $\eta^2 = 0.08$], such that SS/SL_G carriers ($M = 11.64\%$, s.d. $= 10.75$) had higher belief-bias relative to L_AL_A carriers ($M = 5.14\%$, s.d. $= 10.16$) for emotional problems [$t(73) = 2.68$, $P = 0.009$; Figure 1]. Amount of belief-bias did not differ by genotype for non-emotional problems (SS/SL_G: $M = 7.12\%$, s.d. $= 11.19$; L_AL_A: $M = 7.60\%$, s.d. $= 9.18$; $P > 0.8$). Further, SS/SL_G carriers had higher belief-bias for emotional ($M = 11.64\%$, s.d. $= 10.75$) relative to non-emotional ($M = 7.12\%$, s.d. $= 11.19$) problems [$t(33) = 2.234$, $P = 0.032$]; belief-bias in L_A/L_A

carriers did not differ by emotional content ($P > 0.2$). No main effects reached significance (P's > 0.1).

Reaction time

A main effect of congruency [$F(1, 73) = 64.86$, $P < 0.001$, $\eta^2 = 0.47$] showed that participants were faster to evaluate conclusions of congruent ($M = 2477$ ms, s.d. $= 555$) than incongruent ($M = 2747$ ms, s.d. $= 505$) problems. Thus, participants' response latencies exhibited a belief-bias effect. No other main effects or interactions reached significance (P's > 0.1, Table 2).

Working memory

A between-subject ANOVA showed that mean accuracy for two-back (L_AL_A: $M = 92.78\%$, s.d. $= 7.89$; SS/SL_G: $M = 91.84\%$, s.d. $= 9.82$) and three-back (L_AL_A: $M = 88.03\%$, s.d. $= 14.11$; SS/SL_G: $M = 82.17\%$, s.d. $= 17.89$) working memory conditions did not differ between groups (Ps > 0.1). Furthermore, neither two-back ($P = 0.51$) nor three-back ($P = 0.20$) accuracy correlated with emotional belief-bias scores. Including three-back accuracy as a covariate did not change any significance value in our belief-bias ANOVAs or correlational analyses.

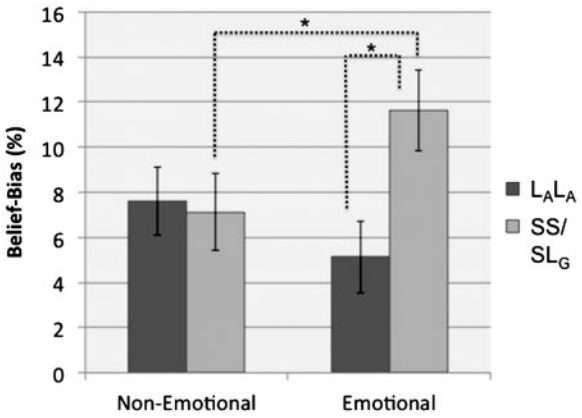

Fig. 1 Mean belief-bias (percentage of correct congruent − incongruent) for relational reasoning problems with emotional and non-emotional content in L_AL_A and SS/SL_G carriers (*$P < 0.05$).

Trait anxiety

A between-subject ANOVA showed that mean standard scores were higher in SS/SL_G ($M = 50.48$, s.d. $= 8.07$) than L_AL_A ($M = 46.32$, s.d. $= 7.56$) participants [$F(1,71) = 5.25$, $P = 0.025$, $\eta^2 = 0.07$]. Further, anxiety scores correlated positively with the amount of belief-bias for problems with emotional ($r = 0.24$, $P = 0.04$) but not non-emotional ($r = 0.03$, $P = 0.789$) content (Figure 2). Thus, individuals with higher trait anxiety were more biased towards their beliefs during reasoning with emotional content alone.

OLS linear regression

In light of the association between anxiety and emotional belief-bias and higher anxiety in SS/SL_G carriers, we examined the role of genotype in the relationship between anxiety and emotional belief-bias. A simple regression model with anxiety scores as the sole independent variable revealed that the estimated association between anxiety and emotional belief-bias was 0.32 with an associated standard error (s.e.) of 0.15 ($P = 0.04$; standardized $\beta = 0.24$, replicating the bivariate correlation). This association was reduced to non-significance ($P > 0.1$) upon adding 5-HTTLPR genotype to the model. This reduction suggests that the positive association between anxiety and emotional belief-bias is explained by the covariance between both behavioral variables (anxiety and emotional belief-bias) and genotype. Moreover, genotype was significantly associated with emotional belief-bias even with anxiety held constant ($b = 5.61$, s.e. $= 2.46$, $P = 0.02$). The unstandardized coefficient of 5.61 indicates that the SS/SL_G group scored 5.61% points higher on emotional belief-bias than the L_AL_A group, even with anxiety held constant. With 5-HTTLPR and anxiety included, the model accounted for 12% of variance in emotional belief-bias.

DISCUSSION

A polymorphism of the 5-HTTLPR genotype influenced the extent to which beliefs interfered with deductive reasoning, selectively for emotional content. Overall, participants exhibited belief-bias, defined by more errors and slower evaluation of conclusions of relational reasoning problems in which beliefs and logical structure were in conflict relative to congruent. However, the amount of belief-bias was larger in carriers of the S/L_G alleles relative to the L_A allele, for problems with highly arousing and emotionally valenced content but not for those with less arousing, less emotional content. Further, trait anxiety correlated positively with belief-bias for emotional problems, and the 5-HTTLPR genotype accounted significantly for the variance in this

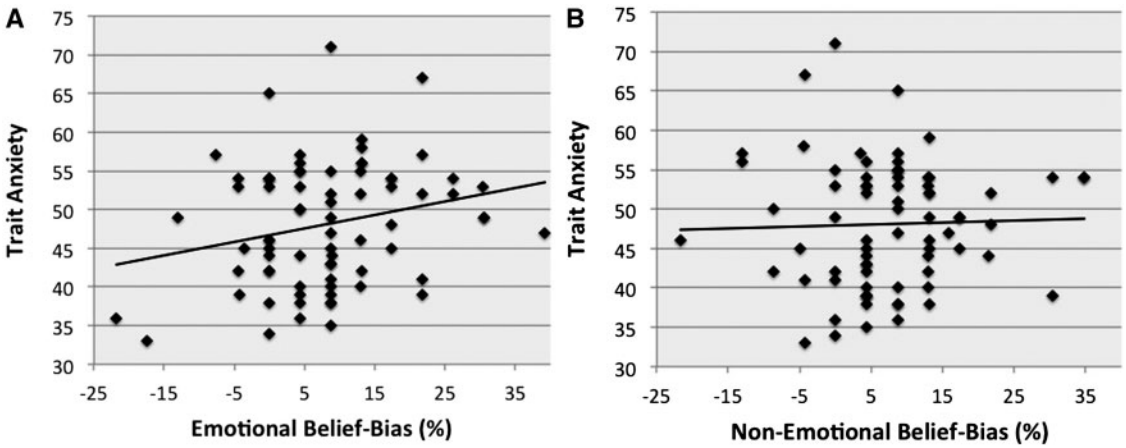

Fig. 2 Correlation between trait anxiety standard scores and (A) emotional and (B) non-emotional belief-bias (percentage of correct congruent–incongruent). *$P < 0.05$.

relationship. Thus, individual variation in deductive reasoning, a higher cognitive ability, depends upon an interaction between semantic content and serotonin-based genetic differences in emotional reactivity.

It has been argued that reasoning with meaningful content involves inhibiting one's semantic knowledge in order to process the logical structure (Houde *et al.*, 2000; Handley *et al.*, 2004; Prado and Noveck, 2007; De Neys *et al.*, 2008; Luo *et al.*, 2008; De Neys and Franssens, 2009). Behaviorally, suppression of one's beliefs is effortful as reflected in failures or slower speed of reasoning for problems where beliefs and logic conflict, as observed in this study. Support for the involvement of inhibitory processing during deductive reasoning comes from two sources. First, inhibitory control abilities are associated with the amount of belief-bias. Children with higher response inhibition (as measured by the stop signal task) had lower belief-bias in conditional and relational reasoning tasks (Handley *et al.*, 2004). Second, functional brain imaging studies show that a brain region known to support inhibitory control, right inferior frontal cortex [IFC; (Aron *et al.*, 2004)] was consistently activated during belief-bias [e.g. incongruent *vs* congruent and neutral problems (Goel *et al.*, 2000; Stollstorff *et al.*, 2012); logical *vs* belief-based responses for incongruent problems (Goel and Dolan, 2003)] and increased activity of this region but not its left-hemisphere homologue was associated with less belief-bias (Tsujii and Watanabe, 2010). Further, disruption of neural activity in the right, but not left, IFC with transcranial magnetic stimulation reduced accuracy for incongruent, but not congruent, syllogisms, thereby increasing belief-bias relative to a control group (Tsujii *et al.*, 2010). Together, these findings suggest that successful logical reasoning requires the inhibition of interference from semantic knowledge.

Our findings suggest that inhibiting emotionally valenced semantic knowledge was selectively effortful for carriers of the 5-HTTLPR short allele. Overall, reasoning abilities were similar across genotype groups, as their accuracy did not differ on either incongruent or congruent problems without emotional content [consistent with Gong *et al.* (2011), who found no relation between analogical reasoning ability and 18 functional genetic variants influencing neurotransmitter function, including several that influence 5-HT function]. Thus, greater interference from beliefs in S carriers was specific to reasoning with emotional material. Logic problems in this study included primarily negatively valenced words, with only a few highly arousing positive words. Thus, our results cannot be examined by valence, but should be in future studies in light of past findings of the 5-HTTLPR polymorphism. Specifically, S/L_G carriers showed a higher attentional bias towards negative faces, whereas L/L_A carriers showed a higher attentional bias towards happy faces in an emotional dot-probe task (Beevers *et al.*, 2009)]. These findings together with the observed interaction between emotional valence and 5-HTTLPR genotype serve to elucidate past findings showing reduced reasoning performance with both negative and positive content relative to non-emotional content (Blanchette and Richards, 2004; Blanchette, 2006). It is possible that *positive* emotional content was detrimental selectively for L_AL_A carriers (due to their attentional bias towards positive stimuli), and *negative* emotional content was detrimental selectively for S/L_G carriers (due to their attentional bias towards negative stimuli). This prediction should be tested in future work. Further, it would also be important to examine whether the 5-HTTLPR genotype influences belief-bias for other types of emotional content such as politically incorrect statements violating social norms. A recent study found reduced belief-bias for such material (Goel and Vartanian, 2011); perhaps such beliefs are easier to suppress as one is practiced at doing so in everyday life. Such content, comprising beliefs one should not have, may differ in its susceptibility to emotional reactivity than emotional content detached from social norms such as that used in our study.

Enhanced belief-bias from emotional content in S carriers who are known to be more emotionally reactive may result from two sources: Parallel to findings from emotional Stroop-like tasks [e.g. color-word and face-word (Koizumi *et al.*, 2010)], S carriers' increased attention to negative emotional content could have increased inhibitory demands making its suppression more difficult than that of non-emotional information. Another possibility is that the emotional content, which was primarily negative, could have temporarily evoked a negative mood state. Indeed, past findings indicate that S carriers have a higher propensity for negative mood (Lesch *et al.*, 1996; Gonda *et al.*, 2009). Thus, negative emotional material may draw more attention and induce a negative affective state, two factors known to impede reasoning (Oaksford *et al.*, 1996; Blanchette and Richards, 2004). Together, they may serve to reduce reasoning accuracy for emotional problems with belief-logic conflict, only in participants with higher emotional reactivity.

Trait anxiety, one property of emotional reactivity, was higher in SS/SL_G than L_AL_A carriers, consistent with previous reports (Lesch *et al.*, 1996; Lonsdorf *et al.*, 2009). Past studies using the emotional Stroop task found greater interference from threat-related words in patients with anxiety disorder (Becker *et al.*, 2001) as well as healthy participants with high anxiety (Dresler *et al.*, 2009). Further, belief-bias during reasoning with social-anxiety-provoking statements was higher in healthy participants with higher levels of social anxiety (Vroling and de Jong, 2009). Similarly, belief-bias for emotional problems was higher in participants with higher trait anxiety in the present study. However, multiple regression analysis revealed that 5-HTTLPR genotype accounted for the relationship between anxiety and emotional belief-bias. Indeed, mediation analysis indicated that anxiety was not a significant mediator between 5-HTTLPR and emotional belief-bias. We suggest that the S-allele leads to a pre-disposition to negative emotional reactivity, which in turn leads to higher anxiety and emotional belief-bias. In contrast, N-back working memory performance did not differ between groups and did not correlate with emotional belief-bias, indicating 5-HTTLPR effects found in the present study have some specificity, acting through *emotional* rather than general cognitive processing mechanisms. Thus, a more anxious temperament due to 5-HTTLPR genotype was related to reduced inhibitory control during reasoning selectively with emotional material.

The ability to make rational decisions relates to success in various aspects of contemporary society. Superior deductive reasoning ability predicts higher academic achievement. Specifically, children showing less belief-biased reasoning errors had higher math and reading performance (Handley *et al.*, 2004). Furthermore, relational reasoning is also important for social functioning (Maclean *et al.*, 2008). For example, if Johnny knows that his older sibling Pat is stronger than him based on previous experience and that Mark, the new kid in school, is stronger than Pat, the ability to *infer* that Mark is therefore stronger than Johnny without having to directly test this hypothesis can be highly beneficial. Interestingly, 5-HTTLPR genotype relates to a variety of social functions, including establishment of social dominance and aggression in animals that live in social groups (Neumann *et al.*, 2010). The present findings show that genotypic differences in the functioning of the serotonin transporter lead some individuals to be more vulnerable to the influence of emotion and its deleterious effects on reasoning, an important ability for academic and social success.

REFERENCES

Armbruster, D., Moser, D.A., Strobel, A., et al. (2009). Serotonin transporter gene variation and stressful life events impact processing of fear and anxiety. *International Journal of Neuropsychopharmacology*, *12*, 393–401.

Aron, A.R., Robbins, T.W., Poldrack, R.A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, *8*, 170–7.

Becker, E.S., Rinck, M., Margraf, J., Roth, W.T. (2001). The emotional Stroop effect in anxiety disorders: general emotional or disorder specificity? *Journal of Anxiety Disorders*, *15*, 147–59.

Beevers, C.G., Wells, T.T., Ellis, A.J., McGeary, J.E. (2009). Association of the serotonin transporter gene promoter region (5-HTTLPR) polymorphism with biased attention for emotional stimuli. *Journal of Abnormal Psychology*, *118*, 670–81.

Blanchette, I. (2006). The effect of emotion on interpretation and logic in a conditional reasoning task. *Memory Cognition*, *34*, 1112–25.

Blanchette, I., Richards, A. (2004). Reasoning about emotional and neutral materials. Is logic affected by emotion? *Psychological Science*, *15*, 745–52.

Bradley, M.M., Lang, P.J. (1999). Affective norms for English words (ANEW): stimuli, instruction manual and affective ratings. *Technical report C-1*. Gainsville, FL: The Center for Research in Psychophysiology, University of Florida.

Byrne, R.M., Tasso, A. (1999). Deductive reasoning with factual, possible, and counterfactual conditionals. *Memory Cognition*, *27*, 726–40.

Caspi, A., Sugden, K., Moffitt, T.E., et al. (2003). Influence of life stress on depression: moderation by a polymorphism in the 5-HTT gene. *Science*, *301*, 386–9.

de Jong, P.J., Mayer, B., van den Hout, M. (1997). Conditional reasoning and phobic fear: evidence for a fear-confirming reasoning pattern. *Behaviour Research Therapy*, *35*, 507–16.

De Neys, W., Franssens, S. (2009). Belief inhibition during thinking: not always winning but at least taking part. *Cognition*, *113*, 45–61.

De Neys, W., Vartanian, O., Goel, V. (2008). Smarter than we think: when our brains detect that we are biased. *Psychological Science*, *19*, 483–9.

Dresler, T., Meriau, K., Heekeren, H.R., van der Meer, E. (2009). Emotional Stroop task: effect of word arousal and subject anxiety on emotional interference. *Psychological Research*, *73*, 364–71.

Evans, J.S., Barston, J.L., Pollard, P. (1983). On the conflict between logic and belief in syllogistic reasoning. *Memory Cognition*, *11*, 295–306.

Goel, V., Buchel, C., Frith, C., Dolan, R.J. (2000). Dissociation of mechanisms underlying syllogistic reasoning. *Neuroimage*, *12*, 504–14.

Goel, V., Dolan, R.J. (2003). Explaining modulation of reasoning by belief. *Cognition*, *87*, B11–22.

Goel, V., Vartanian, O. (2011). Negative emotions can attenuate the influence of beliefs on logical reasoning. [Research Support, Non-U.S. Gov't]. *Cognition and Emotion*, *25*, 121–31.

Gonda, X., Fountoulakis, K.N., Juhasz, G., et al. (2009). Association of the s allele of the 5-HTTLPR with neuroticism-related traits and temperaments in a psychiatrically healthy population. *European Archives of Psychiatry and Clinical Neuroscience*, *259*, 106–13.

Gong, P., Zhang, F., Lei, X., et al. (2011). No observable relationship between the 12 genes of nervous system and reasoning skill in a young Chinese Han population. [Research Support, Non-U.S. Gov't]. *Cellular and Molecular Neurobiology*, *31*, 519–26.

Handley, S.J., Capon, A., Beveridge, M., Dennis, I., Evans, J.S.B. (2004). Working memory, inhibitory control and the development of children's reasoning. *Thinking and Reasoning*, *10*, 175–95.

Houde, O., Zago, L., Mellet, E., et al. (2000). Shifting from the perceptual brain to the logical brain: the neural impact of cognitive inhibition training. *Journal of Cognitive Neuroscience*, *12*, 721–8.

Hu, X.Z., Lipsky, R.H., Zhu, G., et al. (2006). Serotonin transporter promoter gain-of-function genotypes are linked to obsessive-compulsive disorder. *American Journal of Human Genetics*, *78*, 815–26.

Koizumi, A., Kitagawa, N., Kitamura, M.S., Kondo, H.M., Sato, T., Kashino, M. (2010). Serotonin transporter gene and inhibition of conflicting emotional information. *NeuroReport*, *21*, 422–6.

Lefford, A. (1946). The influence of emotional subject matter on logical reasoning. *Journal of General Psychology*, *34*, 127–51.

Lesch, K.P., Bengel, D., Heils, A., et al. (1996). Association of anxiety-related traits with a polymorphism in the serotonin transporter gene regulatory region. *Science*, *274*, 1527–31.

Lonsdorf, T.B., Weike, A.I., Nikamo, P., Schalling, M., Hamm, A.O., Ohman, A. (2009). Genetic gating of human fear learning and extinction: possible implications for gene-environment interaction in anxiety disorder. *Psychological Science*, *20*, 198–206.

Luo, J., Yuan, J., Qiu, J., Zhang, Q., Zhong, J., Huai, Z. (2008). Neural correlates of the belief-bias effect in syllogistic reasoning: an event-related potential study. *Neuroreport*, *19*, 1073–8.

Maclean, E.L., Merritt, D.J., Brannon, E.M. (2008). Social Complexity Predicts Transitive Reasoning in Prosimian Primates. *Animal Behaviour*, *76*, 479–86.

Munafo, M.R., Brown, S.M., Hariri, A.R. (2008). Serotonin transporter (5-HTTLPR) genotype and amygdala activation: a meta-analysis. *Biological Psychiatry*, *63*, 852–7.

Neumann, I.D., Veenema, A.H., Beiderbeck, D.I. (2010). Aggression and anxiety: social context and neurobiological links. *Frontiers in Behavioral Neuroscience*, *4*, 12.

Oaksford, M., Morris, F., Grainger, B., Williams, J.M.G. (1996). Mood, reasoning, and central executive processes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*, 476–92.

Prado, J., Noveck, I.A. (2007). Overcoming perceptual features in logical reasoning: a parametric functional magnetic resonance imaging study. *Journal of Cognitive Neuroscience*, *19*, 642–57.

Roberts, M.J., Sykes, E.D. (2003). Belief bias and relational reasoning. *Quarterly Journal of Experimental Psychology A*, *56*, 131–53.

Roiser, J.P., de Martino, B., Tan, G.C., et al. (2009). A genetically mediated bias in decision making driven by failure of amygdala control. *Journal of Neuroscience*, *29*, 5985–91.

Spielberger, C.D., Gorsuch, R.L., Lushene, R., Vagg, P.R., Jacobs, G.A. (1983). *Manual for the State-Trait Anxiety Inventory for Adults*. Consulting Psychologists Press, Palo Alto, CA.

Stollstorff, M., Vartanian, O., Goel, V. (2012). Levels of conflict in reasoning modulate right lateral prefrontal cortex. *Brain Research*, *1428*, 24–32.

Tsujii, T., Masuda, S., Akiyama, T., Watanabe, S. (2010). The role of inferior frontal cortex in belief-bias reasoning: an rTMS study. *Neuropsychologia*, *48*, 2005–8.

Tsujii, T., Watanabe, S. (2010). Neural correlates of belief-bias reasoning under time pressure: a near-infrared spectroscopy study. *Neuroimage*, *50*, 1320–6.

Tversky, A., Kahneman, D. (1974). Judgment under uncertainty: heuristics and biases. *Science*, *185*, 1124–31.

Vroling, M.S., de Jong, P.J. (2009). Deductive reasoning and social anxiety: evidence for a fear-confirming belief bias. *Cognitive Therapy Research*, *33*, 633–44.