AN INTEGRATED NEURAL MODEL OF SYLLOGISTIC REASONING, INCORPORATING THE EFFECTS OF SEQUENTIALLY- AND CONCURRENTLY-PRESENTED EMOTION

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Abstract

What is the relation between emotion and syllogistic reasoning? Previous neuroimaging research has suggested a reciprocal relationship between ventromedial prefrontal cortex, associated with reasoning about emotionally-provocative material, and dorsolateral prefrontal cortex, associated with reasoning about non-emotional material (Goel & Dolan, 2003b). This dissertation introduces two neuroimaging studies exploring a) the effect of emotion induction *prior* to syllogistic reasoning about non-emotional material and b) the effect of *concurrent* emotional context on syllogistic reasoning about non-emotional material. The first study found that positive emotion appears to bolster a reliance on beliefs rather than logic whereas negative emotion appears to distract the reasoner because of ongoing effects of the images. In the second study, non-emotional syllogism material was delivered auditorially in sad, angry, or neutral tone of voice, with no instruction regarding the vocal character of the voice itself. Behavioural results indicate that overall performance tends to be facilitated by auditory delivery of that content in angry tone of voice, and is unaffected by auditory delivery in sad tone of voice. The finding of different underlying patterns of neural activation associated with sadness and anger is consistent with LeDoux's (1996) postulate of separate neural emotion systems, and suggests that the successful regulation of interference from sad and angry emotions involved different mechanisms. The dissertation proposes a dual-mechanism model of the interaction of reason and emotion (MIRE). The model structure is designed to encourage future research into not only those factors that impair logic-based reasoning,

but also those factors that trigger it. Such an approach takes into account what the brain is doing during syllogistic reasoning in the absence or presence of emotion.

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An Integrated Neural Model of Syllogistic Reasoning, Incorporating the Effects of Sequentially- and Concurrently-Presented Emotion

While I'm taking a break from writing, my husband puts down his book and says "Listen to this." I turn to him, expectantly. Without even thinking about it, I have made an inference. I have reasoned that Bruce has found an interesting detail while reading, and is about to share it with me. If he had sounded alarmed, I might have made a different inference, in which case I might have gone over to sit beside him. His tone of voice would have affected my state of readiness to hear what was coming. If we had been laughing together over some political cartoons in a different book, I might be smiling broadly as I turn in his direction. In that case, I am feeling relaxed and eager to find out what he is going to say. Or perhaps I have just phoned my friend who has been ill and there is no answer; my husband puts down his book and says "Listen to this" but I am worried and tell him that there might be an emergency. This time I have made an inference but it is about my friend rather than about my husband.

In general terms, an emotion signal (such as an alarmed tone of voice) switches us into a particular state of readiness to reason about or take action regarding the event that has been signalled. Switching back from an emotional state (still relaxed and eager) to a neutral state may not always occur. If there are two events in the environment, the one with the emotional signal (possible emergency) may take precedence over the other ("Listen to this"). In all of these examples, events occur sequentially rather than concurrently.

Turning to a different set of circumstances, imagine that a client in therapy is yelling as he relates how his siblings badgered him out of his share of the inheritance after he had taken care of his ailing father for years. The psychotherapist has the dual task of not reacting personally to the yelling, and of initiating a helpful guiding step for the client. She regulates the effect of the emotion on herself, makes an empathic statement directed at the essence of the client's pain, and guides him to start breathing deeply. In this example, the two events for the psychotherapist, that of being a potential target of the yelling and of identifying the appropriate intervention, occur concurrently.

This dissertation explores the relation between emotion and *syllogistic* reasoning in particular, and will present the results of two neuroimaging studies; in one study the emotion induction and reasoning task were presented sequentially whereas in the other they were presented concurrently. This introduction will proceed by clarifying what is meant by "emotion" and by "syllogistic reasoning"; following that will be a literature review, and then a clarification of the distinction between mood and emotion and of the term "affect as information." In ensuing sections, the two neuroimaging studies will be presented. Finally, in the general discussion section, the dissertation author will present an integrated neural model of the relation between emotion and syllogistic reasoning.

What is emotion? Emotion has various components such as physiological arousal, and emotional facial/vocal/bodily expression. In broad terms, one can say that emotion is positively or negatively valenced; intensity is another component. Emotions may be triggered by sensory/perceptual signals or could be awakened by vividly re-experiencing an episodic memory or a provocative idea in imagination. Just as visceral functions have to do with the current physical status of the organism (for example, saliva secretion is related to the functioning of the digestive system), emotions have to do with the current motivational status of the organism. Just as the digestive system performs many functions outside of conscious awareness or volitional control, so too do emotions. When visceral functions enter awareness they do so by means of sensations such as hunger pangs or pain; when emotions enter conscious awareness, they are referred to as feelings (for example, fear or delight), although the term "emotion" is often used in a general sense when precision about emotion *versus* feelings is not being sought. When long-lasting effects of emotion, or moods, enter conscious awareness, they are referred to by the term "affect", although the term "moods" is often used when precision is not crucial. Cognitive processing can operate to some extent outside of awareness, and when the products of cognitive processing are in awareness, they are referred to as thoughts. Here again, the general term "cognition" or "cognitions" can be used when precision is not needed. Unlike viscera and emotions, cognitions are not in themselves valenced, nor are they postulated to be associated with physiological arousal or expression.

What is deductive reasoning? It is a form of inference in which a conclusion is drawn without adding to existing information; more specifically, "deductive inferences are those whose conclusions necessarily follow from their premises or assumptions" (Evans, Newstead, & Byrne, 1993, p. 3). For example, most readers will have been able to draw the conclusion that my husband's name is Bruce even though that information had not been stated until now. A common paradigm in which to present deductive reasoning is the syllogism, which consists of two premises and a conclusion. For example, "All women are caring. Some women have red hair. Some red-haired people are caring" (which is valid). Deductive reasoning is vulnerable to many influences; for instance, reasoners are more likely to accept a conclusion starting with the word "All" when the premises both contain the quantifier "All". This is referred to as the atmosphere effect (Evans, Newstead et al., 1993; Melton, 1995).

Within the reasoning literature, it has been noted that when the logical response to an argument requires going against one's beliefs about the truth or falsity of the content, reasoners will often choose the belief-biased, illogical, response. That is, beliefs trump logic (Evans, 2003; Goel & Dolan, 2003a). An example of such an argument is as follows: "All wise people are experts. No young people are experts. No young people are wise." In this case, the argument is valid; however, as the conclusion is false, reasoners often indicate (incorrectly) that the argument is invalid.

Literature Review

The traditional view of the relation between emotion and reasoning has been shaped by the Christian/Freudian model, which conceptualizes this relation as one in which emotion, being animalistic and maladaptive, must be brought under control by the higher, more sensible, reasoning system. Neuroscientists influenced by this model have interpreted data about human neural functioning as indicating separate instantiation of emotion in the phylogenetically older limbic system and of rationality in the more recently-developed cortex. However, as research has progressed, this traditional view is giving way to a view that, in some circumstances, emotion may actually facilitate reasoning.

The literature review is organized by sections on emotion, reasoning, emotion/reason, and emotion/decision-making. The section on emotion and decision-making has been included because the literature from that field contributes to an understanding of the effects of emotion on reasoning and because the field has been influenced by Damasio's (1994) emotion/decision-making model.

Within each section, the approach to theories or models has been to extract the issues implicit or explicit in those models. Those issues are:

- Does emotion facilitate or impede reasoning?
- How many (non-emotional) reasoning systems are postulated, and how are they characterized?
- How many emotional reasoning systems are postulated, and how are they characterized?

- What is the role of beliefs in the emotion/reason relation?

Within each section, after the theories are considered, evidence from behavioural literature and neuroimaging literature follows.

Emotion

Selected theories or models of emotion. Of the many models of emotion that have been proposed, two have been selected for mention here. James (1890/1950) has proposed that all emotions are necessarily physiological in character. LeDoux (1996) has postulated that there is not one diffuse emotion system, but rather separate emotion systems at the neural level, and that each serves a function.

In terms of whether emotion either facilitates or impedes reasoning, James (1890/1950) did not address this issue. LeDoux (1996) proposed that once a (neural) emotion system is triggered, it is a powerful motivator for future behaviour; the effects on behaviour could be either beneficial or detrimental.

In terms of how many emotions there are, James took the view that “there is no limit to the number of possible different emotions which may exist, and ...the emotions of different individuals may vary indefinitely” (James, 1890/1950, p. 454). As mentioned above, LeDoux (1996) postulated that there are several emotions.

In terms of how emotions themselves are characterized, James viewed emotions as being physiological.

> Without the bodily states following on the perception, the latter would be purely cognitive in form, pale, colourless, destitute of emotional warmth. We might then see the bear, and judge it best to run…but we should not actually *feel* afraid (James,

> 1980/1950, p. 450).

If an actor attempts to portray an emotion, (s)he "may catch the trick with the voluntary muscles, but fail with the skin, glands, heart, and other viscera" (James, p. 450).

LeDoux's (1996) model of emotion has several features, some of which have already been mentioned and others that will be described below when discussing the role of beliefs. The remaining features are as follows: (a) Emotional functions relate to survival. All animals have survival-related behaviours, and neural systems to support these behaviours. (b) A person trembles because his/her danger-detection system has been activated. LeDoux describes how the danger-detection system is comprised of behaviour, physiology, and feelings, as follows:[1]

> Conscious emotional experiences are made up of a number of ingredients. Some of the factors that contribute...[include] direct inputs from the amygdala to cortical areas (sensory and higher-order processing regions), inputs from the amygdala to nonspecific arousal systems and from these to widespread areas of the forebrain (cortical and subcortical areas), and feedback to the amygdala and cortical areas from the bodily expression of emotion. Note that the bodily expressions (visceral and muscular) are themselves controlled by the amygdala (LeDoux, p. 297).

(c) It is an error to begin the study of emotion by studying feelings. Emotional responses can be measured objectively. Study emotional responses directly, to understand underlying mechanisms. LeDoux makes an analogy to the study of perception, by pointing out that perception is commonly researched without addressing the experiencing

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[1] LeDoux's (1996) reference to the amygdala here is specific to the danger-detection system.

of perception. Cognition can be studied the same way, as can emotion. Consciousness occurs when the person becomes privy to the outcome of processing. (d) Neural connections from emotional systems to cognitive systems are stronger than *vice versa*. Emotions happen to a person; conscious control of emotions is weak. The person can choose situations that will provide external emotional stimuli, but the person cannot fake an emotion.

In terms of the role of beliefs in the emotion/reason relation, James (1890/1950) rejected the notion that emotion could occur *only* as the result of an appraisal, but did not rule out appraisals as triggers for *the physiological events* that constitute emotion. Influenced by James (1890/1950), LeDoux (1996) indicated that an emotion system can be triggered directly by a sensory signal without cognitive mediation. Feelings, which are not necessary for emotion, are the conscious awareness of emotion. There is a separate system for the representation of facts; however, there is only one mechanism for conscious awareness, and inputs to awareness from emotion systems will displace inputs from the fact-based system. LeDoux's view of the role of appraisal is similar to that of James. That is, a cognitive appraisal that a situation is dangerous is not sufficient for emotion; the underlying physiological system must additionally be activated. "Something else is needed to turn cognitive appraisals into emotions, to turn experiences into emotional experiences. That something, of course, is the activation of the system built by evolution to deal with dangers. That system...crucially involves the amygdala" (LeDoux, p. 284).

Neuroimaging of emotion. There is support in the literature for differential neural activation evoked by different emotions. A meta-analysis (Murphy, Nimmo-Smith, & Lawrence, 2003) of 106 imaging studies of emotion reported that overall there is no difference in neural activation specifically between happiness and sadness; however, approach-related stimuli were correlated with activation in the left hemisphere whereas withdrawal-related stimuli were correlated with bilateral activation. Furthermore, neural activation differed among fear, disgust, anger, and happiness / sadness, suggesting at least partial support for a theory of separate underlying mechanisms related to different types of emotion. Fear was associated with activation of the amygdala, disgust with the insula and globus pallidus, anger with the lateral orbitofrontal cortex, and happiness/sadness with supracallosal anterior cingulate and dorsomedial prefrontal cortex.

William James (1890/1950) had hypothesized that emotion can be triggered directly by perception; he wrote, "The bodily changes follow directly the perception of the exciting fact...We feel afraid because we tremble" (James, p. 449). Furthermore, James argued that there might not be neural regions dedicated specifically to emotion, that emotion might be intrinsic to perceptual systems. This hypothesis was tested by Bermpohl et al. (2006) in an fMRI study in which they explored neural activation associated with emotional perception versus emotional expectancy. Stimuli were neutral, positive, and negative pictures from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthberg, 1997). In the emotional perception condition, unlike the expectancy condition, there was no pre-cueing as to whether the imminent picture would be emotional or neutral. Upon presentation of the picture, participants pressed a button to ensure attention; no judgment was required.

Emotional expectancy (Bermpohl et al., 2006) was associated with neural activation in the left anterior cingulate (cognitive division), parieto-occipital sulcus, and bilateral superior and middle temporal gyrus (BA 21/22); emotional perception was associated with neural activation in bilateral amygdala, right insula, lateral frontal pole (BA 10), bilateral ventrolateral prefrontal cortex (BA 44/45), bilateral fusiform gyrus, bilateral occipital and lingual gyri, bilateral cerebellum, left putamen, and right midbrain.

Bermpohl et al. (2006) concluded that because expectancy and perception involved dissociable neural networks in the emotion condition, although not in the neutral condition, the Jamesian hypothesis was not supported. However, it is actually not clear that this study has refuted James. James (1890/1950) was addressing the *experiencing* of emotion, whether that experiencing emanated from perception or from an evocative idea. Furthermore, the point of James's thesis was that emotional experiencing, whether through direct perception or by means of an evocative idea, would occur together, that is, as a system. In the emotion perception condition, neural activations did occur bilaterally in the occipital lobes, which are commonly associated with visual processing, as well as in the amygdala, a region commonly reported in association with experiencing of emotion. Therefore, the results of this study cannot be interpreted as clear refutation of the Jamesian hypothesis.

To explore whether positive and negative mood induction would differentially affect perceptual encoding, Schmitz, De Rosa, and Anderson (2009) conducted an fMRI study in which positive, negative, and neutral IAPS pictures were used for mood induction. In the perceptual encoding task, participants viewed a face in centre screen, and a house in the surround. The task was to determine the gender of the face. Faces were always novel; all houses were repeated once. Results indicated that positive and negative mood each biased the encoding of unattended novel objects (houses) in peripheral vision differently. Whereas positive mood broadened focus, negative mood narrowed it. Activation in the parahippocampal place area (PPA) was increased during the positive condition but was decreased during the negative condition. The PPA activation was attenuated during repeated presentations in the positive condition; however, the PPA signal, such as it was, was not attenuated in the negative condition. This finding suggests that participants habituated to houses in the positive condition but failed to encode the houses in the negative condition. Further examination of the evidence demonstrated that this was not an effect of attention, but rather a direct effect of two different neural states, each of which recruits different posterior sensory regions. In the positive condition, activation in PPA was correlated with activation in primary visual cortex, whereas in the negative condition, activation in PPA was inversely correlated with primary visual cortex activation. In addition, activation in right lateral frontal pole (BA 10) and right lateral orbitofrontal cortex (BA 11) was associated with positive mood induction whereas activation in the amygdala was associated with negative mood induction. These results support an account of neural emotion systems rather than an account of valence effects *per se*. Whereas the Jamesian hypothesis discussed above was that emotion can be triggered directly by perception, the results of this study demonstrate that emotion can have direct effects, apparently not mediated by attention, at the level of perceptual encoding.

Positive and negative ratings of picture valence may lead to different patterns of neural activation. Dolcos, LaBar, and Cabeza (2004) tested this hypothesis in an fMRI study in which participants were shown positive, neutral, and negative IAPS pictures. The task was to experience any feelings or thoughts that the picture might evoke, and to rate each picture as negative, neutral or positive. Participants performed a surprise cued-recall test 45 minutes after the scanning. Activation associated with picture viewing, collapsed across valence, was reported in right ventrolateral prefrontal cortex (BA 47). Positive evaluation was associated with activation in left dorsolateral prefrontal cortex (BA 8/9); negative evaluation was associated with activation in right ventrolateral prefrontal cortex (BA 47) and bilateral dorsolateral prefrontal cortex (BA 8/9). The contrast [Emotional *minus* neutral] yielded activation in dorsomedial prefrontal cortex (BA 9). Memory for emotional pictures was associated with increased activation in left dorsolateral prefrontal cortex (BA 9/6) and left ventrolateral prefrontal cortex (BA 47). Thus, this study did demonstrate different patterns of neural activation associated with positive and negative ratings of picture valence.

The neural underpinnings of viewing and rating increasingly aversive IAPS pictures during scanning were investigated in a positron emission tomography (PET) study (Taylor, Liberzon, & Koeppe, 2000). Activation in the amygdala, uncus (which is a transition zone between the amygdala and hippocampus; Insausti & Amaral, 2004), and anterior parahippocampal gyrus was positively correlated with increasingly aversive ratings of the pictures. Mildly aversive ratings were associated, as well, with activation in left sublenticular region, left insula, left lingual, fusiform, and mid-occipital regions, left inferior/middle temporal gyrus, and left cerebellum. Strongly aversive (compared to neutral) ratings were associated with activation in right insula, bilateral lingual, fusiform, and mid-occipital regions, and bilateral inferior/middle temporal gyrus. Strongly aversive (compared to mildly aversive) ratings were associated with activation in left sublenticular region and right lingual gyrus. Both neutral ratings (minus blank screen) and strongly aversive ratings (minus blank screen) were associated with activation in bilateral amygdala and bilateral lateral orbitofrontal cortex. As well, strongly aversive ratings (minus blank screen) were associated with activation in hypothalamus.

Judgment of picture valence during scanning might elicit a pattern of neural regions that differs from the patterns associated with passive picture viewing. To test this hypothesis, Grimm et al. (2006) conducted an fMRI study in which they teased apart neural activation associated with picture viewing and judgment of picture valence, when the trial type had been cued in advance and when it had not been. Stimuli were positive and negative (but not neutral) IAPS pictures. During scanning, a 2 (expect to judge or view passively/ no expectation period) x 2 (provide ratings/view passively) within-subjects design was used. As well, post-scan, the participants rated all the pictures, plus new ones, on valence, intensity, and recognition (yes or new). Neural activation associated with unexpected picture judgment, compared to viewing, involved neural areas such as occipital gyrus, bilateral thalamus, and left dorsal anterior cingulate (BA 24), whereas neural activation associated with unexpected picture viewing involved areas such as bilateral amygdala, right anterior insula, and bilateral lateral frontal pole (BA 10). Thus, Grimm et al. demonstrated that the task of judging picture valence has a different effect neurally than does passive viewing.

Based on the data, Grimm et al. (2006) proposed a model as follows: The intrinsic value of valence regardless of whether that valence is positive or negative is associated with recruitment of ventromedial prefrontal cortex (by which they mean BA 10, BA 11). The evaluative aspect of judgments (that is, judging the valence) is associated with recruitment of dorsolateral prefrontal cortex. Intensity of emotion is associated with recruitment of right ventrolateral prefrontal cortex for cognitive control over the intensity and with dorsomedial prefrontal cortex (BA 9) for attention to and judgment of the intensity. Recall and recognition of emotional events is associated with recruitment of perigenual anterior cingulate (BA 24 subgenual aspect, BA 25, BA 32 emotional subdivision). Retrieval of autobiographical memory is associated with recruitment of posterior cingulate (BA 23).

Neuroimaging studies of emotion involving auditory delivery of stimuli have been conducted. To identify neural regions activated by emotional prosody that was either congruent or incongruent with emotional semantic meaning, Mitchell, Elliott, Barry, Cruttenden, and Woodruff (2003) conducted six experiments using fMRI. The stimuli were sentences with happy or sad semantic content, recorded by the same male in sad, happy, or neutral tone of voice.

In the first experiment only (Mitchell et al., 2003), the recordings were filtered to remove semantic content; participants listened passively to emotional prosody, and neural activation was compared to resting baseline. In experiments two to five, participants listened passively to (a) congruent *versus* neutral prosody, (b) congruent prosody compared to resting baseline, (c) incongruent prosody compared to resting baseline, and (d) incongruent *versus* congruent prosody. The sixth experiment investigated the neural underpinnings of paying attention to emotional prosody *versus* emotional semantics; participants were exposed to emotional prosody, randomized as to congruency and valence. There were two conditions. In condition A, the task was to pay attention to the semantic content and respond (by squeezing a bulb) to happy scenarios; in condition B, the task was to pay attention to emotional prosody and respond to happy intonation.

Each of the conditions elicited a different pattern of neural activations. Mitchell et al. (2003) summarized their findings as follows. Passive listening to emotional prosody, with or without semantic content, was associated with neural activation in lateral superior and middle temporal gyri, moreso in the right than in the left hemisphere. Processing of stimuli in which the semantics and prosody were incongruent involved fewer neural regions than did processing of congruent stimuli. The left hemisphere was recruited extensively when attending to semantics, whereas attention to emotional prosody recruited the right hemisphere including the middle temporal gyrus. Activations associated with happy and/or sad prosody were not reported, as that was not the focus of interest. Nevertheless, this research is pertinent because of the hemispheric lateralization of emotional prosody *versus* emotional semantics.

To determine which neural regions are associated with identification of the particular emotion being expressed in emotional prosody, Ethofer, Van de Ville, Scherer, and

Vuilleumier (2009) conducted an fMRI study in which pseudowords were presented in five prosodic categories (anger, sadness, neutral, relief, and joy) while participants performed a gender discrimination task. All types of prosody were associated with activation in bilateral superior temporal gyrus. Using multivariate pattern analysis, the researchers determined different voxel patterns for each type of prosody within that neural region. Thus, the specific type of emotional prosody is differentiated within bilateral superior temporal gyrus. This report therefore provides an update to the following model which had been proposed by the same group of researchers.

Processing of emotional prosody had been modelled as occuring in three stages (Wildgruber, Ackermann, Kreifelts, & Ethofer, 2006). In stage one, the acoustic processing occurs in right primary and secondary auditory regions, which would correspond to right superior temporal (BA 42) in particular. In stage two, identification of prosody as being emotional in character without yet discriminating among specific emotions occurs in the right posterior temporal sulcus (BA 22/42). Projections from the posterior temporal sulcus proceed in parallel to the left and right frontal lobes (Ethofer et al., 2006). In stage three of the model, preparation for responding to the meaning of an emotional utterance based on explicit judgment of which emotion is being heard is processed in bilateral inferior frontal lobes (BA 11/47), whereas preparation to respond on the basis of (non-emotional) semantic meaning is processed in left inferior frontal gyrus (BA 44/45; Wildgruber et al., 2006).

To explore neural correlates associated with listening to attended *versus* non-attended anger prosody, Sander et al. (2005) conducted an fMRI study. Meaningless utterances in angry or neutral prosody were presented to each ear in a dichotic listening paradigm; the task was to identify the gender of the voice in the currently to-be-attended ear. The main effect of anger minus neutral revealed activation in bilateral superior temporal sulcus (right BA 42, bilateral BA 22), bilateral parietal lobe (BA 19), left ventrolateral PFC (BA 45), and right anterior cingulate (BA 10, affective subdivision). Compared to neutral, attended anger elicited activation in right cuneus, left superior temporal sulcus (BA 22), and left superior frontal gyrus (BA 8), whereas unattended anger elicited activation in right superior temporal sulcus (BA 21, BA 22), left posterior cingulate, and right ventrolateral PFC (BA 47). The direct comparison of attended minus unattended anger revealed activation in right medial orbitofrontal cortex, right posterior superior temporal sulcus (BA 39), bilateral cuneus, left claustrum, left lateral frontal pole (BA 10), and bilateral ventrolateral PFC (BA 47). The reverse contrast, unattended minus attended anger, was associated with activation in right parietal lobe (right precuneus, and BA 40), and left posterior parahippocampal gyrus. Thus, activations associated with anger prosody depend on whether the angry voice itself is currently being attended to or not.

To control for effects of low-level acoustic properties, the Sander et al. (2005) study was followed by an additional fMRI study (Grandjean et al., 2005, experiment 2). Three types of stimuli were used: angry and neutral speech sounds as before, sinusoid sounds matched on the mean fundamental frequencies of the first set of stimuli, and white noise matched to the amplitudes of the first set of stimuli. The task was to judge whether successive sounds from the same category, presented 100 ms apart, were the same or different. Speech sounds, compared to each of the other conditions, were associated with activation in bilateral superior temporal sulcus (STS), with greater activation to the angry than to the neutral prosody. This pattern of activation was not found when comparing angry and neutral sounds in the two acoustic conditions. Thus, the researchers concluded that the bilateral STS activation was related to the angry emotion rather than to acoustic features.

To investigate the neural correlates of sadness and anxiety in healthy subjects, Liotti et al. (2000) conducted a positron-emission tomography (PET) study during which emotion was induced in the scanner by means of autobiographical scripts. Participants were instructed to visualize the memories to magnify the intensity of the emotion, and then to focus on their feelings. Sadness, compared to neutral, was associated with activation in the subgenual anterior cingulate (BA 24/25), right posterior insula and left anterior insula, as well as bilateral cerebellum and right premotor (BA 6) and motor (BA 4) cortex. Relative deactivation was noted in right dorsolateral prefrontal cortex (BA 9), left inferior temporal gyrus (BA 20), bilateral supramarginal gyrus (BA 40), left superior parietal lobe (BA 7), and left inferior parietal lobe (BA 40). The conjunction of the [sadness-neutral] and [anxiety-neutral] contrasts showed the following activations shared by sadness and anxiety: right cerebellum, right cuneus and lingual gyrus. As well, shared relative deactivations were reported in right posterior cingulate and retrosplenial cortex, left inferior temporal gyrus (BA 20), right inferior temporal gyrus (BA 20/37), right inferior parietal lobe (BA 40), left supramarginal gyrus (BA 40), and left superior parietal lobe (BA 7).

Reasoning

Selected theories or models of reasoning.

Two models of reasoning will be presented. Stanovich (2009) has proposed a tri-process theory of cognitive processing in which he differentiates among reflective, algorithmic, and autonomous processes.[2] Goel (2009) has proposed a multi-system model of deductive reasoning.

In terms of whether emotion either impedes or facilitates reasoning, Goel's (2009) neural model of deductive reasoning is silent about the relation between emotion and reasoning. Stanovich (2009) proposes a model of reasoning in which diverse autonomous reasoning processes (characterized by behaviours influenced by stimuli without intervening deliberation) will prevail over the rational analytical (that is, logical) reasoning process. By means of a footnote, Stanovich includes emotion in the class of autonomous processes. Stanovich takes the view that "evolutionarily adaptive" and "rational" are not synonymous. That is, an emotional (or other autonomous) process may contribute to keeping members of a species alive long enough to reproduce; however, if there is a goal mismatch between what is good for the species and what is good for a

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[2] These terms will be explained below. The reader is reminded that the theoretical portion of each section of the literature review is organized by themes: Does emotion facilitate or impede reasoning? How many non-emotional reasoning systems are there and how are they characterized? How many emotional reasoning systems are there and how are they characterized? What is the role of beliefs in the emotion/reason relation?

particular organism, a choice based on autonomous processes is usually detrimental to the organism.[3]

In terms of how many non-emotional reasoning systems there are and how they are characterized, Stanovich (2009) has proposed one rational processing system with two distinct aspects, which he refers to as the reflective mind and the algorithmic mind. Logical reasoning depends on the recruitment of both aspects.

> To be rational, an organism must have well calibrated beliefs (reflective level) and must act appropriately on those beliefs to achieve its goals (reflective level). The organism must, of course, have the algorithmic-level machinery that enables it to carry out the actions and to process the environment in a way that enables the correct beliefs to be fixed and the correct actions to be taken (Stanovich, 2009, p. 57).

The reflective mind can engage in critical thinking skills, and in problem-solving and reasoning in the absence of externally-provided instructions, in which case there is ambiguity as to which feature of the problem to focus on. The ability to overcome belief-bias and reason logically in content-based syllogisms is an example of reflective ability. A key aspect of the reflective mind is "the mechanism that *sends out a call* [emphasis added] to begin... hypothetical reasoning" (Stanovich, 2009, p. 61).

A key aspect of the algorithmic mind is that it *provides the cognitive decoupling* of a representation from its real-world application so that it can be manipulated in imagination

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[3] Stanovich (2009) discusses not only the reflective/algorithmic system (called System 2) but also the various autonomous processes (called System 1 or TASS) at length. For the dissertation, it is the System 2 processes that are being presented.

without being permanently changed (Stanovich, 2009). The linguistic structure of conditional reasoning ("if") can assist this decoupling. Cognitive decoupling is the computationally expensive aspect of rationality; in fact, working memory is postulated as being the ability to sustain decoupled representations.

Stanovich (2009) takes the position that reflective and algorithmic processes share the property of being capacity-limited serial processes. In Stanovich's view, evidence of algorithmic ability can be demonstrated using a task with predetermined rules, requiring the participant to switch back and forth between two sequences, inhibiting distraction and maintaining focus on the current goal. In Stanovich's view, reflective ability can be assessed by a measure in which the task itself is ambiguous and must be determined by the participant; furthermore, the task should be designed so that the participant, not the examiner, decides on an appropriate sequence for choosing which information to consider.

There are three types of cognitive decoupling (Stanovich, 2009): (a) override the inclination to respond on the basis of the autonomously-generated representation, (b) cognitive simulation and transformation of multiple models simultaneously, and (c) interruption of serial associative cognition (which is a quasi-rational process that will be described below when discussing the role of beliefs in the emotion/reason relation), leading either to cognitive simulation or simply to continuing associative processes from a different starting point. The first two types are not necessarily independent of each other. In each of the three cases, the reflective mind must issue an "initiate decoupling" signal; therefore there are three types of signal: (a) initiate override, (b) initiate simulation, and (c) initiate an interruption of serial associative cognition.

Rational cognitive processes depend, at least in part, on learning.

> The rules, procedures, and strategies that can be retrieved by the analytic system (the algorithmic and reflective minds) and used to transform decoupled representations have been referred to as mindware...The mindware available for the analytic system to substitute during ...override is in part the product of past learning experiences. Indeed, if one is going to trump [an autonomous system]-primed response with conflicting information or a learned rule, one must have previously learned the information or the rule (Stanovich, 2009, p. 71).

In terms of how many non-emotional reasoning systems there are and how they are characterized, the views of Goel (2009) are presented next. The question that informed the early work in the Goel opus (Goel, Buchel, Frith, & Dolan, 2000) was whether deductive reasoning involved a language- (actually, syntax-) based system, or whether it involved a visuo-spatial system; whereas the former would provide support for mental logic theories, the latter would suppport mental model theories. Goel et al. (2000) found that reasoning with content-based syllogisms was associated with activation in traditional language areas (a left-hemisphere temporal lobe system) whereas reasoning with syllogisms based on placeholder letters rather than content was associated with activation in parietal lobes; this pattern of results provided support for a dual mechanism theory of deductive reasoning. However, ongoing work based on neuroimaging of normal controls (Goel & Dolan, 2001; Goel & Dolan, 2003a; Goel & Dolan, 2004; Goel, Makale, &

Grafman, 2004; Goel, Stollstorff, Nakic, Knutson, & Grafman, 2009) and a lesion study (Goel et al., 2007) has suggested that a dual mechanism theory provides an inadequate explanation of the underpinnings of deductive reasoning; there are indications that a multi-system model would provide a better account.

Such a model would need to account for three ways in which the deductive reasoning system is fractionated into parts (Goel, 2009). There are different systems for dealing with familiar versus unfamiliar content; there are different systems for relying on beliefs versus being able to set aside beliefs in favour of logic; and there are different systems for dealing with certain and uncertain information. Furthermore, the system that deals with familiar content appears to be affected by the nature of the content; for example, reasoning about familiar spatial environments (London is north of Paris .....) involves neural regions (the posterior hippocampus and parahippocampal gyrus place area) that have been found (Maguire, Frackowiak, & Frith, 1997; Maguire, Frith, Burgess, Donnett, & O'Keefe, 1998) to be activated in spatial memory and navigation tasks.

Familiar content (for example, All apples are red...), which was associated with neural activation in the left frontal and temporal lobes (Left BA 47, 21/22), involves a conceptual language-based heuristic system. Unfamiliar content (for example, All Ps are Qs, or alternatively All quipu are aboki...) which was associated with the bilateral parietal lobes (BA 7, 40), involves a formal / universal logic system that can manipulate abstract information (Goel et al., 2000; Goel & Dolan, 2003a; Goel, Makale, et al., 2004; Goel, Shuren, Sheesley, & Grafman, 2004).

When reasoners fail to detect an incongruence between beliefs and logic (or are unable to set beliefs aside), neural activation occurs in ventromedial prefrontal cortex (BA 11, BA 32); however, when they do succeed in noticing this conflict and engage logical reasoning instead of being swayed by beliefs, the accompanying neural activation occurs in the right lateral/ventrolateral prefrontal cortex (BA 45, BA 46) (Goel & Dolan, 2003a).

Uncertainty can be introduced into a deductive reasoning task by presenting a syllogism in which there is insufficient information to determine whether the conclusion follows from the premises or not. That is, there may be more than one model of the inter-relationship among the argument terms. An example is: "All crunchy tubers are vegetables. Some carrots are crunchy tubers. Some carrots are not vegetables." Goel et al. (2007) recruited patients with focal lesions in left or right prefrontal cortex, and tested them on syllogism arguments involving certain or uncertain models; results demonstrated that the left prefrontal cortex is necessary for reasoning in situations of certainty whereas the right prefrontal cortex is necessary for reasoning in situations of uncertainty. This finding was supported by the results of an fMRI study (Goel et al., 2009) in which healthy participants engaged in relational reasoning involving arguments with familiar or unfamiliar content. Neural activation was reported in right ventrolateral PFC in association with reasoning in uncertainty when the content was unfamiliar. When the content was familiar, results were affected by the belief-bias effect.

The Goel (2009) model of deductive reasoning proposes that language-based reasoning, which is the default reasoning system, is largely belief-biased and heuristic, whereas logical reasoning recruits three components: a conflict detector based in right dorsolateral prefrontal cortex, a mechanism for maintaining uncertainty (that prevents a premature belief-biased response) based in right ventrolateral prefrontal cortex, and usually a formal reasoning system, based in parietal cortex. Goel et al. (2000) chracterized the language-based reasoning system as associative, and the parietal-based logical reasoning system as one involving spatial manipulation. In the syllogism paradigm, the conflict detection mechanism would necessarily have been activated to support logical (correct) responding when the facts in the conclusion were inconsistent with those in the premises, or were incongruent with the logic of the argument (Goel, 2009).

In terms of how many emotion systems there are and how they are characterized, Stanovich (2009) indicates that there are diverse autonomous processes, including emotion. His characterization of emotion can be inferred from the statement that Damasio's OFC-lesioned patients are impaired in decision-making because they may lack the emotions that are necessary to limit response options to a manageable number. Goel (2009) has not included emotion in his model. However, Goel and Dolan (2003b) studied emotional *versus* neutral content, without specifying which emotions. Their interpretation suggested tentative support for a model of separate but parallel and interacting neural systems for emotional reasoning and non-emotional reasoning; their evidence suggested that orbitofrontal cortex (OFC) is engaged by the emotional reasoning process, and the reciprocal response of left dorsolateral prefrontal cortex and OFC “reflects the degree to which reasoning is ‘cold’ or ‘hot’ ” (Goel & Dolan, p. 2320).

Regarding the question of the role of beliefs in the emotion/reason relation, neither Goel (2009) nor Stanovich (2009) specifically address how emotion might interact with beliefs and reasoning. However, Goel and Dolan (2003a) demonstrated that belief-biased and logic-based strategies in responding to syllogisms activated different neural regions; therefore, Goel (2009) has postulated that one dichotomous dimension on which deductive reasoning systems are fractionated is the belief/logic dimension. Stanovich asserts that syllogisms with meaningful content (as opposed to "All Ps are Qs") can be used to assess critical thinking skills because the participant can choose whether to respond on the basis of beliefs or logic. Stanovich regards belief-biased responding as an indication that autonomous processes are at work. Autonomous processes include modules that are products of evolutionary adaptations, but also domain-general processes such as implicit learning, and learned information such as rules overlearned to automaticity.

Stanovich (2009) had postulated that hypothetical thinking, the hallmark of rational processing, required both the reflective mind (which sends out a call to decouple representations from reality) and the algorithmic mind (an analytic process that performs the decoupling or manipulation operations). Thus, whereas counterfactual thinking requires an analytic process, analytic thinking in general does not guarantee counterfactual thinking. Stanovich postulates that there is a quasi-rational type of processing, serial associative cognition with a focal bias. This process is "rather inflexibly locked into an associative mode that takes as its starting point a model of the world that is *given* to the subject" (Stanovich, p. 68). People systematically generate associations within this model but never question the model itself. People tend to be cognitive misers; thus, they choose the model that is most easily constructed. This model represents only one state of affairs, accepts the given starting point as true, ignores discrepancies as being inconvenient, and is identical to or close to one's own beliefs. If this type of processing is subsequently interrupted by a signal from the reflective mind, the person might engage in a reflective process of cognitive simulation but this is not guaranteed; the person might simply continue with associative processes from a different starting point.

Rational processes depend on specific learning, or mindware (Stanovich, 2009). Mindware can be contaminated by culturally-transmitted expectations such as the expectation of punishment for questioning commonly-held ideas and expectation of rewards for unquestioned faith in commonly-held ideas. Another contaminant is "the folk belief that we accurately know our own minds...[which] accounts for the incorrect belief that we always know the causes of our own actions" (Stanovich, p. 76). Mindware *gaps* include aspects of our mental processes that we do not understand; an example is miswanting (Gilbert & Wilson, 2000), which is the gap between predicting how an achievement will make us feel and the reaction we actually have when success is achieved.

Neuroimaging evidence of reasoning. During the presentation of theories of reasoning (above), the Goel (2009) model of deductive reasoning was presented. As that model emerged from a series of neuroimaging studies, it is tied closely to those findings. Therefore, those neuroimaging studies were presented in the theoretical section and will not be repeated here. However, it will be acknowledged here that much that is currently understood about the neural mechanisms of reasoning comes from the Goel opus.

Fangmeier and Knauff (2009) explored the neural correlates of an auditory transitive inference task, in an fMRI study. The task involved listening to the order in which each successive pair of placeholder letters was delivered to each ear (for example, V to the left then X to the right for the first premise) in order to determine whether the placement of the letters in the conclusion followed logically from those heard in the two premises. Neural activation in the reasoning time-window, minus baseline, was found in the left insula / ventrolateral prefrontal cortex (PFC; BA 47) and left frontal (precentral) gyrus (BA 44).

Fangmeier, Knauff, Ruff, and Sloutsky (2006) had conducted a similar experiment in which all stimuli were presented visually. Neural activation associated with reasoning minus baseline was found in left superior PFC (BA 8), bilateral middle PFC (bilateral BA 6, right BA 8), right anterior cingulate (BA 32, cognitive subdivision), and right precuneus. Thus, the auditory and visual presentation of the same task affected the pattern of neural results.

To investigate whether reasoning with mental models would recruit neural mechanisms associated with visual processing, Knauff, Fangmeier, Ruff, and Johnson-Laird (2003) conducted an fMRI study to explore possible dissociations between visual (cleaner / dirtier) *versus* spatial (north / south) relations that are easy or difficult to imagine visually or spatially, in the context of an auditory deductive reasoning task. Reasoning stimuli used the same nouns (dog, cat, ape) in all trials. All stimuli were delivered by headphones; there was no visual presentation. Each condition (minus "rest") was associated with activation in the left middle temporal gyrus (BA 21) and right precuneus. There was additional activation in left precuneus in the visuospatial (above / below) and spatial conditions, in left middle frontal gyrus (BA 11) in the visuospatial and visual conditions, in left ventrolateral PFC (BA 47) in the spatial condition, and in bilateral middle frontal gyrus (BA 9 and BA 6) in the visual condition. The visuospatial minus control (better / worse) and the spatial minus control contrasts yielded no voxels surviving correction. However, the visual minus control contrast revealed activation in right occipital / precuneus (BA 18/31) and left insula. The researchers concluded that all deductive relational reasoning involves mental models but only visual relations invoke visual imagery as well.

To assess the role of the caudate (part of the basal ganglia) in abstract reasoning involving deduction and application of a sequence rule, after subtracting out working memory effects, Melrose, Poulin, and Stern (2007) conducted a within-subjects event-related fMRI study. Neuroimaging results indicated that [reasoning *minus* working memory] was associated with activation in the left caudate head and right ventrolateral PFC (BA 47), as well as other neural regions. Region of interest (ROI) analysis of basal ganglia regions revealed a trend for greater activation in left caudate head in reasoning than in the reasoning control or the working memory conditions. There was significantly more activation during reasoning than during reasoning control in bilateral caudate body. The Melrose et al. (2007) study may be the first to focus on the role of the basal ganglia in deductive reasoning.

Intending to identify frontal regions associated solely with deductive reasoning, Kroger, Nystrom, Cohen, and Johnson-Laird (2008) conducted an fMRI study (without regard to nuancing factors such as were identified later, in Goel, 2009); they used mathematical computation as the contrasting condition.[4] Neuroimaging results indicated that deductive reasoning was associated with activation in bilateral VLPFC (BA 44, 45), bilateral inferior parietal lobe (BA 39, BA 40), right superior frontal gyrus (BA 8, BA 9) and left temporal lobe (BA 41, 42). In contrast, mathematical calculation was associated with activation in left dorsolateral PFC (BA 9/46), bilateral caudate, bilateral superior frontal (BA 8) and bilateral parietal lobe (BA 7). There was also relative deactivation in inferior parietal lobe (BA 40) and left temporal (BA 42). Thus, Kroger et al. demonstrated a dissociation in frontal lobes between deductive reasoning and mathematical computation. However, regarding the hypothesis, it is not clear from the results that the frontal areas associated with deductive reasoning are exclusive to that type of cognition.

To investigate neural underpinnings of fluid reasoning ("decision-making on the fly")[5], Kalbfleisch, Van Meter, and Zeffiro (2007) conducted an fMRI study in which participants were asked to perform a visual matrix reasoning task, but were given only 20% of the time normally needed to complete the task, on each trial. In the introduction of the study, the researchers noted that the role of basal ganglia and cerebellum had not

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[4] One notes that the reasoning involved semantic content whereas the mathematical computation did not; thus, there is a potential confound here.

[5] Curiously, Kalbfleisch et al. (2007) assert that past reasoning studies have involved extensive pre-scan training; they include the Goel opus in that assertion but it is not clear how that misunderstanding arose.

been explored in reasoning studies. Neuroimaging analysis based on correct trials (which occurred at above-chance levels) revealed no involvement of basal ganglia,[6] although there was activation in many neural regions including cerebellum, bilateral precuneus and bilateral lingual gyrus, as well as left VLPFC.

Christoff et al. (2001) hypothesized that prefrontal cortex recruitment in relational reasoning is not explained as task difficulty but is explained specifically by the complex reasoning process of considering multiple relations simultaneously. In an fMRI study of relational reasoning involving matrices, geometric patterns were presented on each trial in a 3 x 3 matrix, except that the bottom right position was left blank. On each trial, the participant had to consider the relations among the patterns in the matrix, make an inference and select one of four response shapes to complete the matrix. In the "zero relational" condition, all patterns in the matrix were identical. In the "one relational" condition, the expected response would involve choosing the pattern that matched the already coupled pattern in the third row. In the "two relational" condition, each pattern varied independently on border type and on internal shape. The expected response would involve inferring and integrating the regularity in the two sequences. During data analysis, reaction time was partialed out, so that the results would relate to relational level without difficulty as a confound. The researchers reported that there were no significant differences in neural activation in the [one relation – zero relation] contrast, although there was subthreshold activation in bilateral extrastriate visual cortex (BA 19), left superior parietal lobe (BA 7), and right thalamus. However, the [two relation – one

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[6] This lack of basal ganglia involvement was not commented on by the researchers.

relation] contrast yielded significant voxels in left ventrolateral PFC (BA 44), left precentral gyrus (BA 6), left middle frontal (BA 10), right middle frontal (BA 46, BA 9), and bilateral caudate, as well as subthreshold activation bilaterally in extrastriate visual cortex (BA 19), superior parietal lobe (BA 7), ventrolateral frontal (BA 46), inferior frontal (BA 6), and left middle frontal (BA 46), left middle and superior (BA 10), and in medial anterior cingulate (BA 32). Thus, prefrontal cortex activation was found to be specific to complex matrix reasoning, after controlling for task difficulty. The researchers speculate that rostrolateral PFC function, especially left middle and superior frontal (BA 10), may be contributing to the process of considering multiple relations simultaneously by means of manipulating self-generated information. In noting that the caudate nucleus (part of the basal ganglia) was the only other neural structure activated solely by complex reasoning, the researchers comment that "there is converging evidence that the PFC and the caudate are major components of a neural system mediating complex reasoning" (Christoff et al., p. 1146).

The behavioural and neural effects of training on logic only *versus* logic plus warnings about bias effects were explored in a mixed between/within subjects study (Houdé et al., 2000, 2001) using positron emission tomography (PET). This study demonstrated that whereas training based on logic has no effect on performance, training about bias effects is very effective and causes a shift neurally from posterior regions to prefrontal cortex.

During scanning, participants were shown an assortment of 12 coloured geometric shapes on each trial (Houdé et al., 2000, 2001). The task during pre-training and during post-training scanning was to falsify a conditional rule, such as "If there is not a red square on the left, then there is a yellow circle on the right." Participants used the mouse to move two shapes into appropriate boxes on the screen. In this type of task, people are vulnerable to a perceptual matching bias; for instance, in the above example they are likely to place a red square on the left and a yellow circle on the right, even though a correct response might be to place a blue square on the left and a green diamond on the right. Behavioural results indicated that, before either type of training, participants were affected by the bias on 90% of trials (that is, the error rate was 90%). Neuroimaging results showed activation in posterior neural regions, specifically bilateral occipital and parietal regions and left temporal lobe. Immediately after the first scanning session, participants received verbal training, using materials from a different perceptual matching paradigm called the Wason card selection task. The "logic only" group was shown how to respond logically on the task. The "logic plus warning" group was also given warnings and demonstrations about the effects of perceptual matching bias. After the training session, all participants were scanned while they performed the task again. For the "logic only" group, the error rate of 90% remained unchanged; however, for the "logic plus warning" group, the performance switched over to a 90% *accuracy* (logic-based) response rate. Neuroimaging results associated with performance after "logic plus warning" (minus "logic only") training demonstrate involvement of the right superior medial frontal pole (BA 10) extending into anterior cingulate, right thalamus (pulvinar), left frontal (precentral) gyrus (BA 6), and left fusiform gyrus.

The Relation Between Emotion and Reason

Theories of the emotion/reason relation.[7] Theories of the relation between emotion and reasoning have been proposed by Epstein (1994) and by Oatley and Johnson-Laird (2002). Neither model explicitly addresses whether emotions will either impede or facilitate logical reasoning. Epstein (1994) reacted to the prevalent negative characterization of emotion by reconceptualizing it as a multi-dimensional and adaptive reasoning system based on experiencing. He also postulated a rational reasoning system, and postulated that although the emotional and rational systems were separate and parallel, they were interactive. Oatley and Johnson-Laird (1996, 2002) proposed that one effect of emotion is to set up currently-appropriate biases of cognitive processing. They argued that when reasoning, it would not be adaptive to come to wrong conclusions most of the time, and emotions usually serve the function of assisting the reasoner to come to adaptive conclusions.

In terms of how many non-emotional reasoning systems are postulated, Epstein (1994) proposed one system for analytical reasoning. Implicit in Oatley and Johnson-Laird's (1996, 2002) model are multiple reasoning systems; that is, there are diverse emotion modes and reasoning is characterized differently within each mode.

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[7] The reader is reminded that the presentation of theories is organized according to the following themes: Does emotion facilitate or impede reasoning? How many non-emotional systems are there and how are they characterized? How many emotional systems are there and how are they characterized? What is the role of beliefs in the emotion/reason relation?

In terms of how non-emotional systems are characterized, Epstein (1994) proposed that the rational system is analytic and is based on reasons. Behaviour is mediated by the conscious appraisal of events. Connections are linked by means of logic, and reality is encoded in abstract symbols, words, and numbers. Processing is oriented toward delayed action, and is therefore comparatively slow. Processing is relatively highly differentiated and is highly integrative, occurring across contexts. Processing is experienced actively and consciously. Current representations of reality in memory can change with the speed of thought. Results of processing require justification by means of logic and evidence.

Implicit in Oatley and Johnson-Laird's (1996, 2002) model is that emotion is ubiquitious in the reasoning process. Nevertheless, their depiction of how reasoning proceeds is as follows: While engaged in reasoning, people generate possibilities (that is, various mental models) of what the given assertions describe. They include only those assertions that they believe to be true; thus, they are relying on explicit knowledge. Reliance on logic alone fails when two or more premises are inconsistent. At this juncture, the person abandons a previous conclusion that had been accepted as valid, changes his / her belief (that one or more of the assertions had been true), and searches for an underlying cause or explanation of the inconsistency[8] so that (s)he can resolve the matter in a way in which the resulting assertions are consistent. Ideally, this search may involve generating more possibilities (more models). However, such a search quickly stretches beyond cognitive capacity; therefore, in experimental settings, people usually

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[8] Reasoning backwards from effect to cause is referred to as abductive inference.

allow belief to trump logic, abandon the search without generating many possibilities, and conclude that one or more assertions are false.

In terms of how many emotion systems are proposed, obviously there are many emotions. In terms of discussing the models, the question has to do with whether emotion is treated as a whole or whether there are distinctions being drawn among emotion systems. Epstein (1994) proposes diverse experiential systems, all of which are affect-based.

In terms of how emotions themselves are characterized, Epstein (1994) proposed that experiencing includes but is not limited to emotional processes. For example, people can be influenced by means of narratives/parables and by pictorial advertising, and decisions may be based on stereotyping, exemplars, irrational fears, superstition, religious belief, or episodic memory. The experiencing system is characterized by reasoning that is pleasure/pain oriented and based on associationist connections. Reality is encoded in concrete images, metaphors, and narratives. Processing, being oriented toward immediate action, is relatively rapid. Current representations of reality in memory are slow to change, and the mechanism of change involves repetitive or intense experience. Processing is crudely differentiated, accepting stereotypes and other generalizations, and is crudely integrated, often relying on context. Processing occurs preconsiously and passively; therefore "we are seized by our emotions" (Epstein, p. 711), and results of processing are "self-evidently valid: 'Experiencing is believing' " (Epstein, p. 711). The experiential system has subsystems, such as those for procedural learning and episodic memory. Behaviour originally learned in the experiential system becomes more procedural with practice, and loses its affective tone, but is still considered to be experiential in nature. Experiential information processing ranges in complexity, and includes, for example, classical conditioning, heuristic processes, and intuitive wisdom. Emotion arises as the result of automatic preconscious appraisals of events, and has a profound influence on thinking; overall, Epstein views the functions of emotion as being adaptive.

Oatley and Johnson-Laird (1996) have proposed that there are “emotion modes” (Oatley & Johnson-Laird, 1987, p. 32) which are various discrete neural states of readiness -- based on happiness, sadness, fear, or anger -- to respond quickly to particular survival- or goal-related events presented by the internal or external environment. When an event occurs that is not served by the currently active mode, the brain responds by eliciting an emotion signal that interrupts processing in that mode and immediately sets the brain into the relevant emotion mode to respond quickly to the stimulus (Oatley & Johnson-Laird, 1987).

> [The signal] sets the whole system into an organized emotion mode without propositional data having to be evaluated by a high-level conscious operating system … The emotion signal simply propagates globally through the system to set it into one of a small number of emotion modes (Oatley & Johnson-Laird, 1987, p. 33).

Oatley (1992) writes, further, that:

> Each goal and plan has a monitoring mechanism that evaluates events relevant to it. When a substantial change of probability occurs of achieving an important goal or subgoal, the monitoring mechanism broadcasts to the whole cognitive system a signal

> that can set it into readiness to respond to this change. Humans experience these signals and the states of readiness they induce as emotions (Oatley, p. 50).

As well, emotions could be caused by "purely bodily changes" (Oatley & Johnson-Laird, 1996, p. 364).

The functions of emotion are “to control the organization of the brain, to make ready mechanisms of action and bodily resources, to direct attention, to set up biases of cognitive processing, and to make the issue that caused the emotions salient in consciousness” (Oatley & Johnson-Laird, 1996, p. 364). The theory is referred to as “communicative” because emotions are based on signals within the brain and because the various emotion modes predispose people to facial expressions that communicate specific emotion to other people.

An emotional experience has two components: the emotion signal, which is nonpropositional (*i.e.*, it lacks semantic content) and a proposition about the event that caused the emotion. These components are dissociable; that is, people may experience an emotion without understanding its cause and intensity, or people may be unaware of their current emotional state (Oatley & Johnson-Laird, 1996).

Although “emotion” is not defined, a mood reflects the brain state associated with current ongoing activity. Moods are “…long-lasting states based on emotion modes sustained by a basic nonpropositional signal: we postulate that the only true moods are those of basic emotions that can occur acausally” (Oatley & Johnson-Laird, 1996, p. 370).

What is the role of beliefs in the emotion / reason relation? Epstein (1994) did not specifically discuss the interaction of beliefs, emotion, and reasoning; however, he posited the general principle that emotion arises as the result of automatic preconscious appraisals of events, and has a profound influence on thinking, whereas behaviour based on analytical reasoning is mediated by the conscious appraisal of events.

Oatley and Johnson-Laird (1996) proposed that emotional experience has two dissociable components: the emotion signal, which is nonpropositional (*i.e.*, it lacks semantic content) and a proposition about the event that caused the emotion. As clarification, they note that people may experience an emotion without understanding its cause and intensity, or people may be unaware of their current emotional state. Oatley and Johnson-Laird (2002) proposed that when reasoners are generating possibilities of what the premises describe, they include only those assertions that they believe to be true; thus, they are relying on explicit knowledge. As the number of possibilities increases, emotion provides a heuristic to limit the search space. However, this statement must be construed within the overall context of the Oatley and Johnson-Laird model, which is that all reasoning occurs within a specific emotion mode. Oatley and Johnson-Laird (2002) also assert that emotion is the mechanism that provides a heuristic for resolving inconsistency; if there never were any inconsistencies, or if human knowledge were perfect, then humans would not need emotion.

Behavioural evidence of the emotion/reason relation. Conditional reasoning was found to be impaired by emotion in a series of behavioural experiments (Blanchette, 2006; Blanchette & Richards, 2004) in which arguments were presented with emotional *versus* neutral content, or in which individual non-emotional words were first classically conditioned as positive or negative using IAPS pictures (Lang et al., 1997), and then were used as argument terms. Different word/emotion pairs were used with each participant; thus, the effect was due to emotion or to a combination of emotion with belief in general but was not due to particular beliefs. The effect of emotional content was obtained even when participants were given a visual reminder on each trial that the task was to reason logically. Post-experiment probing revealed what Stanovich (2009) would call a mindware gap, that was independent of emotion. That is, the more participants perceived the relationships between p and q to be necessary, the more likely they were to have responded illogically to the fallacies; the relation with sufficiency was in the same direction but not as strong. However, post-reasoning ratings of causality and plausibility did not differ as a function of emotion.

To explore whether positive mood would facilitate or impede logical reasoning, Melton (1995) induced positive mood using ratings of cartoons or a taped comedy routine, and then, in what purported to be a separate experiment, presented participants with a syllogistic reasoning task, using paper and pencil. Results indicated that logical reasoning was impaired in the positive compared to the neutral control group even though all participants had more than enough time to complete the task. Participants in the positive condition tended to take less time, and tended not to draw helpful diagrams, compared to controls. Melton interpreted the results in terms of effort reduction rather than distraction; furthermore, referring to other literature, he noted that positive mood *impairs* cognitive processing when the task is analytical, such as when identifying the correct response from a set of known alternatives, whereas positive mood would *enhance* creative cognitive processing when the task involves response generation.

Specific negative emotions can make logical (accurate) reasoning sharper. This has been demonstrated in the following two studies.

To explore the effect of naturally-occurring intense emotion on deductive reasoning, Blanchette, Richards, Melnyk, and Lavda (2007) conducted a behavioural study using syllogisms with content that was neutral, generally emotional, or terrorism-related. Participants were tested within one week after the terrorist attack in London UK in July 2005, and again six months later. The London UK testing location was at a college next to one of the attack sites. As well, participants in Manchester, and in a Canadian city, were tested during the same timeframes. Prior to the reasoning task, participants were asked where they were at the time of the terrorist attacks. Next, participants provided a self-report of their current feelings. After completing the syllogism task, participants estimated the risk of a second terrorist attack. Results indicated that participants in all cities were swayed by belief-bias on the generally emotional incongruent syllogisms, moreso than on the neutral incongruent syllogisms. However, on the syllogisms with terror-related content, participants in London UK, compared to the other groups, responded significantly more logically, and even the participants in Manchester responded more logically than did those in Canada. Among those participants in the UK, the level of accuracy (logical responding) was inversely correlated with short-term risk estimates; that is, those who predicted a low imminent risk performed more accurately (logically) on the terror-related syllogisms. To rule out the possibility that the increased accuracy was due to cultural differences between Britons and Canadians, rather than intense emotion from the attacks, participants were re-tested six months later; at this time, participants in Manchester exhibited a strong belief-bias effect on the terror-related syllogisms. As in the first test, performance among the groups was comparable on the neutral and the generally emotional syllogisms. Blanchette et al. explained the increased accuracy (logical responding) on terror-related items in terms of its consequential subject matter; that is, intense emotion related to recent events with terrifying consequences led to increased logical (accurate) responding, especially among those who rated the risk of a second attack as low.

Goel and Vartanian (2010) explored the effect of politically-incorrect content on deductive reasoning. Participants were asked to reason about arguments that were either neutral in content or were politically incorrect. Mean accuracy in the neutral condition was 93% on valid arguments with believable conclusions (such as "Some animals are not donkeys") but was only 26% on invalid arguments with believable conclusions. Thus, reasoning about neutral content produced a belief-bias effect when content and logical argument were incongruent. However, in the politically-incorrect content condition (for example: "Some Muslims are assassins"), comparable means were 90% (valid and believable) and 58% (invalid and believable); that latter result is significantly greater than the 26% accuracy rate in the comparable neutral condition. Moreover, reasoning took longer in the latter condition, compared to neutral. Thus, when confronted with true but politically-incorrect statements in invalid arguments, participants were able to overcome the belief-bias effect and reason logically (accurately). Goel and Vartanian suggested that the negativity in this study led to systematic reasoning by attenuating the belief-bias effect.

Neuroimaging evidence of the emotion/reason relation. Goel and Dolan (2003b) used event-related fMRI to investigate whether there would be an interaction between left dorsolateral prefrontal cortex and ventromedial prefrontal cortex in reasoning tasks as a function of emotional saliency. The content of the syllogisms was neutral in one condition ("Some people are not children") and emotionally provocative ("Some raping of women is not unjustified") in the other. Participants provided post-scan ratings of how each syllogism had made them feel, using an 11-point scale. Results were interpreted as providing support for a model of separate but parallel and interacting systems for emotional reasoning and non-emotional reasoning; neural activation associated with neutral reasoning was found in left dorsolateral prefrontal cortex (PFC), whereas activation associated with emotional reasoning was found in bilateral medial orbitofrontal cortex, as well as in right fusiform gyrus. Furthermore, the reciprocal relationship between ventromedial PFC / left dorsolateral PFC and the saliency ratings "reflects the degree to which reasoning is 'cold' or 'hot' " (Goel & Dolan, p. 2320).

Relation Between Emotion and Decision-Making

Theories of the emotion /decision-making relation. A theory of the relation between emotion and decision-making has been proposed by Damasio (1994). As well, Forgas (1995) has proposed an affect infusion model (AIM) concerning mood effects on social judgment.

Regarding the question of whether emotion impedes or facilitates reasoning, Damasio (1994) postulated that emotion, specifically a "somatic marker" (gut feeling), is beneficial to decision-making by limiting the search space to options that are not disadvantageous. Forgas (1995) proposed that in social judgment, criteria-selection interacts with processing strategy; affect priming could restrict criteria-selection depending on which strategy had been recruited.

In terms of how many emotion systems there are, Damasio (1994), like William James (1890/1950), proposes that humans have (several) hard-wired primary emotion systems; he also proposes the existence of secondary emotions, which are learned emotional responses. However, Damasio's *focus* is on the positive and negative valence of emotion. Forgas (1995) does not present his model in terms of specific moods.

Concerning how emotions themselves are characterized, Damasio (1994), like William James (1890/1950), proposed that hard-wired primary emotion systems, such as the fear system, are activated directly by a stimulus, such as an unexpected noise, without cognitive mediation. Eventually, feelings emerge in consciousness, at which point the person can respond in a flexible manner. Secondary emotions are learned emotional responses based originally on links between primary emotions and experiences or objects. However, the focus of Damasio's model is on the somatic marker; Damasio has noted an anticipatory skin conductance response in normal healthy participants but not in patients with lesions in the orbitofrontal cortex (OFC), during a gambling game carried out across many trials; this anticipatory marker occurs when healthy participants are reaching toward a card deck that is becoming disadvantageous. There is a correlation between the occurrence of the anticipatory marker and successful outcomes in the gambling task. Damasio has proposed that recruitment of the orbitofrontal cortex is necessary for detection of the somatic marker, and that this is why involvement of the OFC is necessary for good judgment and decision-making.

Forgas (1995) defines emotions as being "intense, short-lived and usually have a definite cause and clear cognitive content" (Forgas, p. 41). Moods are defined as "low-intensity, diffuse and relatively enduring affective states without a salient antecedent cause and therefore little cognitive content (e.g. feeling good or feeling bad)" (Forgas, p. 41). Forgas indicates that the term "affect" in the AIM model is meant in the most general sense, including emotions and moods.

Forgas (1995) proposed four strategies for social judgment. In introducing those strategies, it is helpful to keep in mind that the model assumes that people will normally choose to reach a decision using a thought process that is simple and requires minimal effort.

The direct-access processing strategy (Forgas, 1995) is that mood manipulation will have no effect on judgment when "targets are highly familiar, prior judgments exist, and the task is of low personal relevance" (Forgas, p. 51). The proffered example is that mood induction will not affect beliefs about known consumer products but only about products that are unfamiliar.

Secondly, the motivated processing strategy is a controlled process invoked in situations in which the person is motivated to make a judgment that will (for example) repair his or her mood, will maintain an existing mood, or will contribute to egoenhancement; under these circumstances, the information search is highly selective and guided towards a particular target, and mood induction effects are not found (Forgas, 1995). For example, mood induction may have effects when a person's attention is directed away from his or her own feelings whereas self-directed attention leads to a controlled, motivated, processing strategy. People induced into a happy, sad, or neutral mood (Forgas, 1990) were asked to judge nine stereotypes (such as doctors, farmers, Jews, Catholics); judgments were more positive in the happy than in the sad condition, thus demonstrating a mood induction effect. However, when the procedure was repeated two weeks later, this time in a group setting, positive judgments were increased in the happy condition but there was no effect of mood in the sad condition. "This result is consistent with subjects adopting a motivated processing strategy directed at controlling negativity in judgments, as a result of relevant social norms and values becoming more salient in the course of group interaction" (Forgas, 1995, p. 53).

Thirdly, a person relies on the heuristic processing strategy in those novel situations where (s)he does not have a ready response and judgments do not have critical consequences or personal relevance; effort can be minimized by relying on a restricted amount of information and by utilizing a heuristic as a shortcut (Forgas, 1995).

Finally, a person recruits the substantive processing strategy in more complex novel situations requiring elaborated processing and a careful judgment (Forgas, 1995). For example, participants were videotaped while being interviewed (Forgas, Bower, & Krantz, 1984). The next day they were given criteria by which to evaluate themselves and the interviewer while reviewing the videotapes; happy or sad mood was induced, and then they were given an opportunity to perform the evaluations. Participants in a happy mood judged themselves and the interviewer favourably; however, participants in a sad mood were significantly more critical of their own behaviour than of the interviewer's behaviour.

In terms of the role of beliefs in the emotion/reason relation, Damasio (1994) postulates that the somatic marker is a bodily signal that occurs before the person is able to articulate what they know. However, the somatic marker could only occur by drawing on past learning. Thus, Damasio suggests that propositional (memories stored in imagetic form) and non-propositional (somatic marker) signals are combined in OFC. Forgas (1995) does not address the relation between affect and beliefs.

Behavioural evidence of the emotion / decision-making relation. Evidence from the behavioural literature (Bless, Mackie, & Schwarz, 1992; Bodenhausen, Kramer, & Susser, 1994; Schwarz & Clore, 1983) demonstrates that positive mood induction promotes heuristic rather than systematic cognitive processing. Schwarz and Bless (1991) suggest that a positive, heuristic, system can be considered adaptive in the overall context of an evolutionary account; specifically, they offer the interpretation that positive emotion is a signal that the current situation is safe and requires no action.

In contrast, negative mood induction or depressed mood (Alloy & Abramson, 1979; Bless et al., 1992; Bohner, Crow, Erb, & Schwarz, 1992; Edwards & Weary, 1993) leads to systematic, rather than heuristic, processing. However, the mood induction literature often uses *sadness* to induce people into a negative mood when a negative mood induction is required (Schwarz & Bless, 1991). Therefore, this interpretation should be applied specifically to sadness rather than to negative emotion in general. This systematic processing has been interpreted within the evolutionary perspective. "Negative affective states may signal that the current situation is problematic and may hence elicit a processing style that pays close attention to the specifics of the apparently problematic situation" (Schwarz, 2000, p. 434). This systematic processing has been characterized as "bottom-up processing, with little reliance on preexisting knowledge structures and considerable attention to the details at hand" (Schwarz, p. 434).

Anger induction enhances heuristic rather than analytical processing (Bodenhausen, Sheppard, & Kramer, 1994; Tiedens & Linton, 2001). For instance, people induced to anger rely on the expertise of the source or on stereotypes during an evaluation whereas people in the control group rely on an assessment of the facts of the matter. Keltner, Ellsworth, and Edwards (1993) found that anger induction, and not cognitive appraisal, led to blaming ambiguous events on a human agent, whereas sad induction, and not cognitive appraisal, led to attributing ambiguous events to situations beyond human control. Lerner and Keltner (2001) demonstrated that the positive relation between induced anger and optimism was mediated by one's perception of control over the likelihood of future events; perception of certainty that the events would occur was not a factor and was not correlated with perceived control.

The following two studies on the effects of emotion on simple cognitive tasks demonstrate that performance is not affected by activated fear but may be facilitated by unpredictable loud noise simulating a looming jet aircraft.

Moser, Hajcak, and Simons (2005) conducted a study in which spider-phobic participants performed a choice reaction time task (a flanker task). In the control condition, no spider was present. In the fearful condition, a lab assistant sat near the participant and continually passed a live Chilean rose-haired tarantula between his hands. The two conditions were within-subjects. Even though the fear induction was shown to be effective (for example, spider-phobic participants were crying during the break between sessions), there was no difference in the proportion of correct responses between the control and fear conditions. Nor did reaction time differ between the conditions.

Helton, Matthews, and Warm (2009) conducted a behavioural study in which participants performed a neutral vigilance task, requiring them to continuously scan a repeatedly-presented pattern of unfilled circles on a dark background, and detect the occasional appearance of the letter O (while not reacting to a D occasionally presented). The levels of the "letter" factor were high or low salience (that is, high or low contrast compared to the repeating pattern). There was also a "noise" (present / absent) factor. Loud noise was delivered through two stereo speakers placed on the ceiling in front of the participant. The noise resembled that of a jet aircraft, and "seemed to approach from the observer’s right and then recede towards the left" (Helton et al., p. 207), an effect created by modulating the amplitude up to 95 dB. Noise episodes, as well as the interlude between noise episodes, varied in duration. Before and after testing, participants completed a state stress questionnaire that included scales on task engagement (energetic arousal), distress (tense arousal) and worry. Results showed that correct responses were more prevalent in the high than in the low salience condition, and more prevalent in the noise present than in the noise absent condition. Post-test task engagement scores increased from pre-task levels among participants in the noise condition, but decreased among participants in the noise absent condition. Distress scores increased post-task, especially in the low salience condition, but did not vary by the levels of the noise factor. Thus, performance and task engagement were enhanced in the noise condition, whereas the increased distress was not a function of the noise. Structural equation modelling demonstrated that the noise did not affect performance directly, but was mediated by task engagement. Task engagement was defined in terms of energetic arousal, motivation, and concentration. Helton et al. speculate that the effects of noise on task engagement may be due to direct neurophysiological activation but may also affect participants' appraisal of the task as being (more) challenging.

Neuroimaging evidence of the emotion / decision-making relation. Northoff et al. (2004) used event-related fMRI to investigate whether the introduction of an emotional component to a cognitive task would result in reciprocal attenuation of neural signal, that is, smaller decreases in signal in the medial prefrontal cortex and smaller increases in signal in the lateral prefrontal cortex, compared to neural signal in a non-emotional cognitive task. One factor was emotion condition (positive, negative, or neutral IAPS picture) whereas the other was picture judgment type (valence: positive/negative, feelings elicited: yes/no, picture orientation: portrait/landscape). Thus, there were three types of judgment, two emotional and one cognitive. Emotional judgment was associated with activation in left ventromedial (BA 9) and left dorsomedial (BA 8) prefrontal cortex, compared to non-emotional judgment. Non-emotional judgment was associated with activation in right ventrolateral prefrontal cortex (BA 46, BA 10) and bilateral dorsolateral frontal cortex (BA 9). "The emotional load in the judgment task ... led to attenuation of both signal decreases in VMPFC / DMPFC and, at the same time, signal increases in VLPFC / (d)LPFC, resulting in a pattern of reciprocal attenuation" (Northoff et al., p. 208); thus, the predictions were confirmed.

To explore whether the emotional valence of stimuli employed in a non-emotional cognitive task could influence behaviour as well as neural regions associated with cognitive-task performance, Simpson et al. (2000) conducted an fMRI study. Stimuli were neutral and negative IAPS pictures. The task on each trial required participants to press one key if the picture showed fewer than two humans, and to press the other key if the picture showed two or more humans. Neural activation in the negative-neutral contrast was extensive throughout the brain, evoking activation in left posterior cingulate, amygdala, and caudate, as well as bilateral medial frontal gyrus; as well, there was bilateral activation in various sites in occipital, parietal, temporal and frontal lobes. Activation in the neutral-negative contrast involved only right postcentral (somatosensory) gyrus, right middle (BA 39) and superior (BA 22) temporal gyrus, and left precentral gyrus. Based on reaction times, the researchers comment that task performance deteriorated in the negative as compared to the neutral condition. Thus, negative valence compared to neutral did influence behaviour as well as underlying neural regions even though the non-emotional cognitive task was similar between conditions.

Clarification of the Position Adopted in the Dissertation Regarding Mood, Emotion, and "Affect as Information"

Moods are *long-lasting* states characterized by positive or negative valence; they may (or may not) be the lingering after-effects of a specific emotion. Emotions, in contrast, involve *current* activation of neurophysiology, the pattern of which is different among the various emotions. As described above, emotions involve many elements, not just valence. The study of negative (or of positive) emotion may involve a mixture of emotions of the same valence; however, that mixing is insufficient to characterize such an induction as a mood induction. In the mood induction literature, the term "mood" is used in an imprecise manner; in some reports it actually refers to mixed *emotions* of the same valence, whereas in other reports it refers to one emotion, but only the valence of that emotion is of interest to the researcher.

The dissertation accepts the position that emotion is neurophysiological, and that feelings, which are not necessary for emotion to occur, are the conscious aspect of emotion. Whereas it is possible to factor feelings (which are conscious by definition) into a decision, that does not seem to be the mechanism that explains results from the "affect as information" field. The term "affect as information" itself is ambiguous; it is that ambiguity rather than the research itself that may create misunderstanding when interpreting findings. Most researchers who work in the "affect as information" model are not making a commitment to conscious consultation of feelings; a close inspection of their writing clarifies this. Perhaps this position is generally understood and accepted;

however, rather than assuming that this is so, the following argument is advanced in support of the position.

Information processing models incorporate an important role for neurophysiology. Even before the days of neuroimaging research, Simon (1967) was proposing that the autonomic nervous system plays an important role in emotion and that there is a distinction between emotion and feelings.

> In human beings sudden intense stimuli are commonly associated with reports of the subjective feelings that typically accompany emotional behavior. We shall not be particularly concerned here with these reports, but shall assume, perhaps not implausibly, that the feelings reported are produced, in turn, by internal stimuli resulting from the arousal of the autonomic system (Simon, 1967, p. 35-36).

Oatley and Johnson-Laird do not describe the neurophysiological aspects of emotion, concentrating on the emergent level. Nevertheless, they acknowledge that emotions

> …can sometimes be caused by purely bodily changes… Such changes can occur for many reasons: a nonpropositional[9] signal of emotion can occur although the subject does not know its cause, autonomic effects can occur because the subject has drunk too much coffee, feedback of expressions of emotion can be mimicked, differential activation of right and left hemispheres can occur, and physical activity can cause

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[9] Note that "non-propositional" should not be confused with "diffuse". There are different underlying neural patterns associated with different emotions. An analogy could be made to basic visual processes for (*e.g.*) edge detection in the brain; these are non-propositional but lead to detection of edges, not to vision in general.

changes…” (Oatley & Johnson-Laird, 1996, p. 364).

Furthermore, as was mentioned during the literature review, the same authors propose that the functions of emotion are “to *control the organization of the brain* [emphasis added], to make ready mechanisms of action and bodily resources, to direct attention, to set up biases of cognitive processing, and to make the issue that caused the emotions salient in consciousness” (Oatley & Johnson-Laird, 1996, p. 364). The theory is referred to as “communicative” partly because emotions are based on signals within the brain. The theory makes no commitment as to whether these signals necessarily occur in conscious awareness.

The "affect as information" model entered the behavioural literature as a result of the following experiment. Schwarz and Clore (1983) found that participants' responses to a life-satisfaction questionnaire were correlated with the current sunny or rainy weather conditions, unless the weather itself was brought to participants' attention before they answered the questionnaire. The researchers wrote: "The data suggest...that people use their momentary affective states as information in making judgments of how happy and satisfied they are with their lives in general" (Schwarz & Clore, p. 513). The results of this experiment are consistent with responses arising from the effects of a current underlying emotional (actually, in this case, mood) state; whether participants were consulting their affect consciously or otherwise is a detail that is not necessary to the interpretation.

Bodenhausen, Kramer, et al. (1994) conducted two experiments, with different participants, demonstrating that emotion induction effects are similar whether the induction occurs in awareness or not; thus, the effects of emotion are not dependent on conscious awareness. Participants were asked to judge the innocence or guilt of an accused in a mock criminal case; materials that were provided included stereotyped information as well as non-biased information about the facts of the case. In the first experiment, positive emotion induction, before the task, involved recalling, re-experiencing, and writing about a positive autobiographical event. Participants in the positive condition, compared to the no-induction condition, were more likely to base their judgments on the stereotyped information. In a second experiment, the researchers demonstrate that the effect occurs without participants' realizing it. In the positive condition, participants were instructed to contract their zygomatic muscle (which happens to be the facial muscle involved in spontaneous smiling) while engaged in the judgment of the criminal case. In the neutral condition, participants formed a loose fist with the non-dominant hand. The behavioural results were a replication of those in the first experiment. Thus, positive emotion can exert its effects even though the emotion has been induced, without participants' awareness, by a relevant muscle contraction. Similar results, in which muscle contractions were produced by holding a pen in the mouth, have been obtained by Strack, Martin, and Stepper (1988).

As mentioned above, Forgas (1995) proposed that people resort to a motivated processing strategy, which is a controlled process, in situations in which the person is motivated to make a judgment that will (for example) repair his or her mood; under these circumstances, the information search is highly selective and guided towards a particular target, and emotion induction effects are not found. It is not clear that the evidence cited by Forgas provides appropriate support for a motivated processing strategy. For example, in the within-subjects study, described above, of social norms rated when working alone or in groups, Forgas (1990) reported that, following induced sadness, people's responses demonstrated attenuation of negative judgments when in the group setting. In fact, the results actually demonstrate that ratings provided by people in the sad condition remained unbiased throughout the experiment. Such a result is consistent with various reports summarized earlier indicating that sadness promotes systematic processing; thus the effect found in Forgas (1990) could be a result of the sad induction rather than controlled (motivated) processing.

The Purpose of the Neuroimaging Studies

This literature review has summarized various theories and findings on the relation between emotion and reason. The focus of the dissertation is on the influence of emotion on syllogistic deductive reasoning in particular. As mentioned earlier, Goel and Dolan (2003b) studied this relation in a neuroimaging study by asking participants to engage in reasoning about material that was (or was not) emotionally provocative.

The neuroimaging studies to be presented in the dissertation seek to understand the effect of emotion on syllogistic reasoning, in paradigms where the reasoning material itself is *not* emotional. That is, the emotions being induced are not related to the material being reasoned about. In the first study, positively- and negatively-valenced emotions were induced visually prior to the non-emotional reasoning task, whereas in the second study, the emotion induction, created by delivering the syllogism material in sad, angry, or neutral tone of voice, was concurrent with the non-emotional reasoning task.

The introductory section particular to each study will provide a brief summary of relevant literature, will discuss how the study question relates (or does not relate) to existing theories, and will provide the rationale for the specific hypotheses.

Neuroimaging of the Effects of Positive or Negative Emotion Induction on Subsequent Syllogistic Reasoning: The Pictures Study

The purpose of the pictures study is to determine the effect of emotion induction on a subsequently-presented syllogistic reasoning task that has non-emotional content. The two types of induction chosen for this study are positively- and negatively-valenced emotion.

The impact of emotion induction on neural mechanisms of non-emotional syllogistic reasoning is not yet understood. Behavioural literature suggests that positive emotion induction impairs logical reasoning (Blanchette, 2006; Blanchette & Richards, 2004; Melton, 1995) and promotes a reliance on such heuristic shortcuts as source expertise and stereotyping instead of considering the evidence (Bless et al., 1992; Bodenhausen, Kramer, et al., 1994; Schwarz & Clore, 1983) when making evaluations. Negative emotion induction impairs logical reasoning (Blanchette, 2006; Blanchette & Richards, 2004); however there are important exceptions, described next, each involving a particular negative emotion. Reasoning about terrorist attacks shortly after a real attack has occurred in the same country is significantly more logical than is reasoning about emotional content in general (Blanchette et al., 2007). Belief-bias effects are attenuated when reasoning about politically incorrect subject matter (Goel & Vartanian, 2010). Sadness / depression promotes systematic cognitive processing (Alloy & Abramson, 1979; Bless et al., 1992; Bohner et al., 1992; Edwards & Weary, 1993; Schwarz & Bless, 1991). Cognitive processing is facilitated when in the presence of unpredictable loud noise simulating looming jet aircraft (Helton et al., 2009), and is unimpaired by fear

(Moser et al., 2005). Thus, whereas positive emotion induction promotes a reliance on heuristic shortcuts, the effects of negative emotion induction depend on the specific emotion. The effects of negative emotion described in the above studies do not impede logical reasoning /cognitive processing, and may even facilitate task performance.

Viewing positive and negative IAPS pictures had different effects on perceptual encoding of unattended stimuli (Schmitz et al., 2009). Whereas positive mood broadened focus, negative mood narrowed it; this was not an effect of attention, but rather a direct effect of two different neural states, each of which recruits different posterior sensory regions. In addition, activation in right lateral frontal pole (BA 10) and right lateral orbitofrontal cortex (BA 11) was associated with positive mood induction whereas activation in the amygdala was associated with negative mood induction. These results support an account of neural emotion systems rather than an account of valence effects *per se*.

Viewing positive and negative IAPS pictures and rating them based on one's feelings resulted in a different pattern of neural activation associated with each valence (Dolcos et al., 2004). Activation in the amygdala, uncus, and anterior parahippocampal gyrus was correlated with increasingly aversive ratings, provided during scanning, of neutral and negative IAPS pictures (Taylor et al., 2000). Grimm et al. (2006) demonstrated that the task of judging picture valence has a different effect neurally than does passive viewing. The negative compared to neutral valence of stimuli employed in a simple cognitive task influenced underlying neural regions associated with cognitive-task performance, and behavioural performance was slow compared to neutral (Simpson et al., 2000).

Neuroimaging studies of emotion (without a reasoning task) have demonstrated that both happiness and sadness have been associated with activation in anterior cingulate (cognitive subdivision) and dorsomedial prefrontal cortex (Murphy et al., 2003). In what may be the first neuroimaging study to have examined the emotion / reason relation directly, emotional ("hot") reasoning in general was found to involve ventromedial prefrontal cortex whereas neutral ("cold") reasoning implicated left dorsolateral prefrontal cortex; furthermore, these neural mechanisms were activated in a reciprocal manner (Goel & Dolan, 2003b). Introduction of an emotional component to a general cognitive task yielded a similar pattern of reciprocal neural activation; neural signal was reported in medial prefrontal cortex, associated with emotional cognition, and was reported in lateral prefrontal cortex, associated with neutral cognition (Northoff et al., 2004).

The purpose of the current pictures study was to assess the effect of positively- and negatively-valenced emotion induction on the neural mechanisms of syllogistic reasoning when the emotion induction task and the reasoning task were presented sequentially and the reasoning task itself did not involve emotional content. Specifically, an emotion task (picture viewing/rating) was followed, on each trial, by a reasoning task involving syllogisms with non-emotional content.

This functional magnetic resonance imaging (fMRI) study was designed by Professor Vinod Goel in collaboration with Dr. Oshin Vartanian. A 3 (Emotion) x 2 (Task) within-subjects factorial design was used, where the levels of the emotion factor were positive, negative, and neutral, and the levels of the task factor were reasoning and baseline. The visual emotion induction occurred prior to the reasoning task, on each trial.

A Brief Explanation of the Logic of the Data Analysis

In the next section, the hypotheses will be presented, along with a specification of the particular patterns of behavioural and neuroimaging results that will indicate support for each hypothesis. For the convenience of the reader, a brief explanation of the logic of the data analysis is provided, as follows.

During analysis of behavioural data, a response is coded as "correct" if it matches the logic of the argument; that is, a response of "valid" is coded as "correct" if the syllogism argument is valid. However, one cannot determine whether responses to congruent syllogisms[10] were actually made on the basis of belief-based processing or logic-based reasoning. Therefore, the behavioural results consulted when evaluating the hypotheses are, specifically, the responses to incongruent syllogisms, in which the argument logic and the belief would lead to opposite response choices.

The relevant contrasts in the neuroimaging analysis are those that could reveal a crossover interaction (also known as a double dissociation). The following example[11] from the neuropsychology of language processing will illustrate the principle of a crossover interaction. Two aspects of language processing are speech comprehension (known to be associated with activation in a neural region called Wernicke's area) and

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[10] Congruent syllogisms are those in which the logic of the argument and the belief about the content would lead to the same choice of response key. The argument is valid and the content is true or at least plausible, or the argument is invalid, and the content is false or at least implausible.

[11] This example has been chosen simply because it is easy to follow.

speech production (known to be associated with activation in a neural region called Broca's area). This has been established by studying lesion patients who have a deficit in speech comprehension but not in speech production (group A), and by studying people who have a deficit in speech production but not in speech comprehension (group B). Patients in group A have a lesion localized to Wernicke's area (and no lesion in Broca's area), whereas patients in group B have a lesion localized to Broca's area (and no lesion in Wernicke's area).

The relevant contrasts in the pictures study, in particular, involve comparing activation, during the reasoning time-window, between each emotion condition (in turn) and the non-emotional condition. That is, a comparison is made between activation associated with (for example) the positive reasoning and the non-emotional reasoning time-window. One would think this would simply involve the two contrasts [Positive reasoning *minus* neutral reasoning] and the reverse: [Neutral reasoning *minus* positive reasoning]. However, the reader will recall that the experimental design included baseline trials, which are trials in which two premises are presented but the concluding sentence is taken from another syllogism; on such trials, participants will disengage from the reasoning process altogether during the reasoning time-window. In general, a comparison such as [Positive reasoning *minus* positive baseline] isolates the neural activations associated with the task after accounting for such effects as reading the syllogism. Therefore, our two contrasts (comparing positive and neutral reasoning) are set up as follows: [(Positive reasoning *minus* positive baseline) *minus* (Neutral reasoning *minus* neutral baseline)], and then [(Neutral reasoning *minus* neutral baseline) *minus* (Positive reasoning *minus* positive baseline)]. Of course, we compare negative and neutral reasoning according to the same logic, and we can compare positive and negative reasoning according to the same logic.

A crossover interaction occurs when there are neural activations associated with *each* direction of the comparison. That is, there are neural activations associated with [(Positive reasoning *minus* positive baseline) *minus* (Neutral reasoning *minus* neutral baseline)], and there are also neural activations (which of course will be different) associated with [(Neutral reasoning *minus* neutral baseline) *minus* (Positive reasoning *minus* positive baseline)]. A crossover interaction is interpreted as indicating that there are different neural activations that are specific to each of the two conditions being compared. Of course, there could be other neural regions activated by both conditions, and these would be subtracted out, but the crossover interaction indicates that the two conditions are characterized at least somewhat differently from each other.

Other patterns of results may occur, instead of a crossover interaction. For instance, there may be no voxels reported after performing either the first contrast or its reverse. This is interpreted as indicating that the same neural regions were implicated in both conditions.

Another possible result might be that the contrast in one direction reveals some neural activation but the contrast in the reverse direction produces no voxels. This is interpreted as indicating that the same neural regions were implicated in both conditions, and, in addition, there was some neural activation in one condition over and above that in the other. Suppose there are two neural regions, D and E. Let's say that D and E are involved in positive reasoning, whereas only D is involved in neutral reasoning. We perform our first contrast, [(Positive reasoning *minus* positive baseline) *minus* (Neutral reasoning *minus* neutral baseline)], and the report indicates activation in E. The software had located D and E in positive reasoning, looked for D in non-emotional reasoning (found it and subtracted it) and looked for E in non-emotional reasoning (and could not find it because it does not exist there). We then perform the reverse contrast, [(Neutral reasoning *minus* neutral baseline) *minus* (Positive reasoning *minus* positive baseline)], and the report is that there are no voxels. The software had located (only) D in neutral reasoning, looked for that in positive reasoning, found it and subtracted it.

Hypotheses

Oatley and Johnson-Laird (1987) proposed that when an event occurs that is not served by the currently active processing mode, the brain responds by eliciting an emotion signal that interrupts processing in that mode and immediately sets the brain into the relevant emotion mode to respond quickly to the stimulus. It is not clear from this proposal whether a subsequent non-emotional reasoning task would restore processing to a non-emotional mode; that is, that model does not address such a situation. Furthermore, LeDoux (1996) proposed that once a (neural) emotion system is triggered, it is a powerful motivator for future behaviour; the effects on behaviour could be either beneficial or detrimental. LeDoux also proposed that there is only one mechanism for conscious awareness, and inputs to awareness from emotion systems will displace inputs from the fact-based system. Therefore, the first set of hypotheses[12] are as follows:

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[12] H_0 refers to the null hypothesis whereas H_1 refers to the alternative hypothesis.

1. H_0: Activation of positive emotion will not affect reasoning.

   H_1: Activation of positive emotion will distract from the subsequent reasoning task.

2. H_0: Activation of negative emotion will not affect reasoning.

   H_1: Activation of negative emotion will distract from the subsequent reasoning task.

Evidence will be interpreted as support for the null hypothesis if there are a) no significant differences in the rate of logic-based responding (to incongruent syllogisms) between the relevant emotion and the non-emotional condition in the behavioural results, and b) the neuroimaging contrasts set up to explore crossover effects reveal no neural activation in either direction. That is, there are: i) no differences in neural activation in the relevant emotion (reasoning) condition (minus baseline) after subtracting out neural activations associated with non-emotional reasoning (minus baseline), and ii) no significant differences in neural activation in non-emotional reasoning (minus baseline) after subtracting out neural activations associated with the relevant emotion (reasoning) condition (minus baseline). Evidence will be interpreted as support for the alternative hypothesis if a) behavioural results indicate a greater reliance (among incongruent syllogisms) on belief-based processing in the relevant emotional than in the non-emotional condition, b) there are no significant neural activations associated with non-emotional reasoning (minus baseline) after subtracting out those associated with the relevant emotion (reasoning) condition (minus baseline), and c) there is significant neural activation associated with the relevant emotion (reasoning) condition (minus baseline) after subtracting out neural activations associated with non-emotional reasoning (minus baseline).

Behavioural literature suggests that positive emotion induction promotes a reliance on heuristic shortcuts instead of considering the evidence (Bless et al., 1992; Bodenhausen, Kramer, et al., 1994; Schwarz & Clore, 1983) when making evaluations. Goel et al. (2000) have proposed that there is a language-based reasoning system based on associations; Stanovich (2009) has proposed that there is a type of reasoning referred to as semantic associative cognition with a focal bias. This accumulation of evidence suggests that positive emotion induction may lead to a systematic reliance on belief-based processing. In contrast, other evidence suggests that negative emotion induction may lead to a systematic reliance on logical reasoning. Specifically, behavioural literature suggests that negative emotion induction does not impede cognitive processing (Moser et al., 2005), and may even facilitate logical reasoning or cognitive processing (Alloy & Abramson, 1979; Blanchette et al., 2007; Bless et al., 1992; Bohner et al., 1992; Edwards & Weary, 1993; Goel & Vartanian, 2010; Helton et al., 2009; Schwarz & Bless, 1991). Goel & Dolan (2003a) have reported different neural activation underlying belief-based *versus* logic-based reasoning, and the Goel model of deductive reasoning (2009) proposes that deductive reasoning proceeds differently when the conflict between beliefs and logic is resolved in favour of beliefs than when it is resolved in favour of logic.

Therefore, the next set of hypotheses are as follows:

3. H_0: Activation of positive emotion will facilitate logic-based reasoning.
   H_1: Activation of positive emotion will facilitate belief-based processing.
4. H_0: Activation of negative emotion will facilitate belief-based processing.
   H_1: Activation of negative emotion will facilitate logic-based reasoning.

Evidence will be interpreted as support for belief-based processing if a) behavioural results indicate a greater reliance on belief-based processing (among incongruent syllogisms) in the relevant emotional than in the non-emotional condition, and b) the analysis of neural activations reveal a significant crossover interaction, such that i) there is significant activation associated with the relevant emotional reasoning condition (minus baseline) after subtracting out the activation associated with the non-emotional condition (minus baseline), and ii) there is significant activation associated with the non-emotional reasoning condition (minus baseline) after subtracting out the activation associated with the relevant emotional condition (minus baseline). Evidence will be interpreted as support for logic-based reasoning if a) behavioural results indicate a greater reliance on logic-based reasoning (among incongruent syllogisms) in the relevant emotional than in the non-emotional condition, and b) the analysis of neural activations reveal a significant crossover interaction, as just described.

The emotion inductions themselves are expected to be successful; that is, they are expected to yield different patterns of underlying neural activation. Increasingly negative intensity may be associated with activation in the amygdala, uncus, and anterior parahippocampal gyrus (Taylor et al., 2000). Emotional intensity ratings are expected to be correlated with increased activation in ventromedial or medial prefrontal cortex but not with increased activation in dorsolateral prefrontal cortex.

Method

Participants. Data were acquired from 16 participants (7 males, 9 females). Education levels ranged from partially-completed undergraduate study to completed graduate degrees, with a mean of 17.54 (*SD* = 3.82) years of education. Ages ranged from 19 to 56 (mean age was 28, *SD* = 10 years).

All participants gave informed consent. Scanning was conducted at University College, London England in October 2003 and was supervised by Professor Vinod Goel, who obtained ethics approval from the Joint National Hospital for Neurology and Neurosurgery / Institute of Neurology Ethics Committee, prior to scanning.

Materials. Pictures were taken from the IAPS system (Lang et al., 1997). Pictures in this system have been normed as to emotional valence. This information was used to choose 40 positive, 40 negative and 40 neutral pictures for the experiment (see Figure 1).

Figure 1. Example of positive, neutral, and negative stimuli (IAPS; Lang et al., 1997) used in the pictures study.

Reasoning stimuli consisted of 75 syllogisms that were emotionally neutral in content. The arguments in 38 of these syllogisms were logically valid whereas the arguments in the remaining 37 were logically invalid. An example of a valid syllogism is: "All dogs are pets. All poodles are dogs. All poodles are pets", and an example of an invalid syllogism is: "All paper is absorbent. All napkins are paper. No napkins are absorbent."

The content of the concluding sentence of each argument was factually true in 38 of the syllogisms and factually false in the other 37. The reasoning syllogisms were balanced overall for validity and for congruence between logic and beliefs. That is, the arguments can be organized as follows: 19 valid / true, 19 valid / false, 19 invalid / true, and 18 invalid / false. The reasoning syllogisms are listed in Appendix A.

As well, there were 45 baseline “syllogisms”, in which the “conclusion” was a concluding sentence taken from a different syllogism, thereby ensuring that the conclusion of the baseline would be unrelated to the content of the two premises. An example is as follows: "No women are tailors. All barbers are women. All chairs are useful." Thus, in a baseline trial, the participant would prepare to respond to what was expected to be a syllogism; the only difference in baseline trials is that the neural activation during the conclusion would not involve reasoning. The baseline trials involved reading sentences, and pressing the key to respond, in the usual way. Baselines provide scans of neural activation that, during analysis, can be subtracted from the neural activation obtained during reasoning scans.

Procedure. The study involved 120 trials delivered over 3 sessions.[13] Each trial involved the following sequence: First, the participant saw a slide of xxx for 500 milliseconds. Then the xxx disappeared and the participant viewed a picture and pressed one of eight keys to indicate his/her rating of positive or negative valence and intensity of the picture’s emotional content. The specific meaning of the keys will be explained below. Then, the picture disappeared and a syllogism was presented over three consecutive slides (slide one: first premise alone; slide two: first two premises together; slide three: the two premises plus the conclusion). The syllogism remained in view during

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[13] “Sessions”, or “runs”, occur one right after the other without leaving the scanner.

the reasoning period. The participant pressed a key to indicate whether the syllogism was logically valid or not valid. Disappearance of the picture and syllogism slides was not entrained to the responses but was timed to be in synchrony with the acquisition of the brain scans. Trials varied in length but were approximately 16-20 seconds.

The design of one trial is demonstrated on the following timeline:

xxx Picture response Premise1 &Premise2 &Conclusion response

0 500 6000 9000 12000 ~16000 ms

The specific meaning of the eight picture-rating keys is as follows: valence and intensity were captured in the same keypress. There were eight keys to choose from, four in one direction for “increasingly negative” and four in the other direction for “increasingly positive”. The side was counterbalanced among participants. Participants used the index finger of each hand to respond. All participants were declared as right-handed. During post-scan analysis, data can be analysed by intensity and by emotion category; for category, the two keys nearest the divide are taken to indicate “neutral” whereas, during intensity analyses, all eight keys are considered.

Syllogisms and baseline trials were matched to pictures so that there were equivalent numbers of congruent syllogisms, incongruent syllogisms, and baselines within each level of the Emotion factor (Positive, Negative, and Neutral). Then the order of the 120 trials was randomized. Then the trials were segregated into three presentation sets of 40 trials each. All participants were presented with the same three sets of trials; the order of presentation of these three sets was counterbalanced among participants, one set for each session in the scanner.

The scanning procedure was as follows. A 1.5T Siemens VISION system (Siemens, Erlangen, Germany) was used to acquire T1 anatomical volume images (1 x 1 x 1.5-mm voxels) and T2*-weighted images (64 x 64, 3 x 3-mm pixels, TE = 40 ms), obtained with a gradient echo-planar sequence using blood oxygenation level-dependent (BOLD) contrast. Echoplanar images (2 mm thick) were acquired axially every 3 mm, positioned to cover the whole brain. Each volume (that is, scanning of the entire brain) was partitioned into 36 slices, obtained at 90 milliseconds per slice. Data were recorded during a single acquisition period. Volume (vol) images, 243 volumes per session, were acquired continuously, for a total of 729 volume images over three sessions, with a repetition time (TR) of 3.24 s/vol. The first six volumes in each session were discarded (leaving 237 volumes per session) to allow for T1 equilibration effects.

Behavioural Results and Discussion

Software. Behavioural data were analysed using SPSS, version 16.0 (SPSS Inc., Chicago, Illinois).

Data organization. In the design there were 120 trials, 75 (62.5%) involving reasoning and 45 (37.5%) baselines. Of the original 16 participants, neuroimaging data were usable for 14 of them. Therefore, the behavioural analyses are based on 14 participants. Twelve participants completed all three sessions of 40 trials each. One participant completed two sessions. One other participant completed all three sessions, but because some of the scan volumes were missing from the data, it was necessary to excise three trials from the middle of Session 1 and one trial from the middle of Session 2. Thus, there were a total of 12*120 + 80 + 116 = 1636 trials. Of these, 1021 (62.4%) were reasoning trials and 615 (37.6%) were baselines.

As indicated in the Methods section, participants were shown a picture during each trial, and provided a rating of the valence and intensity of the emotional content of each picture; this was achieved by pressing one key from a selection of eight keys. During data analysis, the valence ratings were sorted into three categories: positive, negative, and neutral. Ratings of –2, –3, or –4 were classified as "negative"; ratings of +2, +3, or +4 were classified as "positive". Ratings of –1 or +1 were considered "neutral".

Picture ratings. The percentage of trials by participants' valence rating was as follows: 42.8% positive, 26.0% neutral, 23.4% negative, and 7.8% no rating.

The mean response time to rate the pictures was calculated for each participant, separately for each valence. A repeated-measures analysis, multivariate approach, was conducted; the within-subjects factor was Emotion and the dependent variable was mean picture rating response time. Data were analysed for 13 participants, as one participant had not rated any picture as "neutral". There was a significant difference in mean picture rating time across Emotion (positive, neutral, negative): $F(2, 11) = 5.739$, $p = .02$, partial $\eta^2 = .511$. The quadratic contrast (+1 positive, -2 neutral, +1 negative) was significant: $F(1, 12) = 6.187$, $p = .029$, partial $\eta^2 = .340$. Participants took significantly longer to rate the emotional pictures than the neutral pictures. Mean response times ($n = 13$) were 2184 (*SD* 483) ms for positive, 1919 (*SD* 623) ms for neutral, and 2092 (*SD* 467) ms for negative.

Engagement with the task. Behavioural results indicate that participants were engaged in the task. Overall, the proportion of logical (correct) responses on baseline trials (choice of "invalid") was 97.24%. A paired *t*-test was conducted to compare the participants' mean reaction time to reasoning *versus* baseline syllogisms; participants responded significantly faster to baselines: *t*(13) = 8.567, *p* = .001. Furthermore, participants responded significantly more slowly on reasoning trials when their response was illogical (incorrect) than when it was logical (correct), regardless of the valence of the trial (the main effect of logic [accuracy] was significant: *F*(1, 12) = 7.537, *p* = .018, partial η^2 = .386; there was no main effect of Emotion and no significant interaction of Logic x Emotion); this result indicates that errors were not a consequence of hasty responding. The proportion of logical (correct) responses was significantly lower to incongruent (.5517, *SD* .184) than to congruent (.7255, *SD* .189) syllogisms (*paired t*(13) = -2.994, *p* = .01), and responses were significantly slower (*paired t*(13) = -5.026, *p* = .001) when beliefs conflicted with the logical argument (3966 ms, *SD* 615) than when they did not (3386 ms, *SD* 424). The direction of these differences in accuracy and reaction time between congruent and incongruent trials is consistent with findings in Goel and Dolan (2003a). Details of the behavioural analyses of the main effect of reasoning *versus* baseline, the simple effect of emotion on reasoning, of the effect of congruence (collapsed across accuracy and emotion), and of mean reaction time (collapsed across accuracy) in the analysis of the Congruence x Emotion interaction, are provided in Appendix C.

Behavioural analyses related to the hypotheses. Support or lack of support for each of the four sets of hypotheses depends on converging evidence from behavioural data and neuroimaging data. As explained above, the behavioural data of interest are those indicating the rate of logic-based ("correct") responding to incongruent syllogisms. The comparison of performance after each emotion induction to performance in the non-emotional condition could yield three possible outcomes: there may be no significant difference, there may be an improvement in logic-based reasoning (and a decrement in belief-based responding), or there may be an improvement in belief-based responding (and a decrement in logic-based reasoning).

As set out in the hypotheses, a lack of significant difference between an emotion condition (positive or negative) and the non-emotional condition would provide partial support for the (null) hypothesis that the particular emotion induction (positive or negative) does not affect performance on a subsequent syllogistic reasoning task. An improvement in logic-based reasoning after emotion induction (positive or negative) compared to the non-emotional condition would provide partial support for the hypothesis that the particular emotion induction facilitated logic-based reasoning on the subsequent syllogistic reasoning task. An improvement in belief-based responding after emotion induction (positive or negative) compared to the non-emotional condition would provide partial support for one of two distinct hypotheses. That is, the particular emotion induction distracts the reasoner away from the subsequent syllogistic reasoning task, or the particular emotion induction facilitates belief-based responding on the subsequent task.

For each participant, the [proportion of logical (correct) responses] to [total number of syllogisms] was calculated, separately for congruent and incongruent syllogisms, within each valence rating. For instance, the proportion of [logical responses to positive congruent syllogisms] to [all positive congruent syllogisms] was calculated, for each participant. Subsequently, a repeated-measures analysis, multivariate approach, was conducted; the factors were Congruence (congruent, incongruent) and Emotion (positive, neutral, negative). Data in each cell were the relevant proportion of logical (correct) responses. Figure 2 portrays the result of this analysis.

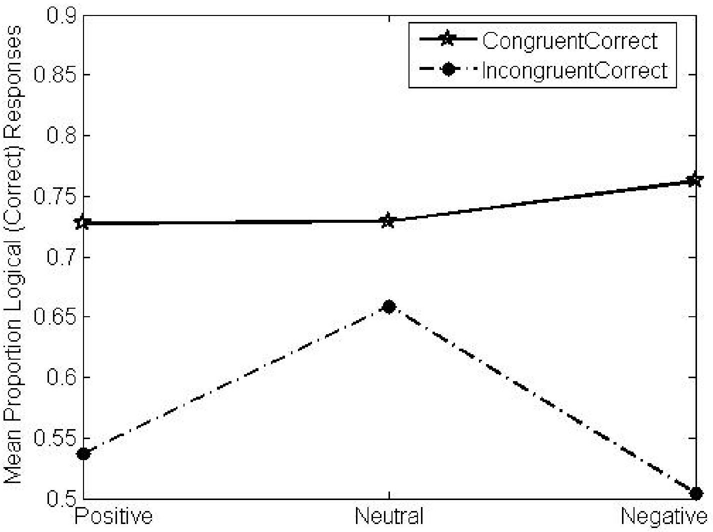

Figure 2. Pictures study: Logical (correct) responding is significantly hindered when the logic of the argument conflicts with beliefs, moreso after emotional than after neutral picture ratings. The quadratic interaction contrast was significant: $F(1, 12) = 6.47$, $p = .026$, partial $\eta^2 = .35$.

The mean proportions (logical (correct):total) were as follows ($n = 13$): For congruent syllogisms, positive:total was .727 (*SD* .252), neutral:total was .729 (*SD* .174), and negative:total was .762 (*SD* .233). For incongruent syllogisms, positive:total was .537 (*SD* .174), neutral:total was .659 (*SD* .267), and negative:total was .504 (*SD* .305).

Mean reaction time for logical (correct) responses was calculated for each participant, by congruence and emotion. A repeated-measures analysis of variance, multivariate approach, was conducted, with mean reaction time when logical (correct) as the dependent variable. The factors were Congruence (congruent, incongruent) and Emotion (positive, neutral, negative). There was a significant main effect of Congruence: *F*(1, 11) = 39.74, $p = .001$, partial $\eta^2 = .783$. The quadratic interaction contrast approached significance: *F*(1, 11) = 4.758, $p = .052$, partial $\eta^2 = .302$. The results of this analysis are portrayed in Figure 3.

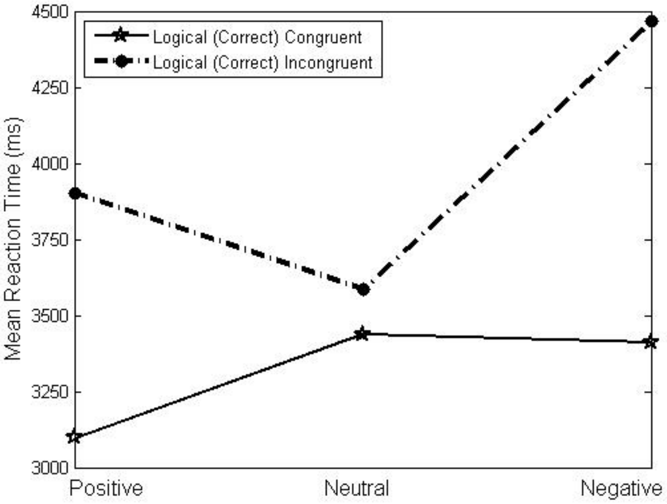

Figure 3. Pictures study: When reasoning logically (correctly), participants responded significantly more slowly when their beliefs were in conflict with the logical argument of the syllogism, tending to be even slower on emotional than on neutral trials.

Mean reaction times (*n* = 12) when responding logically (correctly) were as follows: (a) congruent positive: 3097 ms (*SD* 530); (b) congruent neutral: 3437 ms (*SD* 532); (c) congruent negative: 3410 ms (*SD* 499); (d) incongruent positive: 3901 ms (*SD* 829); (e) incongruent neutral: 3585 ms (*SD* 1077); (f) incongruent negative: 4466 ms (*SD* 625).

Thus, the pattern of results indicates an increase in belief-based responding (and a decrease in logic-based reasoning) after emotion induction, whether positive or negative. As well, participants tend to take longer to respond after emotion induction than in the non-emotional condition; this is an indication that participants were engaged in a cognitive process (as opposed to guessing) during the task. The pattern of results was predicted by two competing hypotheses: Either the emotion induction distracted the reasoner away from the subsequent task, or emotion induction facilitates belief-based responding on the subsequent task. As explained above, support for hypotheses must consider evidence not only from the behavioural analyses but also from the neuroimaging analyses.

Neuroimaging Results and Discussion

Software. The functional imaging data were preprocessed and subsequently analyzed using Statistical Parametric Mapping SPM2 (Friston et al., 1994; Wellcome Department of Imaging Neuroscience; http://www.fil.ion.ucl.ac.uk/spm_spm).

Data preprocessing. All functional volumes were spatially realigned to the first volume. Participant data with head movement greater than 2 mm were discarded. All volumes were temporally realigned to the AC–PC slice, to account for different sampling times of different slices. A mean image created from the realigned volumes was coregistered with the structural T1 volume and the structural volumes spatially normalized to the Montreal Neurological Institute brain template (Evans, Collins, et al., 1993) using nonlinear basis functions (Ashburner & Friston, 1999). The derived spatial transformation was then applied to the realigned T2* volumes, which were finally spatially smoothed with a 12 mm FWHM isotropic Gaussian kernel in order to make comparisons across subjects and to permit application of random field theory for corrected statistical inference (Worsley & Friston, 1995). The resulting time series across each voxel were high-pass filtered with a cut-off of 128 s, using cosine functions to remove section-specific low frequency drifts in the BOLD signal. Global means were normalized by proportional scaling to a grand mean of 100, and the time series temporally smoothed with a canonical hemodynamic response function to swamp small temporal autocorrelations with a known filter.

Data analysis. Condition effects at each voxel were estimated according to the general linear model and regionally specific effects compared using linear contrasts. Each contrast produced a statistical parametric map of the t statistic for each voxel, which was subsequently transformed to a unit normal Z distribution. The activations reported survived either a cluster-level or a voxel-level intensity threshold of $p < .001$ using a random effects model, corrected for multiple comparisons using either the family-wise error rate or the false discovery rate (Genovese, Lazar, & Nichols, 2002). An exception was made for interaction contrasts, which survived either a cluster-level or a voxel-level intensity threshold of $p < .001$ using a random effects model, uncorrected for multiple comparisons. The BOLD signal was modeled as a canonical hemodynamic response function with time derivative. All events were modeled in the design matrix, but events of no interest (the first two sentences, and the two motor responses on a trial by trial basis) were modelled out. Positive, negative, and neutral picture viewing / rating were each modelled as an epoch from picture onset up to but excluding the motor response. Positive, negative, and neutral reasoning, and positive, negative, and neutral baseline were each modelled as an event. The onset of the event was the halfway point between presentation of the concluding sentence and the motor response.

Parametric (correlational) analyses were conducted to determine neural regions associated with increasingly intense positive and negative picture ratings. The BOLD signal was modeled as a canonical hemodynamic response function. All events were modeled in the design matrix, but events of no interest (the three sentences, and the two motor responses on a trial by trial basis) were modelled out. Positive intensity and negative intensity were each modelled as an event from picture onset.

Reasoning syllogisms were balanced, in the design, on congruence between argument logic and believability of the content. Past studies in the Goel opus (Goel et al., 2000; Goel, Makale, et al., 2004), balanced in a likewise manner, have reported neural activation associated with incongruent – congruent reasoning, overall. Therefore, a separate analysis was conducted to examine neural activation associated with the effect of congruence. The BOLD signal was modeled as a canonical hemodynamic response function with time derivative. All events, collapsed across the emotion factor, were modeled in the design matrix, but events of no interest (picture, premise 1, premise 2, conclusion, "reasoning" during baseline trials, the two motor responses) were modelled out. The events of interest, modelled as events, were scans acquired during the reasoning time-window for congruent reasoning trials and for incongruent reasoning trials. The onset of each event was the halfway point between presentation of the concluding sentence and the motor response.

Table 1 indicates the neuroimaging results related to the picture viewing / judging time window; results of the subtraction analyses are shown first, and are followed by the results of the parametric (correlational) analyses. Table 2 indicates the neuroimaging results related to the reasoning time-window; results for the effect of congruence across all reasoning trials are reported at the end of Table 2. Small volume correction was applied to contrasts as noted in each of the tables.

Table 1

Pictures study: Picture viewing / judging time window. Brain regions identified in the stated comparisons

Contrast, Location (Brodmann area)	MNI (x,y,z) coordinates			*Z*-score	*p*-value
Emotion – Neutral					
right middle temporal gyrus (BA 39)	52	-60	10	4.97	.029
left middle temporal gyrus (BA 37)	-50	-60	6	4.52	.047
Neutral – Emotion					
No voxels survived correction.					
Positive – Neutral, with small volume correction (svc) using Emotion – Neutral					
right middle temporal gyrus (BA 39)	46	-54	12	4.24	.004
Neutral – Positive					
No voxels survived correction.					
Negative – Neutral, (svc) using Emotion – Neutral					
No voxels survived correction.					
Neutral –Negative					
No voxels survived correction.					
Positive – Negative, (svc) using Emotion – Neutral					
No voxels survived correction.					
Negative – Positive, (svc) using Emotion – Neutral					
left caudate body	-20	8	24	3.72	.049

Table 1, *continued*

Parametric analysis: Correlations with Increasingly Positive Intensity Ratings					
right medial frontal gyrus (BA 10)	2	60	-6	4.97	.0001
right medial frontal gyrus (BA 10)	2	60	-6	4.97	.0001
left medial frontal gyrus (BA 11)	0	40	-12	4.03	.015
left occipital lobe, cuneus (BA 18)	-4	-98	8	4.94	.008
right middle occipital gyrus (BA 19)	50	-74	-10	4.87	.0001
right occipital gyrus (BA 19)	58	-70	0	4.83	.008
right occipito-temporal lobe, fusiform gyrus (BA 20)	42	-60	-18	3.62	.03
left cerebellum	-2	-60	0	4.17	.012
left cerebellum	-26	-58	-22	4.03	.015
left cerebellum	-34	-54	-24	3.36	.049
right middle occipital gyrus (BA 18)	30	-100	10	3.9	.02
left thalamus	-10	-2	12	3.88	.02
left inferior occipital gyrus (BA 18)	-46	-80	-8	3.65	.029
left inferior occipital gyrus (BA 18)	-36	-84	-10	3.42	.044
left middle occipital gyrus (BA 19)	-54	-70	6	3.38	.047
left ventrolateral frontal gyrus (BA 47)	-40	22	-14	3.35	.05
right occipital gyrus (BA 19)	68	-44	10	3.31	.053
left ventrolateral frontal gyrus (BA 47)	-46	22	-2	3.26	.058

Table 1, *continued*

Parametric analysis: Correlations with Increasingly Positive Intensity Ratings, continued					
right caudate head	4	0	4	3.25	.059
left medial frontal gyrus (BA 9)	-2	50	22	3.16	.07
left parietal lobe, postcentral gyrus (BA 1)	-44	-28	66	3.15	.07
left cerebellum	-42	-56	-24	3.1	.077
Parametric analysis: Correlations with Increasingly Negative Intensity Ratings					
right anterior parahippocampal gyrus (BA 34)	18	-12	-16	5.32	.0001
left cerebellum	-6	-28	-10	3.9	.004
right anterior parahippocampal gyrus (BA 35)	16	-28	-10	3.76	.005
left middle temporal gyrus (BA 39)	-48	-76	10	5.28	.0001
right occipito-temporal lobe, lingual gyrus (BA 18)	8	-84	-6	5.1	.002
right occipito-temporal lobe, fusiform gyrus (BA 37)	50	-60	-8	5.01	.002
left anterior parahippocampal gyrus (BA 34)	-14	-8	-14	4.35	.003
left superior temporal gyrus (BA 38)	-34	14	-28	3.7	.006
left uncus (BA 28)	-28	2	-30	3.68	.006

Table 1, *continued*

Parametric analysis: Correlations with Increasingly Negative Intensity Ratings, continued

left medial frontal gyrus (BA 10)	0	52	-12	3.6	.007
left cerebellum	-38	-46	-24	3.42	.01
right inferolateral frontal gyrus (BA 46)	54	34	8	3.25	.015
right inferior frontal gyrus (BA 11)	28	32	-20	3.16	.019
left anterior parahippocampal gyrus (BA 28)	-20	-24	-10	3.13	.02

Table 2

Pictures study: Reasoning time window. Brain regions identified in the stated comparisons

Contrast, Location (Brodmann area)	MNI (x,y,z) coordinates			*Z*-score	*p*-value
Reasoning – Baseline					
right occipital lobe, cuneus (BA 18)	20	-98	4	5.54	.002
left ventrolateral frontal gyrus (BA 47)	-40	28	-2	3.95	.061
left ventrolateral frontal gyrus (BA 47)	-32	26	-2	3.92	.065
Emotional reasoning – Emotional baseline					
right occipital lobe, cuneus (BA 18)	18	-98	4	5.02	.0001
right occipito-temporal lobe, fusiform gyrus (BA 18)	20	-92	-16	4.65	.012
right inferior occipital gyrus (BA 18)	46	-84	-10	4.49	.012
right midbrain, substantia nigra	8	-18	-10	3.93	.036
left posterior cingulate (BA 31)	-28	-70	18	3.9	.038
right ventrolateral frontal gyrus (BA 45)	52	20	6	3.85	.042
left cerebellum	-12	-68	-28	3.84	.043
right caudate head	16	16	4	3.56	.078
Positive reasoning – Positive baseline, *(svc) using Emotional reasoning – Emotional baseline*					
right occipital lobe, cuneus (BA 17)	20	-94	-2	4.54	.019

Table 2, *continued*

Positive reasoning – Positive baseline, (svc) using Emotional reasoning – Emotional baseline, continued					
right midbrain, red nucleus	4	-22	-12	3.7	.065
Negative reasoning – Negative baseline, (svc) using Emotional reasoning – Emotional baseline					
right occipital lobe, cuneus (BA 18)	18	-98	6	4.92	.015
right medial frontal gyrus (BA 10)	8	58	-4	4.37	.032
Neutral reasoning – Neutral baseline					
No voxels survived correction.					
Emotional reasoning – Neutral reasoning, (svc) using Emotional reasoning – Emotional baseline					
No voxels survived correction.					
Neutral reasoning – Emotional reasoning					
No voxels survived correction.					
Positive reasoning – Neutral reasoning, (svc) using Emotional reasoning – Emotional baseline					
No voxels survived correction.					
Neutral reasoning – Positive reasoning					
right inferolateral frontal gyrus (BA 46)	40	36	4	4.36	.072

Table 2, *continued*

Neutral reasoning – Positive reasoning, continued					
left anterior cingulate gyrus (BA 32, cognitive subdivision)	-20	36	2	4.28	.072
Negative reasoning – Neutral reasoning, *(svc) using Emotional reasoning – Emotional baseline*					
No voxels survived correction.					
Neutral reasoning – Negative reasoning					
No voxels survived correction.					
Positive reasoning – Negative reasoning, *(svc) using Emotional reasoning – Emotional baseline*					
No voxels survived correction.					
Negative reasoning – Positive reasoning, *(svc) using Emotional reasoning – Emotional baseline*					
left insula (BA 13)	-28	22	14	4.02	.017
[(Emotional reasoning –Emotional baseline) – (Neutral reasoning – Neutral baseline)], *(svc) using Emotional reasoning – Emotional baseline*					
left superior frontal gyrus (BA 6)	-18	2	48	3.8	.0001^{u}

Note: The superscript^{u} indicates that the *p*-value is uncorrected.

Table 2, *continued*

[(Emotional reasoning –Emotional baseline) – (Neutral reasoning – Neutral baseline)], (svc) using Emotional reasoning – Emotional baseline, continued					
right parietal lobe, postcentral gyrus (BA 2)	32	-32	34	3.74	$.0001^{u}$
right ventrolateral frontal gyrus (BA 45)	50	18	12	3.55	$.0001^{u}$
left inferior temporal gyrus (BA 38)	-46	18	-38	3.47	$.0001^{u}$
left parietal lobe, postcentral gyrus (BA 2)	-56	-18	30	3.44	$.0001^{u}$
left inferior frontal gyrus (BA 44)	-38	6	26	3.38	$.0001^{u}$
left medial frontal gyrus (BA 6)	-2	-16	48	3.37	$.0001^{u}$
left insula (BA 13)	-34	-10	24	3.2	$.001^{u}$
left middle temporal gyrus (BA 39)	-50	-70	24	3.1	$.001^{u}$
left parietal lobe, postcentral gyrus (BA 40)	-40	-26	46	3.1	$.001^{u}$
[(Neutral reasoning – Neutral baseline) – (Emotional reasoning – Emotional baseline)]					
right ventrolateral frontal gyrus (BA 47)	48	46	0	3.41	$.0001^{u}$

Note: The superscript^{u} indicates that the *p*-value is uncorrected.

Table 2, *continued*

[(Neutral reasoning – Neutral baseline) – (Emotional reasoning – Emotional baseline)], continued					
right anterior cingulate gyrus (BA 32, emotional subdivision)	14	48	0	3.23	.001^{u}
left caudate tail	-32	-30	4	3.14	.001^{u}
[(Positive reasoning – Positive baseline) – (Neutral reasoning – Neutral baseline)], (svc) using Emotional reasoning – Emotional baseline					
left middle frontal gyrus (BA 6)	-20	0	52	3.87	.0001^{u}
left superior temporal gyrus (BA 38)	-52	18	-18	3.74	.0001^{u}
left inferior temporal gyrus (BA 21)	-62	-6	-16	3.47	.0001^{u}
left superior temporal gyrus (BA 38)	-44	18	-36	3.25	.001^{u}
left frontal lobe, precentral gyrus (BA 6)	-56	0	10	3.23	.001^{u}
left middle lateral frontal gyrus (BA 46)	-46	24	22	3.2	.001^{u}
left middle lateral frontal gyrus (BA 9)	-42	28	30	3.15	.001^{u}
left middle temporal lobe (BA 21)	-58	-30	-12	3.12	.001^{u}

Note: The superscript^{u} indicates that the *p*-value is uncorrected

Table 2, *continued*

[(Neutral reasoning – Neutral baseline) – (Positive reasoning – Positive baseline)]					
right superior frontal gyrus (BA 10)	20	66	14	4.07	.0001^{u}
right inferior frontal gyrus (BA 10)	46	46	0	3.42	.0001^{u}
left superior temporal gyrus (BA 13)	-34	-28	6	3.4	.0001^{u}
right medial frontal gyrus (BA 10)	16	50	0	3.23	.001^{u}
[(Negative reasoning – Negative baseline) – (Neutral reasoning – Neutral baseline)], (svc) using Emotional reasoning – Emotional baseline					
left inferior parietal lobe (BA 40)	-56	-20	28	4.41	.0001^{u}
right ventrolateral frontal gyrus (BA 45)	52	18	12	4 19	.0001^{u}
right middle temporal gyrus (BA 39)	42	-66	18	3.77	.0001^{u}
left inferolateral frontal gyrus (BA 9)	-38	6	26	3.59	.0001^{u}
left middle frontal gyrus (BA 6)	-36	12	56	3.28	.001^{u}
left middle frontal gyrus (BA 6)	-34	12	60	3.21	.001^{u}
left parietal lobe, postcentral gyrus (BA 2)	-50	-26	56	3.22	.001^{u}
left frontal lobe, precentral gyrus (BA 4)	-36	-14	58	3.21	.001^{u}

Note: The superscript^{u} indicates that the *p*-value is uncorrected.

Table 2, *continued*

[(Negative reasoning – Negative baseline) – (Neutral reasoning – Neutral baseline)], (svc) using Emotional reasoning – Emotional baseline, continued					
left parietal lobe, postcentral gyrus (BA 40)	-42	-28	46	3.15	.001^u
left middle temporal gyrus (BA 39)	-48	-70	24	3.11	.001^u
left inferior temporal gyrus (BA 19)	-46	-54	0	3.1	.001^u
[(Neutral reasoning – Neutral baseline) – (Negative reasoning – Negative baseline)]					
No suprathreshold voxels.					
[(Positive reasoning –Positive baseline) – (Negative reasoning – Negative baseline)], (svc) using Emotional reasoning – Emotional baseline					
left inferior parietal lobe (BA 40)	-48	-36	34	3.44	.0001^u
left inferior temporal lobe (BA 20)	-62	-24	-16	3 17	.001^u
[(Negative reasoning – Negative baseline) – (Positive reasoning –Positive baseline)], (svc) using Emotional reasoning – Emotional baseline					
right middle temporal gyrus (BA 39)	40	-60	18	4.09	.0001^u
left claustrum	-24	12	20	3.74	.0001^u
right medial frontal gyrus (BA 10)	8	58	-6	3.61	.0001^u

Note: The superscript^u indicates that the *p*-value is uncorrected.

Table 2, *continued*

[(Negative reasoning – Negative baseline) – (Positive reasoning –Positive baseline)], (svc) using Emotional reasoning – Emotional baseline, continued					
left anterior cingulate (BA 32, cognitive)	-10	30	30	3.49	.0001^{u}
right occipital lobe, cuneus (BA 18)	14	-98	12	3.35	.0001^{u}
right inferior occipital lobe (BA 18)	38	-90	-2	3.31	.0001^{u}
right middle temporal lobe, fusiform gyrus (BA 37)	42	-62	-2	3.18	.001^{u}
left middle frontal gyrus (BA 6)	-36	12	56	3.18	.001^{u}
right inferior occipital lobe (BA 18)	44	-82	-6	3.18	.001^{u}
left superior frontal gyrus (BA 8)	-18	42	48	3.15	.001^{u}
Congruent reasoning – Incongruent reasoning					
right inferior lateral frontal gyrus (BA 9)	44	6	24	3.7	.062
Incongruent reasoning – Congruent reasoning					
No voxels survived correction.[f]					

Note: The superscript^{u} indicates that the *p*-value is uncorrected. [f]However, when the threshold was set to *p* = .05, there was a voxel in right ventrolateral prefrontal cortex (BA 47). MNI (*x y* z) co-ordinates: 56, 32, -10; *Z* = 1.72, *p* (uncorrected) = .043.

Success of the emotion induction. Pictures from the IAPS (Lang et al., 1997) were rated by participants on the dimensions of valence and intensity. These positive and negative emotion manipulations led to different patterns of underlying neural activations

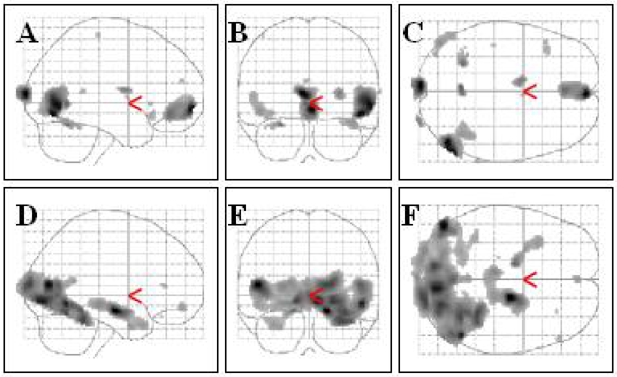

Figure 4.[14] Pictures study: Neural activations associated with increasing intensity of picture ratings. A) Positive: sagittal view,[15] B) Positive: coronal view C) Positive: axial view D) Negative: sagittal view E) Negative: coronal view F) Negative: axial view.

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[14] Specifically, figure 4 shows three views of a template brain with all the voxels that were activated in association with increasingly positive (A-C) or negative (D-F) intensity. A quick inspection of A-C (positive) and D-F (negative) reveals that the patterns of activation were dissimilar overall between these conditions.

[15] In the sagittal view, the brain template is shown along the (*y*-axis) plane from posterior (left side: back of the head) to anterior (right side: closest to the face). In the coronal view, the template is shown along the (*z*-axis) plane from inferior or ventral (bottom: closest to the neck) to superior or dorsal (top: closest to the top of the head). In the axial or horizontal view, the template is shown along the (*x*-axis) plane from left hemisphere (top: closest to left ear) to right hemisphere (bottom: closest to right ear).

(see Figure 4). As will be demonstrated below, the pattern of results are consistent with the findings of Goel and Dolan (2003b) and of Northoff et al. (2004), who found that emotional processing was associated with ventromedial prefrontal cortex whereas cognitive processing was associated with dorsolateral prefrontal cortex.

Neural activation associated with picture viewing/judging. As indicated in Table 1, there was neural activation associated with viewing and rating of emotional pictures (collapsed across valence), after subtracting activation associated with viewing and rating of non-emotional pictures; however, no voxels survived correction in the reverse contrast (Neutral-Emotion). This pattern indicates that activations associated with the emotional conditions are over and above any associated with viewing of neutral pictures.

Neural activation correlated with increasing intensity of picture ratings. Parametric (correlational) analyses were conducted to determine neural regions associated with increasingly intense positive and negative picture ratings. The results were reported above, in Table 1. However, for ease of comparison, the neural regions from each of these parametric analyses are listed as follows:

Correlations Between Ratings and Neural Activation

Positive Valence	*Negative Valence*
left cerebellum (3 voxels plus 1 trend)	left cerebellum (2 voxels)
right caudate head	
left thalamus	
left parietal lobe, postcentral gyrus (BA 1)	
right middle occipital gyrus (BA 19) (1 voxel plus 1 trend)	

Positive Valence, continued	*Negative Valence, continued*
right occipital gyrus (BA 19)	
right middle occipital gyrus (BA 18)	
left inferior occipital gyrus (BA 18) (2 voxels)	
left middle occipital gyrus (BA 19)	
right occipito-temporal lobe, fusiform (BA 20)	
	right occipito-temporal lobe, fusiform (BA 37)
left occipital lobe, cuneus (BA 18)	right occipito-temporal lobe, lingual (BA 18)
	left middle temporal gyrus (BA 39)
	right anterior parahippocampal gyrus (BA 34)
	right anterior parahippocampal gyrus (BA 35)
	left anterior parahippocampal gyrus (BA 34)
	left anterior parahippocampal gyrus (BA 28)
	left uncus (BA 28)
	left superior temporal gyrus (BA 38)
left medial frontal gyrus (BA 9)	right inferior frontal gyrus (BA 46)
left medial orbitofrontal gyrus (BA 11)	right lateral orbitofrontal gyrus (BA 11)
left ventrolateral frontal gyrus (BA 47)	
right medial frontal gyrus (BA 10)	left medial frontal gyrus (BA 10)

In posterior cortex, activations are primarily bilateral, with much involvement of the occipital lobe in positive picture viewing and much involvement of temporal lobe regions, especially the anterior parahippocampal gyrus, in negative picture viewing. In the frontal lobes, activation is primarily in the left hemisphere in positive picture viewing, and primarily in the right hemisphere in negative picture viewing; the exception is the activation in medial frontal gyrus (BA 10).

It was expected that increasingly negative intensity may be associated with activation in the amygdala, uncus, and anterior parahippocampal gyrus, as predicted by Taylor et al. (2000). This expectation was borne out; significant activation was noted in uncus and anterior parahippocampus, and the cluster extends into the amygdala (see Figure 5).[16]

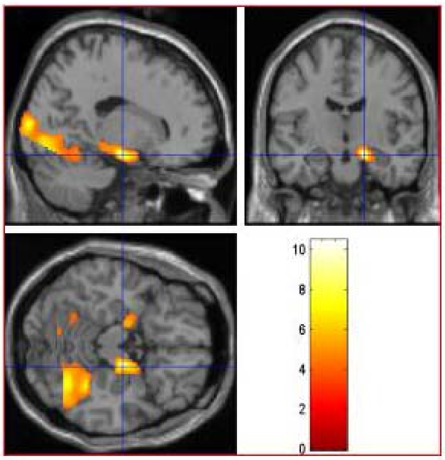

Figure 5. Pictures study: Activation in anterior parahippocampus, extending into amygdala, as picture ratings increase in negative intensity (MNI co-ordinates: 18, -12, -16, $p = .0001$, $Z = 5.32$).

Emotional intensity ratings were expected to be correlated with increased activation in ventromedial or medial prefrontal cortex but not with increased activation in dorsolateral prefrontal cortex. This expectation was borne out. Increasingly positive ratings were associated with activation in medial frontal pole (BA 10) and medial orbitofrontal cortex (BA 11); increasingly negative ratings were associated with activation in medial frontal

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[16] The cluster still extends into the amygdala when tested at a tighter threshold ($p = .0005$).

pole (BA 10) and right lateral orbitofrontal cortex (BA 11). Neither positive nor negative ratings were associated with activation in dorsolateral prefrontal cortex.

The activations associated with increasing intensity of picture ratings map onto findings that Grimm et al. (2006) reported for passive picture viewing rather than for the conditions promoting expectation of a particular valence or requiring rating of valence. In Grimm et al., increasingly positive intensity (based on unexpected minus expected passive picture viewing plus post-scan ratings) was associated with increased activation in ventromedial prefrontal cortex (by which Grimm et al. meant BA 10 and BA 11); increasingly negative intensity (on the same basis) was associated with increased activation in right amygdala.

Grimm et al. found that orbitofrontal cortex (BA 11), medial pole (BA 10), and dorsomedial prefrontal cortex (medial BA 9), were associated only with the unexpected (non-cued) passive picture viewing condition and not with the other conditions. Both the positive and the negative intensity ratings in the current study were correlated with activation in BA 10 and BA 11; also, activation in dorsomedial prefrontal cortex (medial BA 9) was reported in association with positive ratings. However, in Grimm et al., increasingly positive intensity (based on *expected* minus unexpected passive picture viewing plus post-scan ratings) was associated with increased activation in left dorsolateral prefrontal cortex; that finding was not mirrored in the pictures study. Thus, the current results, and those from Grimm et al., are consistent with the findings of Goel and Dolan (2003b) and of Northoff et al. (2004), who found that emotional processing was associated with ventromedial prefrontal cortex whereas cognitive processing was associated with dorsolateral prefrontal cortex.

It will be proposed, in the dissertation model of the interaction of reason and emotion (MIRE), that there is a neural mechanism associated with ongoing monitoring[17] of the external environment for possible perturbations and that this mechanism is the orbitofrontal cortex (OFC). This postulated role for the OFC will be argued during the general discussion, and will include evidence from the work of O'Doherty, Kringelbach, Rolls, Hornak, and Andrews (2001), Windmann et al. (2006), and others.

As well, the model will include a role for consultation of (conscious) feelings. Evidence from the literature supports the view that consultation of feelings is associated with activation in dorsomedial prefrontal cortex (medial BA 9). This region was activated when participants were rating the intensity of IAPS pictures as emotional (across valence) on the basis of the feelings (Northoff et al., 2004) or the feelings and thoughts they were having (Dolcos et al., 2004). Grimm et al. (2006) obtained activation in dorsomedial prefrontal cortex (BA 9) in only the passive viewing condition; nonetheless, they postulated the role of this region to be attention to and judgment of the intensity. Activation in this region is associated with positive intensity in the current (pictures) study. It is not associated with negative intensity; however, in that condition, activation is reported in the uncus and anterior parahippocampus extending into amygdala, suggesting that negative intensity involves different processes from positive intensity.

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[17] The dissertation model does not specify whether the signal from OFC is registered in conscious awareness. The state of existing research is inconclusive on this point.

The MIRE model also proposes a role for dual focus on the external environment as well as on feelings / thoughts, such as occurs when participants maintain a focus on the pictures while simultaneously consulting their feelings. The underlying neural region for dual focus is proposed to be the frontal pole (BA 10). Support for this view comes from research in the lab of Paul Burgess (Gilbert, Gollwitzer, Cohen, Oettingen, & Burgess, 2009; Simons, Scholvinck, Gilbert, Frith, & Burgess, 2006). They have reported that focus on the external environment (focus on external cues), while simultaneously noticing internal processing, is associated with activation in *medial* frontal pole (BA 10), whereas focus on internal processing (and with self-initiated cuing), while simultaneously noticing the external environment, is associated with activation in *lateral* frontal pole (BA 10).

Neural activation associated with the reasoning time-window. Neural activations associated with the reasoning time-window are listed in Table 2. As was explained earlier when describing the logic of analysis, the contrasts related to the hypotheses are the interaction contrasts comparing activation in each emotion condition with that in the non-emotional condition (after subtracting out baseline activations), in each direction.

Three possible patterns of results from such analyses were identified when stating the hypotheses. One possible pattern is that no voxels survive correction in either direction. A second possibility is that that the contrast favouring the (particular) emotion condition will yield voxels but that the contrast favouring the non-emotional condition will not. The third possibility is that the interaction contrasts in each direction will yield voxels; such a pattern is referred to as a crossover interaction (or a double dissociation).

The first such pattern would support the (null) hypothesis that the (particular) emotion induction has no effect on the subsequent task. This pattern is not expected, because the behavioural pattern that would support that hypothesis was not found.

The second pattern would support the alternative hypothesis (particular to the relevant emotion) that the emotion induction distracted the reasoner away from being able to engage fully in the subsequent task. The third possibility would support the relevant second set of hypotheses. That is, if the behavioural results showed an increase in logic-based reasoning after emotion induction (compared to the non-emotional condition), then a crossover interaction between the particular emotional and non-emotional condition would provide evidence that the emotion induction facilitated logic-based reasoning. If the behavioural results showed an increase in belief-based responding after emotion induction (compared to the non-emotional condition), then a crossover interaction between the particular emotional and non-emotional condition would provide evidence that the emotion induction facilitated belief-based responding.

Neuroimaging analyses reveal that a crossover interaction was found, when comparing results from the positive and non-emotional reasoning time-window. Specifically, there were activations associated with the interaction contrast [(Positive reasoning – positive baseline) – (Neutral reasoning – neutral baseline)], and (different) activations associated with the reverse contrast [(Neutral reasoning – neutral baseline) – (Positive reasoning – positive baseline)]. Earlier, it was noted that the rate of belief-based responding (to incongruent syllogisms) had increased (and the rate of logic-based reasoning had decreased) after positive emotion induction, compared to the non-emotional condition.

These neuroimaging and behavioural results provide converging evidence that belief-based responding was facilitated following a positive emotion induction.

Evidence from the behavioural literature (Bless et al., 1992; Bodenhausen, Kramer, et al., 1994; Schwarz & Clore, 1983) demonstrates that positive mood induction promotes heuristic rather than systematic cognitive processing. Schwarz and Bless (1991) suggest that a positive heuristic system can be considered adaptive in the overall context of an evolutionary account; specifically, they offer the interpretation that positive emotion is a signal that the current situation is safe and requires no action.

Positive processing compared to neutral reasoning in the relevant interaction contrast [(Positive reasoning – positive baseline) – (Neutral reasoning – neutral baseline)] was found to involve a left-hemisphere fronto-temporal lobe system (see Figure 6). As reported above (during the literature review in the general introduction), Goel et al. (2000) found that reasoning with content-based syllogisms was associated with activation in traditional language areas (a left-hemisphere temporal lobe system). The Goel (2009) model of deductive reasoning proposes that language-based reasoning, characterized as the default reasoning system, is largely belief-biased and heuristic.

Furthermore, logic-based reasoning responses to incongruent syllogisms necessarily involve detecting the conflict between beliefs and logic; Goel and Dolan (2003a) found that when participants did succeed in noticing this conflict and engaged in logical reasoning instead of being swayed by beliefs, the accompanying neural activation occurred in the right lateral/ventrolateral prefrontal cortex (BA 45, BA 46). As it happens, no voxel was reported in that neural region in association with processing during the reasoning time-window after positive emotion induction.

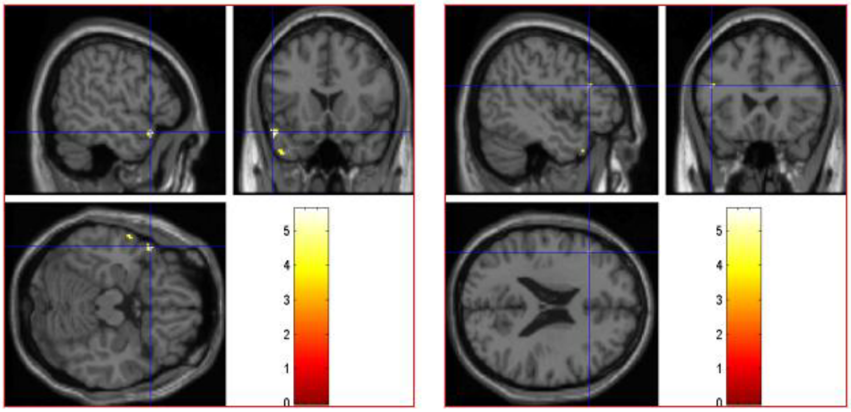

Figure 6.[18] Pictures study. Positive reasoning shows activation (left panel) in left superior temporal pole (BA 38: MNI co-ordinates -52, 18, -18, $p = .0001$ uncorrected, $Z = 3.74$), and (right panel) in left midlateral prefrontal cortex (BA 46: MNI co-ordinates -46, 24, 22, $p = .001$ uncorrected, $Z = 3.2$).

The results regarding neural activation corresponding to the reasoning time-window following negative emotion induction are presented next. The relevant analyses revealed that the contrast favouring the negative emotion condition yielded voxels but the contrast favouring the non-emotional condition did not. Specifically, although there were

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[18] MNI is the abbreviation for Montreal Neurological Institute. Locations in the brain are described in 3D co-ordinates, as the locations on the *x, y*, and *z* axis. Keeping in mind that a person is lying down in the scanner, the *x*-axis is the plane running from left (closest to left ear; *minus* values) to right (closest to right ear; *plus* values) hemisphere; the *y*-axis is the plane running from posterior (closest to the back of the head; *minus* values) to anterior (closest to face; *plus* values), and the *z*-axis is the plane running from ventral or inferior (closest to neck; *minus* values) to dorsal or superior (closest to the top of the head; *plus* values).

activations associated with [(Negative reasoning – negative baseline) – (Neutral reasoning – neutral baseline)], the reverse contrast revealed no suprathreshold voxels. Thus, reasoning in the negative condition does not involve a system that is separate from neutral reasoning; it involves neutral reasoning plus additional activations associated with the negative condition. This was the second possible pattern described above. Given that the behavioural results showed an increase in belief-based responding to incongruent syllogisms after negative emotion induction (compared to the non-emotional condition), this pattern indicates support for the (alternative) hypothesis that the negative emotion induction distracted participants away from being able to engage fully in the subsequent task.

Past studies involving a mix of negative emotions for mood induction (Blanchette, 2006; Blanchette & Richards, 2004) have reported that logical reasoning is impaired; however, when negative mood inductions are specific to a particular emotion such as sadness/depression (Alloy & Abramson, 1979; Bless et al., 1992; Bohner et al., 1992; Edwards & Weary, 1993; Schwarz & Bless, 1991), cognitive processing is found to be systematic (rather than heuristic). In the current study, negative emotion induction involved images (for example, a sobbing child, a stormy twilight scene, mutilated bodies, a gun pointed at the viewer) that would evoke various negative emotions. However, whereas this observation is worth noting, it does not provide a strong explanation of the effects of negative emotion induction in the current study. The current behavioural results, considered on their own, could suggest that logical reasoning was impaired; however, once one considers the neuroimaging pattern, one observes that neural activation after negative induction involved voxels over and above those also implicated in non-emotional reasoning. Participants were recruiting the system for non-emotional reasoning but effects from the negative induction were distracting them from fully engaging in the task.

The following account is offered as an explanation of the results. The (various) negative emotions activated systems (as proposed by LeDoux, 1996) or emotion modes (as proposed by Oatley & Johnson-Laird, 1987) for resolving the negative issue. It is not necessary to specify exactly what participants might have been thinking; perhaps they were ruminating over the consequences of the portrayed situations, perhaps they were cogitating over which intensity rating would be appropriate, or perhaps they were vividly recalling past negatively-valenced memories. However, even after the syllogism task was introduced, the issue would continue to occupy attention.

Two of the voxels associated with the negative reasoning time-window are shown in Figure 7 (for a complete list, please refer to Table 2). As mentioned above, Goel and Dolan (2003a) had associated activation in the right lateral/ventrolateral prefrontal cortex (BA 45, BA 46) with successful detection of the conflict between beliefs and logic in syllogistic reasoning. In 2009, Goel proposed that the role of the right ventrolateral prefrontal cortex in deductive reasoning is in providing a mechanism for maintaining uncertainty (that prevents a premature belief-biased response). It is interesting to note that, in the current contrast, this region is involved.[19]

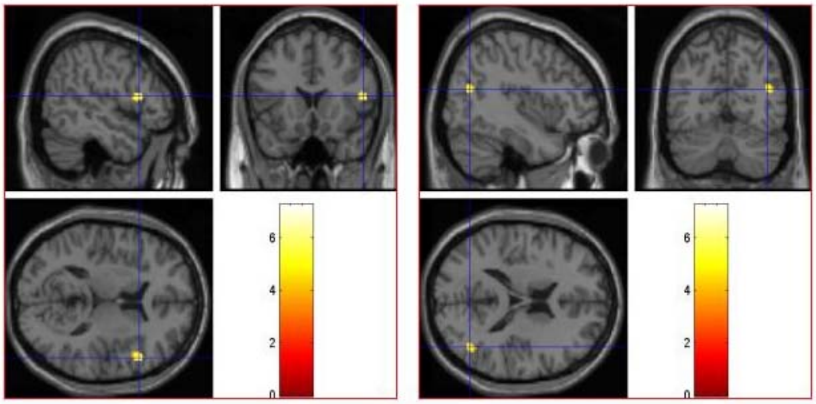

Figure 7. Pictures study. Negative reasoning shows the involvement (left panel) of right ventrolateral prefrontal cortex (BA 45: MNI co-ordinates 52, 18, 12, *p* = .0001 uncorrected, *Z* = 4.19), and (right panel) of right middle temporal gyrus (BA 39: MNI co-ordinates 42, -66, 18, *p* = .0001 uncorrected, *Z* = 3.77).

It should be noted that, when the results for the reasoning time-window were compared directly between the positive and the negative conditions, there was a crossover interaction. Specifically, the interaction contrast [(Positive reasoning – positive baseline) – (Negative reasoning – negative baseline)], and the reverse contrast, each yielded different patterns of voxels. Thus, although the behavioural responses to incongruent syllogisms were not significantly different between the two emotion conditions, the underlying neural pattern indicates that such performance cannot be

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[19] ...and a separate subregion (right BA 47) of right ventrolateral prefrontal cortex (VLPFC) is noted in the contrast [(Neutral reasoning – neutral baseline) – (Emotional reasoning – emotional baseline)], indicating that right VLPFC is indeed involved in neutral as well as in negative reasoning.

explained by the same account. Indeed, the current discussion has offered two accounts of the results. Positive emotion induction faciliates a reliance on belief-based responding whereas negative emotion induction distracts participants when they attempt to engage in logic-based reasoning.

Conclusions

In summary, the positive and negative emotion inductions were associated with neural activation patterns that are consistent with the findings of Goel and Dolan (2003b) and of Northoff et al. (2004), who found that emotional processing was associated with ventromedial prefrontal cortex whereas cognitive processing was associated with dorsolateral prefrontal cortex.

Positive emotion induction facilitates belief-based processing on a subsequent syllogistic reasoning task. This finding is consistent with the finding in the literature that positive mood induction leads to a reliance on heuristics instead of relevant facts (Bless et al., 1992; Bodenhausen, Kramer, et al., 1994; Schwarz & Clore, 1983), and with past behavioural studies reporting that logical reasoning was impaired after positive mood induction (Blanchette, 2006; Blanchette & Richards, 2004; Melton, 1995). The MIRE model will propose that the normal mode of mundane functioning relies on built up knowledge, habits, and beliefs (mental infrastructure) in the absence of perturbations from the environment, and that the positive emotion induction, being a signal that the environment is even more stable than usual, bolsters that reliance on beliefs. Positive belief-based processing is characterized as a left-lateralized fronto-temporal lobe system. Processing in the negative condition is portrayed as an attempt at (non-emotional, logic-based) reasoning that is impeded by distraction from continued rumination about unresolved issues related to the negative induction.

One of the goals of the dissertation was to determine the effect of emotion induction on a subsequently-presented syllogistic reasoning task that was, itself, non-emotional in character. The general finding is that emotion induction continues to exert its own characteristic effects on the subsequent task. The presentation of a syllogistic reasoning task, with the general instruction to determine whether the conclusion follows from the premises or not, does not register as a perturbation of a currently very stable environment. Nor is it powerful enough to be effective in interrupting ongoing processing of an unresolved negative issue.

Neuroimaging of the Effects of Sad or Angry Emotion Induction on Concurrent Syllogistic Reasoning: The Tone of Voice Study

The purpose of the tone of voice study is to determine the effect of concurrently-delivered emotion induction on syllogistic reasoning that has non-emotional content. The literature suggests that sadness and anger may have different types of influence on reasoning, and it is these two emotions that have been chosen for the emotion inductions.

LeDoux (1996) has postulated that there are separate emotion systems at the neural level, and that each serves a function. Oatley and Johnson-Laird (1996) have proposed that there are discrete neural states of readiness -- based on happiness, sadness, fear, or anger -- to respond quickly to particular survival- or goal-related events presented by the internal or external environment. In both of these models, it is clear that emotion includes the relevant underlying neurophysiological aspect; in fact, that is its primary defining feature in the LeDoux model. It was William James who said:

> If we fancy some strong emotion, and then try to abstract from our consciousness of it all the feelings of its bodily symptoms, we find we have nothing left behind, no ‘mind-stuff’ out of which the emotion can be constituted, and that a cold and neutral state of intellectual perception is all that remains (James, 1890/1950, p. 451).

In the neuroimaging literature, there is support for different patterns of neural activation associated with fear, disgust, anger, and happiness / sadness, suggesting at least partial support for a theory of separate underlying mechanisms related to different types of emotion. Fear was associated with activation of the amygdala, disgust with the insula and globus pallidus, anger with the lateral orbitofrontal cortex, and happiness/sadness with supracallosal anterior cingulate and dorsomedial prefrontal cortex (Murphy et al., 2003).

Neural activation associated with hearing the voice of an angry speaker (Sander et al., 2005) was noted in bilateral superior temporal sulcus (right BA 42, bilateral BA 22), and this activation was specific to emotion rather than to low-level acoustic features (Grandjean et al., 2005). Other activations found by Sander et al. include cuneus, left superior frontal gyrus (BA 8), right medial orbitofrontal cortex, left lateral frontal pole (BA 10), right superior temporal sulcus (BA 39), and bilateral ventrolateral prefrontal cortex (BA 47).

Neural correlates of sadness invoked by autobiographical scripts (Liotti et al., 2000) were reported in the subgenual anterior cingulate (BA 24/25), right posterior insula, and left anterior insula. Relative deactivation was noted in right dorsolateral prefrontal cortex (BA 9), bilateral inferior temporal gyrus (left BA 20, right BA 20/37), right posterior cingulate / retrosplenial cortex, and bilateral parietal lobes.

The behavioural literature provides evidence that sadness or depression promotes systematic cognitive processing, during which evaluations are based on the facts rather than on such heuristics as source expertise (Alloy & Abramson, 1979; Bless et al., 1992; Bohner et al., 1992; Edwards & Weary, 1993). In contrast, anger induction enhances heuristic rather than analytical processing (Bodenhausen, Sheppard, et al., 1994; Tiedens & Linton, 2001). Sadness induction, and not cognitive appraisal, led to attributing ambiguous events to situations beyond human control, whereas anger induction, and not cognitive appraisal, led to blaming ambiguous events on a human agent (Keltner et al., 1993). Perceived control, and not a sense of certainty, mediates the relation between optimism about the likelihood of (good or bad) future events and induced anger (Lerner & Keltner, 2001).

This fMRI study was designed collaboratively by Dr. Laura-Lee Balkwill, Dr. Oshin Vartanian, and Professor Vinod Goel. A 3 (Emotion) x 2 (Task) within-subjects factorial design was used, where the levels of the emotion factor were sad, angry, and neutral and the levels of the task factor were reasoning and baseline. Participants were required to engage in reasoning about syllogisms that were non-emotional in content; however, on each trial, the syllogism was delivered auditorially in a sad, angry, or neutral tone of voice that was unrelated to the content of the reasoning material. Thus, the reasoning stimuli were embedded in the emotion induction. An example of a syllogism is as follows: "All rabbits are fluffy. All fluffy creatures are tadpoles. All rabbits are tadpoles" (which is valid).

Hypotheses[20]

It is not clear from existing theories, such as that of Oatley and Johnson-Laird (1987), what the effect will be on syllogistic reasoning that involves subject matter that is not relevant to the concurrently activated emotion mode or system. Emotion could exert its influence by being a source of interference, in which case it could either be regulated or it could distract reasoners away from the reasoning task. Alternatively, emotion could exert its influence by being incorporated into the reasoning process.

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[20] The reader is referred to the section "A Brief Explanation of the Logic of the Data Analysis" provided prior to presenting the hypotheses in the pictures study.

The hypotheses that relate to the issue of possible interference are as follows:

1. H_0: Activation of sad emotion will be a source of interference that impairs reasoning.
   H_1: Activation of sad emotion will be a source of interference that is regulated.
2. H_0: Activation of angry emotion will be a source of interference that impairs reasoning.
   H_1: Activation of angry emotion will be a source of interference that is regulated.

Evidence will be interpreted as support for the null hypothesis if a) behavioural results indicate a greater reliance (among incongruent syllogisms)[21] on belief-based processing in the relevant emotional than in the non-emotional condition, b) there are no significant neural activations associated with non-emotional reasoning (minus baseline) after subtracting out those associated with the relevant emotion (reasoning) condition (minus baseline), and c) there is significant neural activation associated with the relevant emotion (reasoning) condition (minus baseline) after subtracting out neural activations associated with non-emotional reasoning (minus baseline). Evidence will be interpreted as support for the alternative hypothesis if there are a) no significant differences between the relevant emotion and the non-emotional condition in the behavioural results (among incongruent syllogisms), and b) the analysis of neural activations reveal a significant crossover interaction, such that i) there is significant activation associated with the

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[21] Congruent syllogisms are those in which the logic of the argument and the belief about the content would lead to the same choice of response key. The argument is valid and the content is true or at least plausible, or the argument is invalid, and the content is false or at least implausible. Incongruent syllogisms are those in which the logic and the belief lead to different responses. The argument is valid but the content is false or implausible, or the argument is invalid but the content is true or plausible.

relevant emotional reasoning condition (minus baseline) after subtracting out the activation associated with the non-emotional condition (minus baseline), and ii) there is significant activation associated with the non-emotional reasoning condition (minus baseline) after subtracting out the activation associated with the relevant emotional condition (minus baseline).

Emotion could exert its influence by being incorporated into the reasoning process. Evidence from behavioural literature suggests that sadness promotes systematic cognitive processing (Alloy & Abramson, 1979; Bless et al., 1992; Bohner et al., 1992; Edwards & Weary, 1993) whereas anger induction enhances heuristic processing (Bodenhausen, Sheppard, et al., 1994; Tiedens & Linton, 2001).

Therefore, the next set of hypotheses are as follows:

3. H_0: Activation of sad emotion will facilitate belief-based processing.
   H_1: Activation of sad emotion will facilitate logic-based reasoning.
4. H_0: Activation of angry emotion will facilitate logic-based reasoning.
   H_1: Activation of angry emotion will facilitate belief-based processing.

Evidence will be interpreted as support for belief-based processing if a) behavioural results indicate a greater reliance on belief-based processing (among incongruent syllogisms) in the relevant emotional than in the non-emotional condition, and b) the analysis of neural activations reveal a significant crossover interaction, as described above. Evidence will be interpreted as support for logic-based reasoning if a) behavioural results indicate a greater reliance on logic-based reasoning (among incongruent syllogisms) in the relevant emotional than in the non-emotional condition, and b) the analysis of neural activations reveal a significant crossover interaction, as described above.

The emotion inductions themselves are expected to be successful; that is, they are expected to yield different underlying neural patterns. Based on the findings of Sander et al. (2005), in which the "to be attended ear" activations and the main effect are relevant, anger might be associated with activation in the superior temporal sulcus, bilaterally, and with activation in left prefrontal cortex and bilateral ventrolateral prefrontal cortex. Based on Liotti et al. (2000), sadness might be associated with activation in the subgenual anterior cingulate and bilateral insula, and with relative deactivation in dorsolateral prefrontal cortex.

Method

Participants. Data were acquired from 17 participants (10 males, 7 females). Education levels ranged from partially-completed undergraduate study to completed graduate degrees, with a mean of 16 (*SD* = 2.04) years of education. Ages ranged from 20 to 38 (mean 26.5 years, *s.d.* 5.95).

All participants gave informed consent. Scanning was conducted at University College, London England in July 2004 and was supervised by Professor Vinod Goel, who obtained ethics approval from the Joint National Hospital for Neurology and Neurosurgery / Institute of Neurology Ethics Committee, prior to scanning.

Materials. Reasoning stimuli consisted of 80 syllogisms that were emotionally neutral in content. These reasoning syllogisms were balanced in terms of congruence between logic and beliefs, as follows: The arguments in 39 of these syllogisms were logically valid whereas the arguments in the remaining 41 were logically invalid. Examples of syllogisms are "All gentle pets are canines. Some kittens are gentle pets. Some kittens are canines" (which is valid), and "No beautiful people are evil. All women are evil. Some women are beautiful" (which is invalid).

The content of the concluding sentence of each argument was factually true in 39 of the syllogisms and factually false in the other 41. Thus, the arguments can be organized as follows: 17 valid / true, 22 valid / false, 22 invalid / true, and 19 invalid / false. The reasoning syllogisms are listed in Appendix B.

As well, there were 40 baseline “syllogisms”, in which the “conclusion” was a concluding sentence taken from a different syllogism, thereby ensuring that the conclusion of the baseline would be unrelated to the content of the two premises. Thus, in a baseline trial, the participant would prepare to respond to what was expected to be a syllogism; the only difference in baseline trials is that the neural activation during the conclusion would not involve reasoning. An example of a baseline trial is "Some movie-goers are men. All men are French. No people are priests." Baselines provide scans of neural activation that, during analysis, can be subtracted from the neural activation obtained during reasoning scans.

Procedure. The study involved 120 trials delivered over 3 sessions. On each trial, the participant listened to a syllogism through earphones; the task was to press a key to indicate whether the syllogism was logically valid or not valid. Each participant used one hand for both responses; choice of hand was counterbalanced among participants. When the left hand was used, the key pressed with the index finger indicated "not valid" whereas the key pressed with the middle finger indicated "valid." When the right hand was used, the key pressed with the index finger indicated "valid" whereas the key pressed with the middle finger indicated "not valid." Soundfiles varied in length from 7.4 seconds to 15.6 seconds (mean 10.74 seconds, *SD* 1.77 seconds). However, presentation of the next sound stimulus was not entrained to the preceding response but was timed to be in synchrony with the acquisition of the brain scans. Therefore, trials varied in length from 16.53 seconds to 16.74 seconds (mean 16.65 seconds, *SD* 0.024 seconds).

The design of one trial can be represented on the following timeline:

Soundfile begins Premise 1 *gap* Premise 2 *gap* Conclusion Soundfile ends End of trial

0 ~ 16.6 sec.

x ------------------------x

response occurs
during this period

Pre-recorded trials were chosen such that there were 20 neutral baseline trials, and 10 each of sad and angry baseline trials; the syllogisms were chosen so that for each cell of congruent valid, congruent invalid, incongruent valid, and incongruent invalid, there were five sad, five angry, and ten neutral trials.[22] Then all 120 trials were placed in random order. Then they were segregated into three presentation scripts, each 40 trials in length. The order of presentation of these three scripts was counterbalanced among participants, one script for each session in the scanner.

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[22] After corrections to coding during data analysis, changes to the reasoning syllogism count were as follows: Sad: congruent valid 6, congruent invalid 4, Angry congruent valid 4, congruent invalid 6, Neutral congruent valid 7, congruent invalid 9, neutral incongruent valid 12, incongruent invalid 12.

The scanning procedure was as follows. A 1.5T Siemens VISION system (Siemens, Erlangen, Germany) was used to acquire T1 anatomical volume images (1 x 1 x 1.5-mm voxels) and T2*-weighted images (64 x 64, 3 x 3-mm pixels, TE = 40 ms), obtained with a gradient echo-planar sequence using blood oxygenation level-dependent (BOLD) contrast. Echoplanar images (2-mm thick) were acquired axially every 3 mm, positioned to cover the whole brain. Each volume (scanning of the entire brain) was partitioned into 36 slices, obtained at 90 milliseconds per slice. Data were recorded during a single acquisition period. Volume (vol) images, 215 volumes per session, were acquired continuously, for a total of 645 volume images over three sessions, with a repetition time (TR) of 3.24 s/vol. The first six volumes in each session were discarded (leaving 209 volumes per session) to allow for T1 equilibration effects.

Behavioural Results and Discussion

Software. Behavioural data were analysed using SPSS, version 16.0 (SPSS Inc., Chicago, Illinois).

Data organization. In the design there were 120 trials, 80 (66.6%) involving reasoning and 40 (33.3%) baselines. Data from 15 of the original 17 participants were usable in the neuroimaging analysis; therefore, the behavioural analyses are based on 15 participants.

Examination of reaction time data revealed that one participant responded, in the third session only, before the start of the concluding sentence on all 25 reasoning and 14 of 15 baseline trials. This person's responses to baselines were all logical (as he chose "not valid" on all of them). However, his responses to the reasoning trials were close to chance

(14 of 25 correct: 56%). Therefore, it is apparent that this person was not engaged in the task in session 3, and this person's data for session 3 have been removed from all subsequent analyses of behavioural data.

There were a total of 1760 trials remaining: 1175 reasoning (66.76%) and 585 baselines (33.24%). 50% of trials were neutral; 25% were sad and 25% were angry. Thus, half of all trials were neutral and half were emotional.

Engagement with the task. Behavioural results indicate that participants were engaged in the task. Overall, the percentage of correct responses ("not valid") to baseline trials was 99.3%, and participants responded significantly more slowly to reasoning trials than to baselines (paired t (14) = -6.366, p = .001). The proportion of logical (correct) responses was significantly lower to incongruent (.5856, *SD* .154) than to congruent (.7700, *SD* .163) syllogisms (*paired t*(14) = -6.741, p = .001), and responses were significantly slower (*paired t*(14) = -5.385, p = .001) when beliefs conflicted with the logical argument (1904 ms, *SD* 583) than when they did not (1395 ms, *SD* 443). The direction of these differences in accuracy and reaction time between congruent and incongruent trials is consistent with findings in Goel and Dolan (2003a). Details of the behavioural analyses of the main effect of reasoning *versus* baseline, of the simple effect of emotion on reasoning, of the effect of congruence (collapsed across accuracy and emotion), and of mean reaction time (collapsed across accuracy) in the analysis of the Congruence x Emotion interaction, are provided in Appendix D.

Behavioural analyses related to the hypotheses. Support or lack of support for each of the four sets of hypotheses depends on converging evidence from behavioural data and neuroimaging data. As explained above, the behavioural data of interest are those indicating the rate of logic-based ("correct") responding to incongruent syllogisms. The comparison of performance in each emotion induction condition to performance in the non-emotional condition could yield three possible outcomes: there may be no significant difference, there may be an improvement in logic-based reasoning (and a decrement in belief-based responding), or there may be an improvement in belief-based responding (and a decrement in logic-based reasoning).

As set out in the hypotheses, a lack of significant difference (among incongruent syllogisms) between an emotion condition (sad or angry) and the non-emotional condition would provide partial support for the (alternative) hypothesis that the effect of the particular emotion induction (sad or angry) is a potential source of interference that is regulated; as a consequence, participants can engage in logic-based reasoning to the same extent as in the non-emotional condition. An improvement in logic-based reasoning (and a decrease in belief-based responding) in an emotion induction (sad or angry) condition compared to the non-emotional condition would provide partial support for the hypothesis that logic-based reasoning was incorporated into the particular emotion mode or system as "sad reasoning" or "angry reasoning". An improvement in belief-based responding (and a decrease in logic-based reasoning) in a particular emotion induction condition (sad or angry) compared to the non-emotional condition would provide partial support for one of two distinct hypotheses. That is, the particular emotion induction distracts the reasoner away from the concurrent syllogistic reasoning task, or belief-based processing was incorporated into the particular emotion mode or system as "sad belief-based processing" or "angry belief-based processing".

For each participant, the proportion of [logical (correct) congruent: total congruent] syllogisms was calculated within each level on the Emotion (tone of voice) factor, as was the proportion of [logical (correct) incongruent: total incongruent] syllogisms. The proportion of logical (correct):total responses was analysed for Congruence (congruent, incongruent) X Emotion (sad, neutral, angry) using a repeated-measures analysis (multivariate approach). There was no significant interaction between congruence and emotion on proportion logical:total responses. The main effect of Congruence was significant: $F(1, 14) = 36.018$, $p = .001$. The proportion of logical (correct) responses was significantly lower for incongruent syllogisms than for congruent syllogisms. 72% of the total variability in proportion of logical (correct) responses can be attributed to the congruence aspect of the syllogisms, regardless of the tone of voice. Given the hypotheses, this finding is consistent with the prediction that each of the particular emotion inductions (sad and angry) is a potential source of interference that is regulated.

Further support (still referring to the behavioural data) for the prediction of regulation of interference (as opposed to incorporation of processing into an emotion mode or system) comes from the following observations. There was a tendency for proportion logical (correct):total to differ by the tone of voice of aural delivery: $F(2, 13) = 2.848$, $p = .094$, as shown in Figure 8. Visual inspection suggests that (a) sad tone of voice did not influence the proportion of logical (correct) responses (that is, the gap in performance between congruent and incongruent trials in the sad condition was similar to the gap in the neutral condition), and (b) the proportion of logical (correct) responses was somewhat greater under the influence of angry (compared to neutral or sad) tone of voice in *each of* the congruent and incongruent conditions. In fact, there is a significant linear contrast for Emotion within the context of its interaction with Congruence: $F(1, 14) = 5.746$, $p = .031$, partial $\eta^2 = .291$. That is, the *combined* effect of specific tone of voice on congruent as well as on incongruent syllogisms is that angry tone of voice significantly increases the proportion of logical (correct) responses compared to neutral or sad tone of voice. Given that this effect is reported within the context of an interaction effect that was a trend ($p = .094$), the overall interpretation is as follows: There is a tendency for angry tone of voice to faciliate accurate responses to all syllogisms, collapsed across the Congruence factor, and this tendency accounts for 29.1% of the total variance in accurate responding to reasoning syllogisms. Thus, it would appear that (a) angry tone of voice exerts its effect on task performance in general, rather than tending to facilitate logic-based reasoning in particular, and (b) given that the behavioural results provide partial support for the hypothesis that each of the particular emotion inductions (sad and angry) is a potential source of interference that is regulated, that regulation may be more efficient in the angry than in the sad condition.

The mean proportions logical (correct):total by congruence and emotion are as follows: congruent sad .758 (*SD* .225), congruent neutral .742 (*SD* .165), congruent angry .827 (*SD* .153), incongruent sad .564 (*SD* .166), incongruent neutral .579 (*SD* .156), incongruent angry .625 (*SD* .225).

The mean reaction time to the reasoning syllogisms where the response was logical (correct) was analysed for Congruence (congruent, incongruent) X Emotion (sad, neutral, angry) using a repeated-measures analysis (multivariate approach). There was no significant interaction (*p* = .121) between congruence and emotion on mean reaction time.

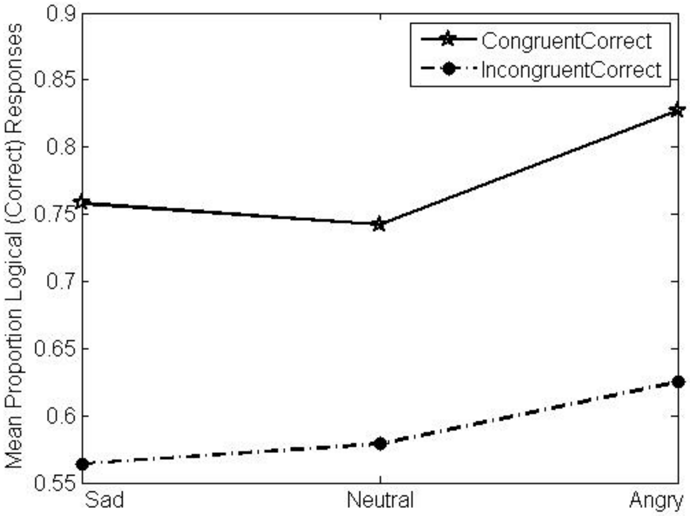

Figure 8: Tone of voice study: There is a decrease in logic-based reasoning when beliefs conflict with the logic of the argument (compared to when they do not). The rate of logic-based reasoning (among incongruent syllogisms) was not affected by emotional tone of voice, although angry tone of voice tends to improve task performance in general.

The main effect of Congruence was significant: *F*(1, 14) = 31.215, *p* = .001. The mean reaction time, when the response was logical (correct), was significantly slower to incongruent syllogisms than to congruent syllogisms (Figure 9). 69% of the total variability in mean reaction time can be attributed to the congruence aspect of the syllogisms. There was no main effect of Emotion (*p* = .513); that is, the mean reaction time, when responding logically, did not differ by tone of voice of aural delivery.

Mean reaction times (RT) when responding logically (correctly), by congruence and emotion, were as follows: congruent sad 1280 ms (*SD* 660), congruent neutral 1452 (*SD* 555), congruent angry 1364 (*SD* 456), incongruent sad 2055 (*SD* 980), incongruent neutral 1736 (*SD* 541), incongruent angry 2149 (*SD* 873).

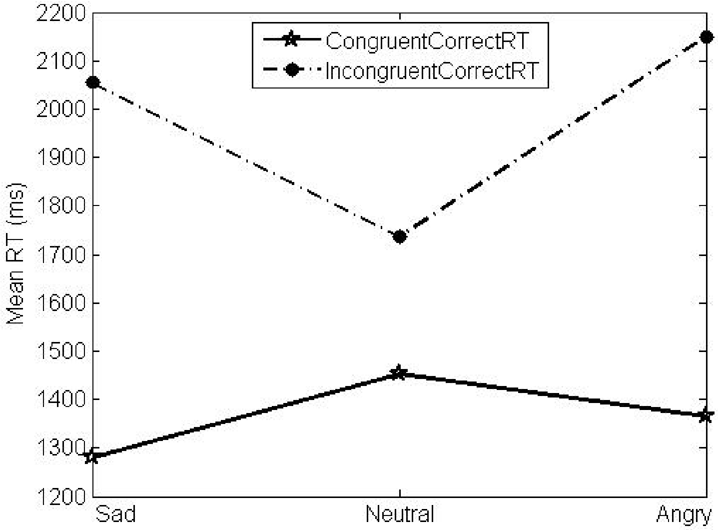

Figure 9: Tone of voice study: Mean reaction time when responding logically (correctly) is slower when beliefs conflict with the logic of the argument, regardless of tone of voice.[23]

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[23] The apparent interaction suggested in Figure 9 was washed out by wider variance in the incongruent sad and incongruent angry cells than in the other cells.

In summary, the rate of logical ("correct") responses (among incongruent syllogisms) was not significantly different among the sad, angry, and neutral conditions. The behavioural results support the hypothesis that the sad and angry tones of voice were sources of interference that were successfully regulated, with a tendency for more efficient regulation of anger than of sadness. The current study was not designed to address the possible mechanisms by which regulation occurs. The neuroimaging evidence will be presented next, after which the issue of regulation will be discussed further, in terms of possible questions for future research.

Neuroimaging Results and Discussion

Software. The functional imaging data were preprocessed and subsequently analyzed using Statistical Parametric Mapping SPM2 (Friston, *et al.*, 1994; Wellcome Department of Imaging Neuroscience; http://www.fil.ion.ucl.ac.uk/spm_spm).

Data preprocessing. All functional volumes were spatially realigned to the first volume. Participant data with head movement greater than 2 mm were discarded. All volumes were temporally realigned to the AC–PC slice, to account for different sampling times of different slices. A mean image created from the realigned volumes was coregistered with the structural T1 volume and the structural volumes spatially normalized to the Montreal Neurological Institute brain template (Evans, Collins, et al., 1993) using nonlinear basis functions (Ashburner & Friston, 1999). The derived spatial transformation was then applied to the realigned T2* volumes, which were finally spatially smoothed with a 12 mm FWHM isotropic Gaussian kernel in order to make comparisons across subjects and to permit application of random field theory for corrected statistical inference (Worsley & Friston, 1995). The resulting time series across each voxel were high-pass filtered with a cut-off of 128 s, using cosine functions to remove section-specific low frequency drifts in the BOLD signal. Global means were normalized by proportional scaling to a grand mean of 100, and the time series temporally smoothed with a canonical hemodynamic response function to swamp small temporal autocorrelations with a known filter.

Neuroimaging data analysis: general. On each trial, the participant had listened to the aural delivery of premise one, premise two, and the conclusion of the syllogism. Following this was a period of silence during which time the participant would indicate, by a keypress, whether the argument in the syllogism was valid or invalid. During neuroimaging data analysis, the emotion induction time window was defined as "listening to premise one and premise two, plus the gap following premise two." The reasoning time window was defined as "the gap from offset of the conclusion up to but not including the actual motor response." Each of these time windows was analysed separately.

Within each stimulus soundfile, the mean decibel level was calculated for the time segment corresponding to each brain scan that had being acquired. During the first level of neuroimaging analysis, described below, the potential confound of mean decibel level was covaried out.

Initially, neuroimaging data were analysed for each participant separately ("first level analysis"). The BOLD signal was modelled as a hemodynamic response function with time derivative. At the first level of analysis, condition effects were estimated at each voxel according to the general linear model.

Neuroimaging data analysis: emotion induction time window. For first-level analysis of the emotion induction window, the scans acquired while the participant was listening to "premise one and premise two plus the gap following premise two" were modelled as three conditions: sad, angry, and neutral, whereas the remaining scans were modelled without regard to emotional level (as separate conditions: conclusion, thinking, and motor response). The purpose of modelling these conditions that are outside the time window is to ensure that they are not contributing to the error term.

Onset for the sad, angry, and neutral conditions was the start of hearing premise one, whereas the duration was [the length of the syllogism *minus* the length of the conclusion]. Onset for the conclusion condition was the start of hearing the conclusion; onset for the thinking condition was the end of hearing the conclusion; and onset for the motor response was the scan being acquired at the onset time of each motor response (for each participant for each trial). Within each stimulus soundfile, the mean decibel level was calculated for the time segment corresponding to each brain scan that had being acquired. Mean decibel level for each scan was covaried out during the first level analysis.

For the model just described, there were 6 (conditions) x 3 (sessions) = 18 contrast images generated for each participant. For example, the data for the condition effects at each voxel for the condition "sad session 1" would be captured in one contrast image named Sad:Session1. There would be one "Sad:Session1" image, one "Sad:Session2" image, and one "Sad:Session3" image for each of the participants.

The second-level or group analysis involves using the first-level contrast images in a new general linear model. A one-way analysis of variance, within-subjects, was conducted with 18 conditions, with correction for non-sphericity. The analysis generates one *F* test for the effects of interest. The *F* test generated a statistical parametric map of the *F-ratio* for each voxel. The subsequent comparisons each generated a statistical parametric map of the *t*-statistic for each voxel, which was subsequently transformed to a unit normal *Z*-distribution. The activations reported below survived a voxel-level intensity threshold of $p < .001$ using a random effect model, corrected for multiple comparisons using false discovery rate (FDR, Genovese et al., 2002) or family-wise error rate. Comparisons for the emotion induction window were conducted, and results are reported in Table 3.

Table 3

Tone of voice study: Emotion induction time-window. Brain regions identified in the stated comparisons

Contrast, Location (Brodmann area)	MNI (x,y,z) coordinates			*Z*-score	*p*-value
Emotion - Neutral					
right anterior cingulate cortex (BA 24, subgenual)	6	26	2	4.6	.034
right putamen	22	12	-8	3.7	.07
left posterior parahippocampal gyrus (BA 19)	-38	-40	-6	4.1	.043
left posterior parahippocampal gyrus (BA 36)	-30	-34	-10	4.02	.048
right parietal lobe, precuneus (BA 31)	6	-48	32	3.61	.081
Neutral – Emotion					
No voxels survived correction.					
Sad-neutral, masked inclusively (at p < .05) with emotion-neutral					
left posterior parahippocampal gyrus (BA 36)	-32	-34	-12	5.56	.0001
left posterior cingulate (BA 31)	-12	-54	28	5.12	.0001
left anterior cingulate cortex (BA 24, subgenual)	-2	30	2	5.39	.0001

Table 3 *continued*

Sad-neutral, masked inclusively (at p < .05) with emotion-neutral, continued

left medial frontal gyrus (BA 10)	-8	56	4	4.69	.001
right medial frontal gyrus (BA 10)	4	54	-2	4.49	.001
right fusiform gyrus (BA 20)	42	-34	-16	4.19	.003
right inferior temporal gyrus, gray matter (BA 20)	40	-8	-24	4.17	.003
right middle temporal gyrus (BA 38)	42	2	-38	3.69	.007
right superior frontal gyrus (BA 8)	20	38	38	3.87	.005
left parietal lobe, precuneus (BA 39)	-40	-70	34	3.71	.007
right anterior cingulate gyrus (BA 24)	22	-12	38	3.56	.009
right anterior cingulate gyrus (BA 32, cognitive subdivision)	20	10	38	3.13	.021
left parietal lobe, precuneus (BA 7)	0	-78	54	3.55	.01
left insula (BA 13)	-40	6	-8	3.49	.011
left retrosplenial cortex (BA 30)	-10	-52	8	3.34	.014
left superior frontal gyrus (BA 6)	-20	8	68	3.2	.018
left posterior cingulate (BA 31)	-6	-64	16	3.2	.018
right superior temporal gyrus (BA 38)	36	20	-36	3.19	.019
right cerebellum	6	-56	-26	3.19	.019
right frontal lobe, precentral gyrus (BA 4)	26	-24	60	3.15	.02

Table 3 *continued*

Sad-neutral, masked inclusively (at p < .05) with emotion-neutral, continued					
right inferior frontal gyrus (BA 44)	52	2	20	3.1	.022
Neutral – Sad					
right superior temporal gyrus (BA 21)	62	-10	-2	8.1	.0001
right superior temporal gyrus (BA 13)	48	-20	8	5.18	.0001
left superior temporal gyrus (BA 41)	-54	-20	4	7.57	.0001
left ventrolateral frontal gyrus (BA 47)	-56	18	-2	4.26	.001
left middle temporal gyrus (BA 22)	-66	-40	4	4.12	.002
right cerebellum	34	-62	-28	4.28	.001
left cerebellum	-48	-66	-30	4.17	.001
left middle lateral frontal gyrus (BA 9)	-46	16	32	3.72	.007
left cerebellum	-22	-84	-26	3.69	.008
right cerebellum	6	-82	-26	3.25	.028
left cerebellum	-6	-84	-26	3.17	.034
left occipito-temporal (lingual) gyrus (BA 17)	-4	-94	-2	3.33	.022
right middle frontal gyrus (BA 11)	42	56	-12	3.12	.039
Angry-neutral, masked inclusively (at p < .05) with emotion-neutral					
right superior temporal gyrus (BA 22)	54	0	-4	5.87	.0001
right superior temporal gyrus (BA 22)	48	-12	-8	4.3	.001

Table 3 *continued*

Angry-neutral, masked inclusively (at p < .05) with emotion-neutral, continued					
left superior temporal gyrus (BA 22)	-46	-14	2	5.67	.0001
left frontal lobe, precentral gyrus (BA 43)	-54	-10	10	4.24	.002
right parietal lobe, postcentral gyrus (BA 40)	62	-24	14	4.85	.0001
right superior temporal gyrus (BA 22)	54	0	-4	5.87	.0001
right superior temporal gyrus (BA 22)	48	-12	-8	4.3	.001
right caudate head	14	14	0	4.17	.002
right putamen	22	10	-6	4.04	.003
left superior temporal gyrus (BA 22)	-56	-52	6	4.11	.003
left putamen	-18	6	-8	3.31	.027
Neutral – Angry					
left superior frontal gyrus (BA 6)	-24	-10	58	4.65	.001
right inferior frontal gyrus (BA 11)	22	48	-18	4.0	.035
left middle lateral frontal gyrus (BA 46)	-48	30	24	3.62	.069
right inferior frontal gyrus (BA 10)	36	58	-2	3.5	.087
right middle occipital gyrus (BA 19)	52	-72	22	3.5	.087
Sad-Angry, masked inclusively (at p < .05) with emotion-neutral					
left posterior parahippocampal gyrus (BA 36)	-34	-32	-16	4.93	.002

Table 3 *continued*

Sad-Angry, masked inclusively (at p < .05) with emotion-neutral, continued

left posterior parahippocampal gyrus (BA 19)	-36	-44	0	3.76	.005
left parietal lobe, precuneus (BA 31)	-14	-56	26	4.69	.003
left posterior cingulate (BA 31)	-18	-34	34	4.62	.003
left posterior cingulate (BA 31)	-8	-32	38	4.62	.003
right occipito-temporal (fusiform) gyrus (BA 20)	42	-34	-16	4.67	.003
left medial frontal lobe (subgenual) (BA 11)	-8	26	-8	4.62	.003
right medial frontal lobe (BA 10)	4	50	-2	4.45	.003
left medial frontal lobe (BA 10)	-8	56	6	4.15	.003
right superior frontal gyrus (BA 8)	20	38	38	4.29	.003
right occipito-temporal (fusiform) gyrus (BA 20)	38	-10	-24	4.16	.003
left parietal lobe, precuneus (BA 7)	-10	-54	54	3.92	.004
right anterior cingulate gyrus (BA 24)	22	-12	36	3.67	.006
right posterior cingulate (BA 31)	20	-40	22	3.53	.007
left parietal lobe, precuneus (BA 7)	-2	-76	56	3.44	.008
right posterior cingulate (BA 23)	8	-18	28	3.42	.009
left parietal lobe, precuneus (BA 19)	-38	-72	34	3.3	.01

Table 3 *continued*

Sad-Angry, masked inclusively (at p < .05) with emotion-neutral, continued					
left posterior cingulate (BA 31)	-6	-64	16	3.18	.013
right anterior cingulate gyrus (BA 24)	20	2	36	3.16	.013
left superior frontal gyrus (BA 6)	-20	8	68	3.12	.014
Angry-Sad, masked inclusively (at p < .05) with emotion-neutral					
right superior temporal gyrus (BA 22)	54	0	-4	6.97	.0001
right superior temporal gyrus (BA 22)	48	-12	-8	4.75	.0001
left superior temporal gyrus (BA 22)	-48	-12	0	6.94	.0001
left frontal lobe, precentral gyrus (BA 43)	-54	-10	10	4.62	.0001
right parietal lobe, postcentral gyrus (BA 40)	62	-24	14	5.58	.0001
right superior temporal gyrus (BA 22)	60	-34	10	4.61	.0001
left superior temporal gyrus (BA 22)	-56	-50	8	4.24	.0001
right caudate body	12	8	6	3.65	.004
right putamen	18	2	10	3.15	.021

Neuroimaging data analysis: reasoning time window. For first-level analysis of the reasoning window, the scans acquired while the participant was engaged in reasoning were modelled by task level (reasoning, baseline) and emotion level (sad, angry, neutral) whereas all other conditions were modelled without regard to these factors. Thus, for example, there would be separate contrast images generated for "Sad Reasoning: Session 1" and " Sad Baseline: Session 1" for each participant.

Onset for the six Emotion x Task conditions was the end of the conclusion sentence. Duration was from that moment until the individual participants' motor responses on each trial. However, on trials where there was no response, or the response occurred after the start of the next trial, the duration was set as "start of the next soundfile *minus* 200 milliseconds." On trials where participants responded during the concluding sentence (that is, on 109 of 1800 -- 6% -- of trials), the duration was set as 100 / 3240 (0.03 TR); this strategy allowed us to include the contrast image (rather than having an unbalanced design) while ensuring minimal contribution of the activations to the analysis. Onset for each premise and the conclusion was the beginning of the relevant sentence; onset of the motor response was the actual timepoint (in milliseconds) at which that response occurred. Duration of the modelled-out conditions was set to zero. Thus, altogether, 10 (conditions) x 3 (sessions) contrast images were generated for each participant. Mean decibel level for each scan was covaried out.

For the group (second-level) analysis, contrast images from the first-level analysis were entered into a model accounting for 10 conditions times 3 sessions.

Implementation of this research design in the SPM software involves choosing a one-way analysis of variance, within-subjects, with 30 conditions, with correction for non-sphericity. The analysis generates one *F* test for the effects of interest.

In SPM, any contrasts that are generated become embedded into the statistical parametric map. Therefore, before any *a priori* tests were generated, the entire folder was copied into a second folder. In one folder there were no tests contrasting sad and neutral conditions; in the other folder, there were no tests contrasting sad and angry conditions. In this way the potential problem of linear dependence was circumvented.

The *F* test and the subsequent *a priori* tests each generated a statistical parametric map of the *t*-statistic for each voxel, which was subsequently transformed to a unit normal *Z*-distribution. The activations reported below survived a voxel-level intensity threshold of $p < .001$ using a random effect model, corrected for multiple comparisons (unless otherwise indicated below) using FDR (Genovese et al., 2002) or family-wise error rate. *A priori* tests for the reasoning window were conducted; results are reported in Table 4.

Reasoning syllogisms were balanced on congruence between argument logic and believability of the content. Past studies in the Goel opus (Goel et al., 2000; Goel, Makale, et al., 2004) balanced in a likewise manner, have reported neural activation associated with incongruent – congruent reasoning, overall. Therefore, a separate analysis was conducted to examine neural activation associated with the effect of congruence. The BOLD signal was modeled as a canonical hemodynamic response function with time derivative. All events, collapsed across the emotion factor, were modeled in the design matrix, with mean decibel level as a covariate, but events of no interest (premise 1, premise 2, conclusion, "reasoning" during baseline trials, the motor response) were modelled out. The events of interest, modelled as events, were scans acquired during the reasoning time-window for congruent reasoning trials and for incongruent reasoning trials. The onset of each event of interest was the end of the conclusion sentence. *A priori* tests were conducted, and results are reported at the end of Table 4.

Table 4

Tone of voice study: Reasoning time-window. Brain regions identified in the stated comparisons

Contrast, Location (Brodmann area)	MNI (x,y,z) coordinates			*Z*-score	*p*-value
		Reasoning-Baseline			
left caudate body	-8	4	6	6.25	.0001
right ventrolateral frontal gyrus (BA 47)	32	24	-4	5.28	.0001
right caudate head	12	16	2	3.89	.01
right thalamus, pulvinar	8	-30	14	3.8	.013
left middle frontal gyrus (BA 6)	-34	-4	44	3.59	.024
left frontal lobe, precentral gyrus (BA 4)	-32	-18	42	3.26	.055
left cerebellum	-32	-60	-36	3.46	.035
right cerebellum	42	-72	-32	3.42	.038
right posterior parahippocampal gyrus (BA 19)	32	-46	0	3.33	.047
right middle frontal gyrus (BA 6)	24	6	48	3.31	.049
left occipito-temporal (lingual) gyrus	-28	-70	0	3.31	.049
left insula (BA 13)	-32	22	0	3.26	.055
left ventrolateral frontal gyrus (BA 47)	-44	20	0	3.13	.073
left inferior frontal gyrus (BA 11)	-44	36	10	3.15	.071
left ventrolateral frontal gyrus (BA 47)	-46	46	-10	3.12	.075

Table 4 *continued*

Emotional Reasoning-Emotional Baseline					
left caudate body	-8	2	6	5.71	.0001
right insula (BA 13)	32	24	-2	4.21	.006
right thalamus, pulvinar	8	-32	14	3.85	.017
left middle frontal gyrus (BA 6)	-34	-4	44	3.84	.017
left frontal lobe, precentral gyrus (BA 4)	-30	-16	40	3.17	.086
right middle frontal gyrus (BA 6)	26	6	46	3.72	.024
left cerebellum	-32	-58	-34	3.35	.06
right caudate tail	32	-28	0	3.28	.069
right posterior parahippocampal gyrus (BA 19)	30	-46	0	3.23	.077
right medial frontal gyrus (BA 9)	22	42	16	3.2	.081
left middle frontal gyrus (BA 9)	-28	16	32	3.17	.085
right cerebellum	44	-70	-32	3.12	.094
left occipital lobe, precuneus (BA 31)	-20	-56	30	3.11	.095
Sad Reasoning-Sad Baseline, *with small volume correction (svc) (Emotional Reasoning-Emotional Baseline)*					
left globus pallidus	-14	0	2	3.98	.019

Table 4 *continued*

Angry Reasoning-Angry Baseline, with svc (Emotional Reasoning-Emotional Baseline)					
left caudate head	-8	6	10	4.51	.001
right thalamus	6	-2	4	4.1	.02
right caudate body	12	4	18	3.33	.05
right thalamus, pulvinar	8	-30	14	4.13	.02
left middle frontal gyrus (BA 6)	-36	-6	42	4.13	.02
right anterior cingulate (BA 32, cognitive subdivision)	18	8	40	3.75	.028
right middle frontal gyrus (BA 8)	26	22	46	3.68	.032
right ventrolateral frontal gyrus (BA 47)	30	22	-6	3.71	.031
Neutral Reasoning-Neutral Baseline					
right ventrolateral frontal gyrus (BA 47)	32	24	-4	4.53	.054
left caudate body	-8	10	8	4.34	.008
left occipito-temporal (lingual) gyrus	-26	-72	2	3.72	.091
Emotional Reasoning- Neutral Reasoning, with svc (Emotional Reasoning-Emotional Baseline)					
no voxels survived correction					

Table 4 *continued*

Neutral Reasoning-Emotional Reasoning						
left frontal lobe, precentral gyrus	(BA 6)	-22	-14	64	4.26	.01
Sad Reasoning- Neutral Reasoning, with svc (Emotional Reasoning-Emotional Baseline)						
left caudate body		-16	0	14	3.81	.084
Neutral Reasoning-Sad Reasoning						
no voxels survived correction						
Angry Reasoning-Neutral Reasoning, with svc (Emotional Reasoning-Emotional Baseline)						
no voxels survived correction						
Neutral Reasoning-Angry Reasoning						
no voxels survived correction						
Sad Reasoning-Angry Reasoning, with svc (Emotional Reasoning-Emotional Baseline)						
left ventrolateral frontal gyrus	(BA 47)	-46	20	-10	3.85	.074
Angry Reasoning-Sad Reasoning, with svc (Emotional Reasoning-Emotional Baseline)						
no voxels survived correction						

Table 4 *continued*

[(Emotional Reasoning-Emotional Baseline) – (Neutral Reasoning-Neutral Baseline)], with svc (Emotional Reasoning-Emotional Baseline)					
right globus pallidus	20	-6	6	3.78	$.0001^{u}$
right medial frontal gyrus (BA 9)	22	44	14	3.35	$.0001^{u}$
right middle frontal gyrus (BA 6)	28	6	44	3.22	$.001^{u}$
left inferior parietal lobule (BA 40)	-60	-26	28	3.21	$.001^{u}$
right frontal lobe, precentral gyrus (BA 44)	64	12	6	3.19	$.001^{u}$
left cerebellum	-20	-40	-26	3.18	$.001^{u}$
[(Neutral Reasoning-Neutral Baseline)- (Emotional Reasoning-Emotional Baseline)]					
right middle temporal gyrus (BA 21)	66	-26	0	3.63	$.0001^{u}$
left occipito-temporal (lingual) gyrus (BA 18)	-4	-86	-12	3.58	$.0001^{u}$
right middle temporal gyrus (BA 22)	50	-42	-2	3.35	$.0001^{u}$
right parietal lobe, precuneus (BA 19)	14	-84	40	3.15	$.001^{u}$

Note. The superscript^{u} indicates that the *p*-value is uncorrected.

Table 4 *continued*

[(Sad Reasoning- SadBaseline) – (Neutral Reasoning-Neutral Baseline)], with svc (Emotional Reasoning-Emotional Baseline)					
right frontal lobe, precentral gyrus (BA 44)	64	8	6	3.72	.0001^{u}
left inferior parietal lobule (BA 40)	-64	-28	24	3.63	.0001^{u}
left superior frontal gyrus (BA 6)	-10	-14	62	3.36	.0001^{u}
right globus pallidus	22	-6	4	3.35	.0001^{u}
left putamen	-24	4	2	3.15	.001^{u}
[(Neutral Reasoning-Neutral Baseline)- (SadReasoning-SadBaseline)]					
right inferior temporal lobe (BA 37)	48	-42	-2	3.4	.0001^{u}
right parietal lobe, precuneus (BA 19)	12	-84	42	3.36	.0001^{u}
left occipito-temporal (lingual) gyrus (BA 18)	-2	-88	-10	3.12	.001^{u}
[(Angry Reasoning-Angry Baseline) – (Neutral Reasoning-Neutral Baseline)], with svc (Emotional Reasoning-Emotional Baseline)					
right middle frontal gyrus (BA 8)	26	20	46	3.87	.054
right anterior cingulate (BA 32, cognitive subdivision)	16	8	38	3.8	.0001^{u}

Note. The superscript^{u} indicates that the *p*-value is uncorrected.

Table 4 *continued*

[(Angry Reasoning-Angry Baseline) – (Neutral Reasoning-Neutral Baseline)], with svc (Emotional Reasoning-Emotional Baseline), continued					
right thalamus	14	-6	8	3.67	$.0001^{u}$
left middle frontal gyrus (BA 6)	-34	-6	42	3.3	$.0001^{u}$
[(Neutral Reasoning-Neutral Baseline)- (Angry Reasoning-Angry Baseline)]					
right superior temporal gyrus (BA 42)	62	-22	0	3.85	$.0001^{u}$
right superior temporal gyrus (BA 22)	68	-32	12	3.49	$.0001^{u}$
left superior medial frontal gyrus (BA 8)	-10	50	48	3.28	$.001^{u}$
right parietal lobe, precuneus (BA 7)	14	-62	50	3.09	$.001^{u}$
[(Sad Reasoning-SadBaseline) – (Angry Reasoning-Angry Baseline)], with svc (Emotional Reasoning-Emotional Baseline)					
left middle frontal gyrus (BA 6)	-54	2	42	3.21	$.001^{u}$
right retrosplenial cortex (BA 29)	14	-46	8	3.14	$.001^{u}$
[(Angry Reasoning-Angry Baseline)-(Sad Reasoning-SadBaseline)], with svc (Emotional Reasoning-Emotional Baseline)					
right anterior cingulate (BA 32, cognitive subdivision)	18	10	38	3.21	$.0001^{u}$

Note. The superscript^{u} indicates that the *p*-value is uncorrected.

Table 4 *continued*

Congruent reasoning – Incongruent reasoning

No voxels survived correction.

Incongruent reasoning – Congruent reasoning

No voxels survived correction.^{f}

Note. The superscript^u indicates that the *p*-value is uncorrected. ^{f}However, when the threshold was set to $p = .05$, there was a voxel in right ventrolateral prefrontal cortex (BA 45). MNI (*x y* z) co-ordinates: 52, 28, 6; $Z = 1.88$, *p* (uncorrected) = .03.

Success of the emotion induction. Neural activations associated with sadness were generally as predicted by the literature, with one important exception as will be explained below. Whereas the activation in the literature is related to an intense focus on the sad feelings themselves, the one exception in the current study points to the interpretation that reasoners were focused on learning the syllogism during the emotion induction. Neural activations associated with anger were as predicted from the literature. Figure 10 reveals that the neural patterns associated with the sad and angry emotional inductions were dissimilar.[24]

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[24] Specifically, figure 10 shows three views of a template brain with all the voxels that were activated in the sad (A-C) or angry (D-F) emotion induction time-window, after subtracting out the activations associated with the neutral time-window. A quick inspection of A-C (sad) and D-F (anger) reveals that the patterns of activation were dissimilar overall between these conditions.

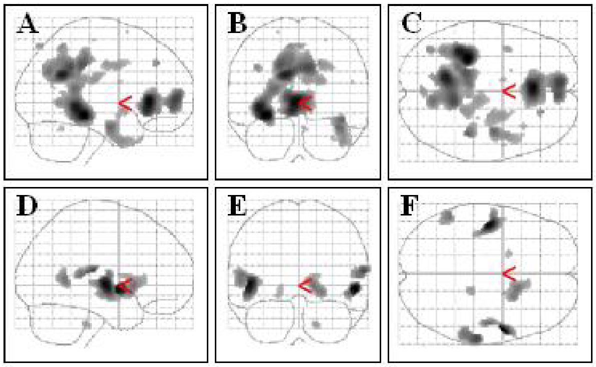

Figure 10. Tone of voice study, emotion induction time-window: Neural activations associated with [sad-neutral], masked: A) sad: sagittal view, B) sad: coronal view, C) sad: axial view, and [angry-neutral], masked: D) angry: sagittal view, E) angry: coronal view, F) angry: axial view.

Neural activation associated with the emotion induction time-window. Neural activations associated with the emotion induction time-window are listed in Table 3. In the tone of voice study, participants heard the syllogisms being delivered in sad, angry, or neutral tone of voice. The first question of interest is whether the emotion inductions themselves were successful. Evidence indicates that they were. The contrasts [Sad-neutral] and the reverse, the contrasts [Angry-neutral] and the reverse, and the contrasts [Sad-angry] and the reverse all showed different patterns of neural activation rather than indicating that there were no voxels surviving correction.

Regarding sadness, evidence from Liotti et al. (2000) suggests that activation might be expected in subgenual anterior cingulate and insula, and relative deactivation might be expected in dorsolateral prefrontal cortex. Such a pattern associated with emotion would be consistent with the findings of ventromedial prefrontal cortex in emotional processing *versus* dorsolateral prefrontal cortex for cognitive processing (Goel & Dolan, 2003b; Grimm et al., 2006; Northoff et al., 2004). In the current study, the contrast [Sad-neutral] yielded activation in subgenual anterior cingulate (BA 24, $z = 2$) and left insula, and the contrast [Sad-angry] yielded activation in subgenual medial frontal lobe (BA 11, $z = -8$). See Figure 11.

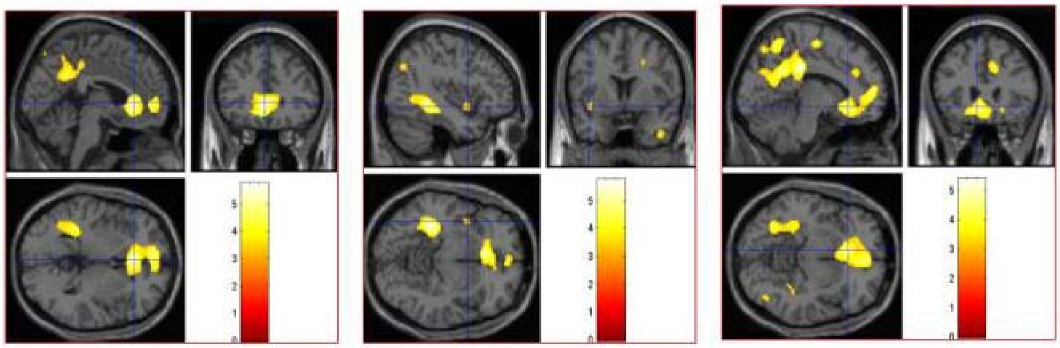

Figure 11. Tone of voice study. Sad tone of voice elicits activation in subgenual anterior cingulate (left panel: BA 24, MNI co-ordinates: -2, 30, 2; $p = .0001$, $Z = 5.39$), left insula (centre panel: MNI co-ordinates: -40, 6, -8; $p = .011$, $Z = 3.49$), and subgenual medial frontal cortex (right panel: BA 11, MNI co-ordinates: -8, 26, -8; $p = .003$, $Z = 4.62$).

However, rather than relative deactivation in dorsolateral prefrontal cortex, sad emotion induction was associated with activation, yielding voxels in right superior frontal gyrus (BA 8) and left superior frontal gyrus (BA 6), in the contrast [Sad-neutral] and also in [Sad-Angry]. See Figure 12.

Whereas participants in Liotti et al. (2000) were instructed to feel intense sadness, participants in the sad induction condition of the tone of voice study were learning the

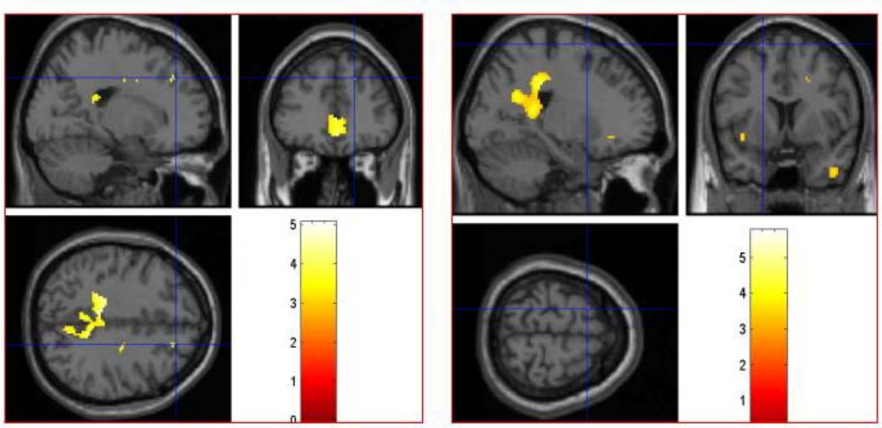

Figure 12. Tone of voice study. Sad tone of voice elicits activation in right superior frontal gyrus (left panel: right BA 8, MNI co-ordinates: 20, 38, 38; *p* = .003, *Z* = 4.29), and in left superior frontal gyrus (right panel: left BA 6, MNI co-ordinates: -20, 8, 68; *p* = .018, *Z* = 3.2).

syllogism, with no instruction particular to the tone of voice itself. Therefore, the activation in dorsolateral prefrontal cortex is not surprising; presumably these activations are related to the task, which is cognitive. That interpretation is, once again, consistent with Goel and Dolan (2003b), Northoff et al. (2004) and with the model proposed by Grimm et al. (2006).

Sadness was often found to be associated with activation in supracallosal anterior cingulate and dorsomedial prefrontal cortex, in a meta-analysis of activations associated with different emotions (Murphy et al., 2003). Dorsal (or supracallosal) anterior cingulate is often associated with monitoring of ongoing conflict (Botvinick, Cohen, & Carter, 2004). In the sadness condition of the tone of voice study, activation was noted in dorsal anterior cingulate (BA 24) in both [Sad-neutral] and in [Sad-angry], as well as in anterior cingulate (BA 32, cognitive subdivision) in [Sad-neutral]. However, activation was not noted in dorsomedial prefrontal cortex, even at a looser threshold ($p = .05$).[25]

Grimm et al. (2006) proposed that attention to and judgment of the intensity of emotion was associated with involvement of dorsomedial prefrontal cortex (not found in the sadness induction condition of the current study), whereas recall and recognition of emotional events was associated with involvement of subgenual anterior cingulate (which *was* reported in the sadness induction condition of the current study).

Thus, evidence shows that while participants were learning the syllogism, they were being affected, concurrently, by the (successful) sad induction.

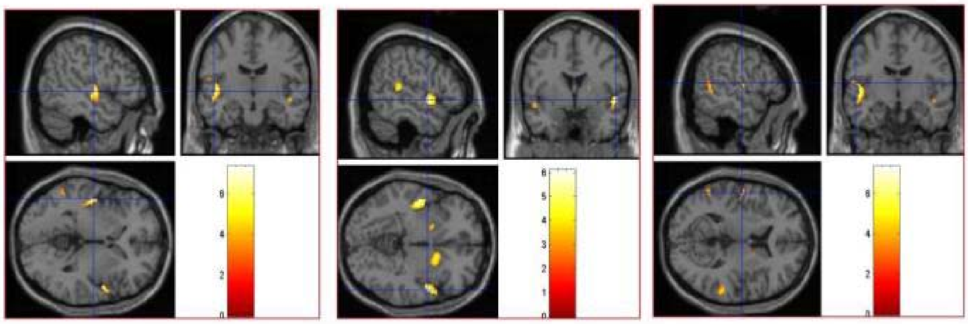

Figure 13. Tone of voice study. Activations associated with the angry tone of voice. Left panel: Left superior temporal gyrus (BA 22), MNI co-ordinates –48, -12, 0, $p = .0001$, $Z = 4.62$; middle panel: Right superior temporal gyrus (BA 22), MNI co-ordinates 54, 0, -4, $p = .0001$, $Z = 5.87$; right panel: Left frontal lobe, precentral gyrus (BA 43), MNI co-ordinates –54, -10, 10, $p = .0001$, $Z = 4.62$.

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[25] The contrasts [Sad-Neutral] and [Sad-Angry] were each tested, masked inclusively (at $p < .05$) with emotion-neutral.

For the angry condition, evidence from Sander et al. (2005) suggested that activation might be expected in bilateral superior temporal sulcus (right BA 42, bilateral BA 22), left prefrontal cortex, and bilateral ventrolateral prefrontal cortex. Each of the contrasts [Angry-neutral] and [Angry-sad] yielded activation in bilateral superior temporal gyrus (BA 22) and left frontal (precentral) gyrus (BA 43). See Figure 13. Activation was not reported in ventrolateral prefrontal cortex; however, when the contrast [Angry-neutral][26] was queried at a looser threshold (*p* = .05), there were found to be trends for activation in both right (BA 47, BA 45) and left (BA 47) ventrolateral prefrontal cortex.

Grandjean et al. (2005) demonstrated that the superior temporal lobe activation was not associated with low-level acoustical properties of the stimulus, but with the emotion itself.[27] This interpretation is consistent with the findings of Mitchell et al. (2003), who reported superior temporal lobe activation, especially in right hemisphere, associated with emotional prosody, and in left hemisphere, associated with the semantic meaning of the spoken sentences. It is also consistent with the finding that the identification of the particular emotion in prosody has been localised to bilateral superior temporal lobe (Ethofer et al., 2009).

In Sander et al. (2005), participants were instructed to identify the gender of the speaker's voice; there was no instruction related to the emotional character of the voice itself. This cognitive task was common to all conditions in that study. Similarly, in the

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[26] ... as usual, masked inclusively (at *p* < .05) with emotion-neutral. The contrast [Angry-sad] was not queried at the looser threshold.

[27] ... and mean decibel level was covaried out in the current study during the neuroimaging analysis.

tone of voice study, participants were instructed to engage in the cognitive task of learning the syllogism with no instruction related to the emotionality of the voice.

Hearing human vocal sounds, whether speech or laughter, in the background, while performing an auditory detection task, was found to be associated with activation in left anterior superior temporal gyrus (BA 22) extending into left frontal (precentral) gyrus (BA 43; Meyer, Zysset, von Cramon, & Alter, 2005). In the current study, while participants were engaged in learning the syllogism with no instruction related to the angry tone of voice, there was activation in left frontal cortex (BA 43), in the same location; that is, the activation in left BA 43 extended into left superior temporal gyrus (BA 22).

Anger was often found to be associated with activation in the lateral orbitofrontal cortex, in a meta-analysis of activations associated with different emotions (Murphy et al., 2003). This activation was not predicted by Sander et al. (2005), nor was it noted in the angry emotion induction time-window of the current study. However, there is a specific problem in the literature, involving unstandardized terminology; that is, right ventrolateral prefrontal cortex (BA 47) is often referred to as lateral orbitofrontal cortex. Sander et al. did predict the ventrolateral prefrontal cortex activation, and it did occur, sub-threshold, in the current condition.

In summary, the sad and angry tone of voice emotion inductions were successful. Sadness was associated with activations in subgenual anterior cingulate, insula, dorsolateral prefrontal cortex, dorsal anterior cingulate, as well as other neural regions. Anger was associated with activations in bilateral superior temporal gyrus and left frontal precentral gyrus, as well as other regions, and also with trends for activation (subthreshold) in bilateral ventrolateral prefrontal cortex. Thus, evidence shows that while participants were learning the syllogism, they were being affected, concurrently, by the (successful) emotion induction, whether in the sad or in the angry condition.

Neural activation associated with the reasoning time-window. Neural activations associated with the reasoning time-window are listed in Table 4. As was explained earlier when describing the logic of analysis, the contrasts related to the hypotheses are the interaction contrasts comparing activation in each emotion condition with that in the non-emotional condition (after subtracting out baseline activations), in each direction.

Two possible patterns of results from such analyses were identified when stating the hypotheses. One possibility is that that the contrast favouring the (particular) emotion condition will yield voxels but that the contrast favouring the non-emotional condition will not. The second possibility is that the interaction contrasts in each direction will yield (different) voxels; such a pattern is referred to as a crossover interaction (or a double dissociation).

The first pattern would support the (null) hypothesis (particular to the relevant emotion) that the emotion induction distracted the reasoner away from being able to engage fully in a task for which the material had been delivered concurrently with the induction. Given that the behavioural results reported above do not provide support for this hypothesis, this pattern is not expected. The second possibility would support any of the remaining hypotheses. However, given that the behavioural results indicate that neither emotion induction significantly affected the rate of logical (correct) responses (among incongruent syllogisms), compared to the neutral condition, evidence of a crossover interaction in the neural results would provide converging evidence that the emotion inductions were a source of interference but the effects were (successfully) regulated.

Neuroimaging analyses reveal that a crossover interaction was found, when comparing results from the sad and neutral reasoning time-window. Specifically, the contrast [(Sad reasoning – sad baseline) – (Neutral reasoning – neutral baseline)] yielded voxels (see Figure 14), and the reverse contrast, [(Neutral reasoning – neutral baseline) – (Sad reasoning – sad baseline)], did also. Thus, the converging behavioural and neuroimaging evidence supports the hypothesis that the sad induction was a source of interference but its effects were regulated.

The current study was not designed to probe the possible mechanisms by which regulation of sadness would be achieved; however, an interpretation that is consistent with the findings is hypothesized, as a direction for future research. First, as in all of the conditions, the task instruction itself would provide an expectation that logic-based reasoning was required. Being spoken to may promote a meta-awareness of the task environment and the instructions. Secondly, the voice quality may have registered a (neural) signal that the environment had been mildly perturbed; as a result, a mechanism for response inhibition may have been engaged to regulate the effects of the sadness. The MIRE model will propose that perturbations are associated with activation in orbito-frontal cortex (OFC), a region that was involved while the syllogism was being

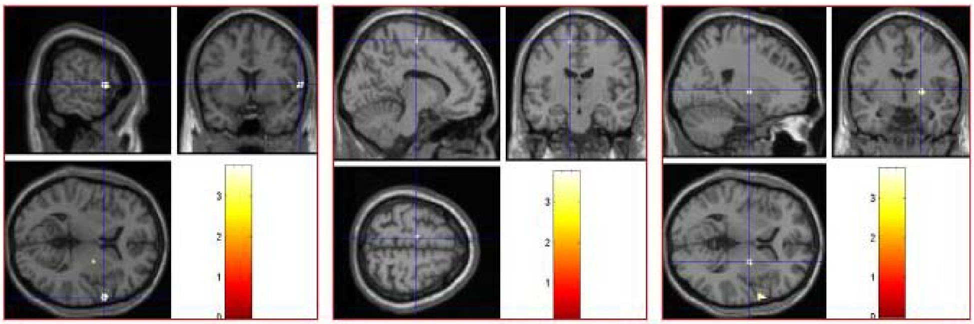

Figure 14. Tone of voice study. Reasoning in the sadness induction condition involves frontal lobe and basal ganglia. Left panel: right frontal (precentral) gyrus (BA 44; MNI co-ordinates 64, 8, 6; *p* = .0001, *Z* = 3.72). Middle panel: left superior frontal gyrus (BA 6; MNI co-ordinates -10, -14, 62; *p* = .0001, *Z* = 3.36). Right panel: right basal ganglia (globus pallidus; MNI co-ordinates 22, -6, 4; *p* = .0001, *Z* = 3.35).[28]

learned during sadness induction.[29] In a review of the literature on response inhibition, Aron, Robbins, and Poldrack (2004) identified right ventrolateral prefrontal cortex (specifically subregion BA 44) as being associated with response inhibition; as it happens, that subregion was involved during the sad emotion induction.[30] In this case, its proposed role is inhibition of the effects of the sadness; these effects are not specified but may include, for example, evocation of sad memories.

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[28] These images derive from the interaction contrast [(Sad reasoning – sad baseline) – (Neutral reasoning – neutral baseline)].

[29] See the contrast [Sad-angry] in Table 3. Left medial frontal (BA 11) is medial OFC.

[30] See Table 3, contrast [Sad-neutral]; involvement of right BA 44 is reported there.

Neuroimaging analyses reveal that a crossover interaction was found, when comparing results from the angry and neutral reasoning time-window. Specifically, the contrast [(Angry reasoning – angry baseline) – (Neutral reasoning – neutral baseline)] yielded voxels (see Figure 15), and the reverse contrast, [(Neutral reasoning – neutral baseline) – (Angry reasoning – angry baseline)], did also. Thus, the converging behavioural and neuroimaging evidence supports the hypothesis that the angry induction was a source of interference but its effects were regulated. In fact, the behavioural evidence suggests that the regulation of anger tended to be more efficient than was the regulation of sadness.

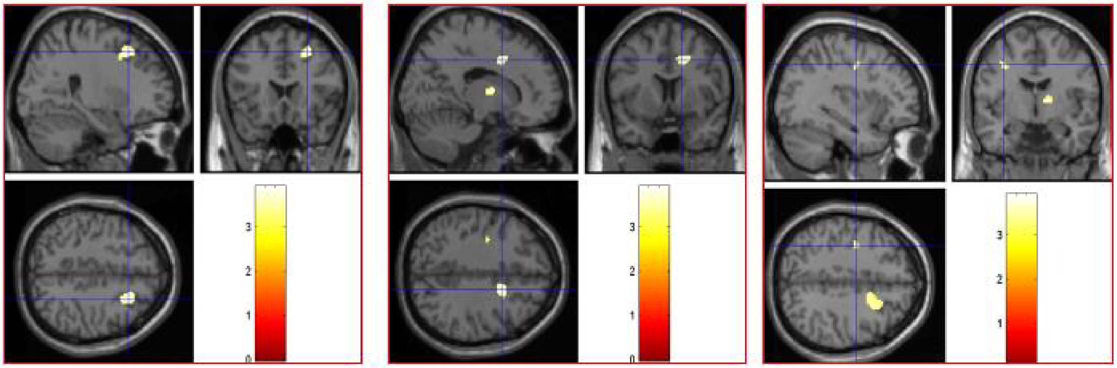

Figure 15. Tone of voice study. Reasoning in the anger induction condition. Left panel: right middle frontal gyrus (BA 8; MNI co-ordinates 26, 20, 46; p = .054, Z = 3.87). Middle panel: right anterior cingulate (BA 32, cognitive subdivision; MNI co-ordinates 16, 8, 38; p = .0001, Z = 3.8); right thalamus is also seen, below the crosshair (MNI co-ordinates 14, -6, 8; p = .0001, Z = 3.67). Right panel: left middle frontal gyrus (BA 6; MNI co-ordinates –34, -6, 42; p = .0001, Z = 3.3).[31]

To explain the results related to anger induction, an interpretation of emotion regulation that is consistent with the findings is hypothesized, once again, as a direction

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[31] See the contrast [(Angry reasoning – angry baseline) – (Neutral reasoning – Neutral baseline)].

for future research. As in all of the conditions, the task instruction itself would provide an expectation that logic-based reasoning was required. As explained above, being spoken to, and especially having the task material itself delivered vocally (that is, by another person) may promote a meta-awareness of the task environment and the instructions.

Secondly, the angry voice may have registered a (neural) signal that the environment had been strongly perturbed. The MIRE model will propose that, although logical reasoning could obviously be triggered by many possible causes, one trigger is a strong perturbation of the environment. A strong perturbation indicates that the current processing strategy must be set aside and a different strategy must be found; in the logical reasoning setting, this would be a change from belief-based processing to logic-based reasoning. The MIRE model will propose that right ventrolateral prefrontal cortex is implicated (instead of OFC) in the change of strategy after a strong perturbation. As explained earlier, Goel and Dolan (2003a) had associated activation in the right lateral/ventrolateral prefrontal cortex with successful detection of the conflict between beliefs and logic in syllogistic reasoning. In 2009, Goel proposed that the role of the right ventrolateral prefrontal cortex in deductive reasoning is in providing a mechanism for maintaining uncertainty (that prevents a premature belief-biased response). In the current tone of voice study, activation was noted in the same region, right ventrolateral prefrontal cortex (this time in the subregion BA 47), in the contrast [Angry reasoning – angry baseline] and again in the contrast [Neutral reasoning – neutral baseline].[32]

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[32] This would explain why the voxel was not found in the interaction contrast [(Angry reasoning – angry baseline) – (Neutral reasoning – neutral baseline)] or the reverse.

Thirdly, either the strong perturbation, or simply being in the presence of an angry speaker, may increase the general level of arousal in the central nervous system, and this may be reflected in activation of the thalamus.[33] Lastly, angry processing, but not sad processing, recruited a neural region, the cognitive subdivision of the anterior cingulate,[34] that has been associated with the monitoring of ongoing conflict during logical reasoning (De Neys, Vartanian, & Goel, 2008); in the current paradigm, the conflict would be that between beliefs and logic. Therefore it is proposed that the combination of these factors contributed to the regulation of the effects of anger induction, and tended to do so more efficiently than was the case in the regulation of the effects of sadness induction.

Finally, neuroimaging analyses reveal that a crossover interaction was found, when comparing results from the sad and angry reasoning time-window. Specifically, the contrast [(Sad reasoning – sad baseline) – (Angry reasoning – angry baseline)] yielded voxels, and the reverse contrast, [(Angry reasoning – angry baseline) – (Sad reasoning – sad baseline)], did also. This finding provides additional support for the view that regulation of sadness and of anger involved different processes.

Conclusion

To determine the effect of concurrently-delivered emotion induction on syllogistic reasoning that has non-emotional content, the syllogism material was delivered in sad,

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[33] See Table 4, contrast [(Angry reasoning – angry baseline) – (Neutral reasoning – neutral baseline)], and also [Angry reasoning – angry baseline], for reports of activation in the thalamus.

[34] See Table 4, contrasts [(Angry reasoning – angry baseline) – (Sad reasoning – sad baseline)], and the reverse contrast. See also the contrast [(Angry reasoning – angry baseline) – (Neutral reasoning – neutral baseline)].

angry, or neutral tone of voice. There was no instruction related to the vocal tone itself; participants were simply instructed to listen to the sentences, and use the two response keys to indicate whether the concluding statement followed (or not) from the preceding statements. Converging evidence from the behavioural and neuroimaging data indicate that concurrently-delivered auditory sad or angry emotion induction creates a potential source of interference with the task, but that this interference is successfully regulated, tending to be more efficiently regulated when the voice is angry than when it is sad. A proposal for future research is that being spoken to (that is, auditory delivery) fosters a meta-awareness of the task environment and the instructions; moreover, it is proposed that the sad voice signals a *mild* environmental perturbation that is regulated by means of inhibition of sadness effects whereas the angry voice signals a *strong* environmental perturbation, heightening attention and triggering a change of strategy from belief-based to logic-based reasoning.

General Discussion

The purpose of the dissertation is to broaden our understanding of the relation between emotion and reasoning, by studying emotion induction effects on syllogistic reasoning in particular. Previously it has been reported that when syllogism material is emotional in nature, underlying neural activation is found in bilateral medial orbitofrontal cortex; in contrast, when the material is non-emotional, underlying neural activation is found in left dorsolateral prefrontal cortex (Goel & Dolan, 2003b). Furthermore, these neural activations were found to be correlated with ratings (acquired after the scanning session) of the emotional saliency of the syllogisms; the researchers commented that the reciprocal relationship between left dorsolateral and ventromedial prefrontal cortex involvement and the saliency ratings “reflects the degree to which reasoning is ‘cold’ or ‘hot’ ” (Goel & Dolan, p. 2320).

However, it is not clear how syllogistic reasoning about a non-emotional issue might be affected if emotion that is *not related to* the reasoning issue has either already been activated or is activated concurrently with the issue being reasoned about. To investigate these questions, two neuroimaging studies were conducted. In the pictures study, positively- or negatively-valenced emotion was induced visually prior to the reasoning task. Specifically, on each trial, participants were asked to view and rate the valence and intensity of a positive, negative, or neutral picture prior to presentation of a syllogism with unrelated non-emotional content. Behavioural data showed that the rate of logic-based responding to syllogisms where beliefs about the content and the logic of the argument would lead to opposing responses, decreased significantly after either emotion induction from the level in the neutral control condition. Neuroimaging analysis revealed that when the patterns of neural activation associated with reasoning after positive induction and in the neutral control condition were compared, a crossover interaction was found; this indicates that, neurally, these conditions are characterized (at least to some extent) differently. When the patterns of neural activation associated with reasoning after negative induction and in the neutral control condition were compared, it was noted that there were activations associated with the negative condition over and above those in the neutral condition; this indicates that a similar underlying reasoning process was recruited in both conditions but that there were additional effects from the negative induction. Lastly, a crossover interaction was found when the reasoning time-window of the positive and negative induction conditions were compared with each other. Thus, different explanations must be applied to the effects of positively- and negatively-valenced emotion induction on subsequent syllogistic reasoning.

In the tone of voice study, non-emotional syllogism material was delivered auditorially in (concurrent) sad, angry, or neutral tone of voice. Participants were given no instruction related to the voice quality. Behavioural data indicated that there was no significant difference among the three conditions in the rate of logical (correct) responding to syllogisms where beliefs about the content and the logic of the argument would lead to opposing responses, although there was a tendency for a higher rate of correct responses to all reasoning trials in the angry condition. Neuroimaging analysis revealed that when the patterns of neural activation associated with reasoning in each of the emotion induction conditions and in the neutral control condition were compared, a crossover interaction was found. As well, a crossover interaction was found when the two emotion induction conditions were compared with each other. These results indicate that different underlying processes were implicated in each of the three reasoning conditions. Thus, different explanations must be applied to the apparent lack of effect of sadness and anger on concurrently-presented syllogistic reasoning.

The behavioural results of the current neuroimaging studies could be interpreted according to a model in which emotion may distract the reasoner when the content is unrelated to the emotion. In the pictures study, the rate of logic-based responding to incongruent syllogisms[35] fell from the control rate of approximately 65% to approximately 50-55% after emotion induction; here, we could say that emotion impaired logical reasoning. In the tone of voice study, the rate did not change significantly from the control to the emotion induction conditions, and we could model this as "emotion did not impair logical reasoning". We do not need the neuroimaging findings to draw these conclusions. However, as it turns out, the neuroimaging results suggest different underlying patterns of activation that suggest a more complex interpretation. In the pictures study, there is a crossover interaction associated with reasoning after positive induction but not after negative induction. In the tone of voice study, performance seemed not to be affected by the emotion inductions, yet the neural results indicated a crossover interaction showing that sadness and anger each activate different neural regions, and each emotion was regulated by different strategies, supported by different

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[35] Incongruent syllogisms are those in which beliefs about the content and the logic of the argument lead to opposing responses.

underlying mechanisms. Furthermore, why would a crossover interaction underlying concurrent vocal emotion be accompanied by a different pattern of results than a crossover interaction underlying a previous positive visual induction? A model needs to be able to incorporate these various findings in an integrated way; otherwise, there is not much point in using neuroimaging to assist in interpreting behaviour. The MIRE model to be proposed below offers a way of understanding the different effects of the positive and negative visual emotion inductions; pending further research, it provisionally accommodates the effects of sad and angry vocal emotional induction into that framework.

Taking a position that unrelated emotion distracts the reasoner away from logic-based reasoning arises from the study design: logic-based reasoning is the expected response and results would be interpreted as (not) indicating movement away from the expected response. However, there is a distinction to be made between how responses are coded within a design, and how they should be interpreted at the more general level of a model. The solution adopted in the dissertation model of the interaction of reason and emotion (MIRE) involves *not* skewing the *model* towards logic-based reasoning as the norm. The advantages of this approach are threefold: First, a model can be proposed that integrates the various results. Secondly, by relying on evidence from neuroimaging as well as from behaviour, the model can provide a structure constrained by knowledge of how the brain works. And lastly, if the model can avoid such a skew, then perhaps it can provide a basis for formulating research questions that address, not only what factors might impede logical reasoning, but also what factors might *trigger logical processing*. Such factors might not simply be the opposite of whatever factors lead people away from the use of logic.

For example, Stanovich (2009) proposes that rational (logical) thinking begins with a call to initiate cognitive decoupling from the existing belief. What factors might trigger such a call? For instance, does the angry tone of voice of (another) speaker tend to make the listener more aware of his or her own thought processes, and is it this meta-awareness that tends to promote a focus on the task instructions? If so, do humans always tend to take more care in responding when in conversation with someone who is angry? Does that depend on whether the speaker's interests are aligned with or against those of the listener? Does the angry tone of voice trigger a neural process that directly promotes the triggering of such a call? Alternatively, did attention to the *task* of learning the syllogism promote meta-awareness, including meta-awareness of the emotion, and therefore the opportunity to regulate the effect of the emotion? A balanced (as opposed to a skewed) model provides a structure in which such further research could be accommodated.

The current author has developed a model to integrate the evidence from the current neuroimaging studies with evidence from the literature into a coherent account of syllogistic reasoning, incorporating the effects of emotion. The main features of this model will be presented first, and then explained; the explanation will be followed by presentation of evidence in support of the model.

A Model of the Interaction of Reason and Emotion (MIRE)

The main features of the MIRE model are as follows:

- There is a neural mechanism supporting ongoing monitoring of the organism's external environment. The default report (a sort of "psychological homeostasis") is that the environment is unperturbed ("All is well").
- The MIRE model is a dual-mechanism model in which the dual mechanisms are belief-based and logic-based reasoning (see Figure 16 for a depiction of most components of the model in the absence of emotion). Belief-based processing, rather than logic, is the default type of processing in a unperturbed environment.
- An indication, such as a positive event, that the stability of the environment has increased encourages a greater reliance on beliefs.
- A mild or moderate perturbation of the environment is tolerated without triggering a change of strategy away from a reliance on beliefs. Nevertheless, the organism may be distracted from engaging fully in another task presented subsequently.
- A change of strategy, to logic-based reasoning, could be triggered by various means, including but not restricted to a strong perturbation of the environment.
- In an interaction with another person, who is speaking with active emotion, the emotional state of the target individual (the reasoner) is activated; nevertheless, the reasoner can regulate interference from the emotion and engage in reasoning.

- Syllogisms (that have meaningful content) will automatically activate a belief. Therefore, logic-based reasoning necessarily entails a temporary disconnection from the influence of that belief.
- A hypothesis for future research, included provisionally in the model, is that there may be more than one disconnection mechanism; that is, one type of disconnection mechanism may operate primarily as an inhibitory mechanism, another may be implicated following conflict detection, and another may operate primarily by fostering a search for novel / non-dominant / alternative models.
- A second hypothesis for future research, included provisionally in the model, is that logical reasoning is *supported by* a mechanism (the "processor") for updating and integrating the *configuration* of argument terms as reasoning proceeds.
- People can consult their (conscious) feelings. Also, people can maintain simultaneous focus on stimuli in the external environment and on their (conscious) feelings and their thinking (conscious processing strategies).
- The reasoning process (whether belief-based or logic-based) will produce a final configuration. That configuration is then mapped, by a matching device, onto the response choice ("valid" or "not valid").

Each of these features will be explained briefly, and following that, supporting evidence will be presented in a separate subsection.

Ongoing monitoring of the external environment. The human is an organism that is in constant interaction with an external environment. The organism has a neural mechanism that registers environmental perturbations; this mechanism computes whether the current situation is benign, mildly perturbed, or strongly perturbed. When the environmental signal indicates no perturbation, the organism can carry on with daily functioning.

For example, as I left campus last week, I caught the express bus that connects to the subway system. I have been using buses in this city for many years, and as I caught the bus this time, it did not occur to me (there was no perturbation) to question whether the driver has a driver's licence. I perceived the driver, wearing the standard uniform, and I proceeded to find a seat without noticing that assumption. This example could be extended to the underlying belief that there is a civic infrastructure in place that ensures that these bus drivers are qualified.

There are dual mechanisms for reasoning, and belief-based processing is the default type of processing. The MIRE model is a type of dual-mechanism model that includes, not only belief-based, but also logic-based reasoning. Accordingly, when a syllogistic reasoning task is introduced in the context of an unperturbed environment, people *can* base their responses, to some extent, on logical reasoning. In the current experimental situation, people do not receive training on logic, nor are they instructed specifically to engage in logical reasoning. However, the instruction to determine whether the conclusion follows from the information given in the premises, and if so, to choose the key indicating "valid", can by the nature of the task, trigger at least some reliance on logic-based responding. Furthermore, in the current paradigm, syllogism forms were chosen selectively from a list of 64 possible forms; Dirkstein (1978, as cited in Evans, Newstead et al., 1993) has shown that people provide logic-based responses more readily to some forms than to others, and the current experiments use forms associated with a high rate of logic-based responding.

When syllogisms (with meaningful content rather than placeholder letters) are presented, the syllogism content triggers a pre-existing belief. As already mentioned, beliefs, knowledge, and habits provide us with a mental infrastructure that permits daily functioning in unperturbed circumstances. In such unperturbed circumstances, reliance on beliefs (rather than on logic) is the default type of processing.

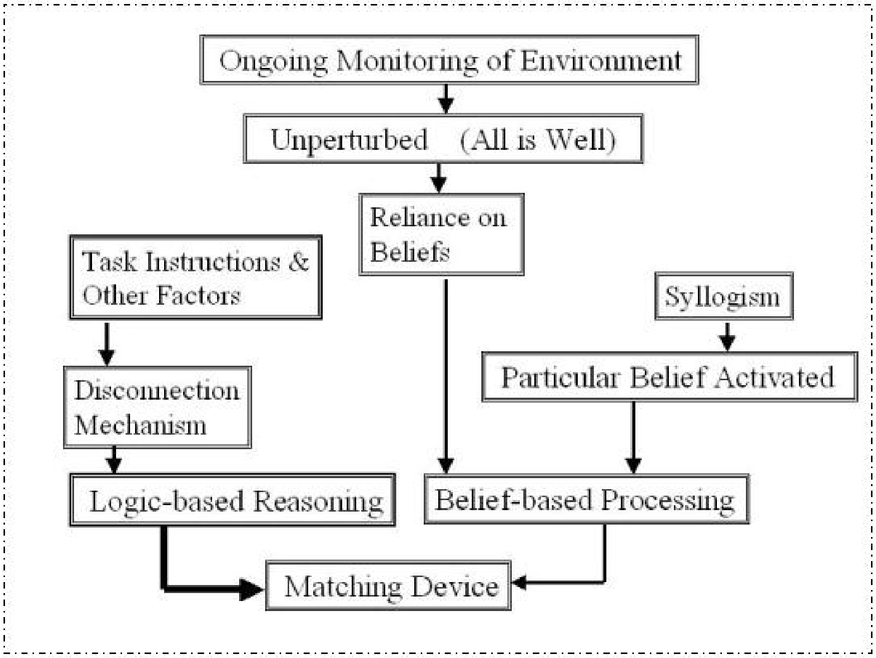

Figure 16. Basic components of the MIRE model in the absence of emotion.

A positive event signals increased stability of the environment and bolsters a reliance on beliefs. When the environment is unperturbed ("all is well"), belief-based responding is the default. This default reliance on beliefs is *bolstered* when the environment is more stable than normal ("all is pleasant").

When a syllogistic reasoning task is introduced in these circumstances, people can still base some of their responses on logic. However, given that the belief-based system has been bolstered, there is now less triggering of logic-based responding (see Figure 17).

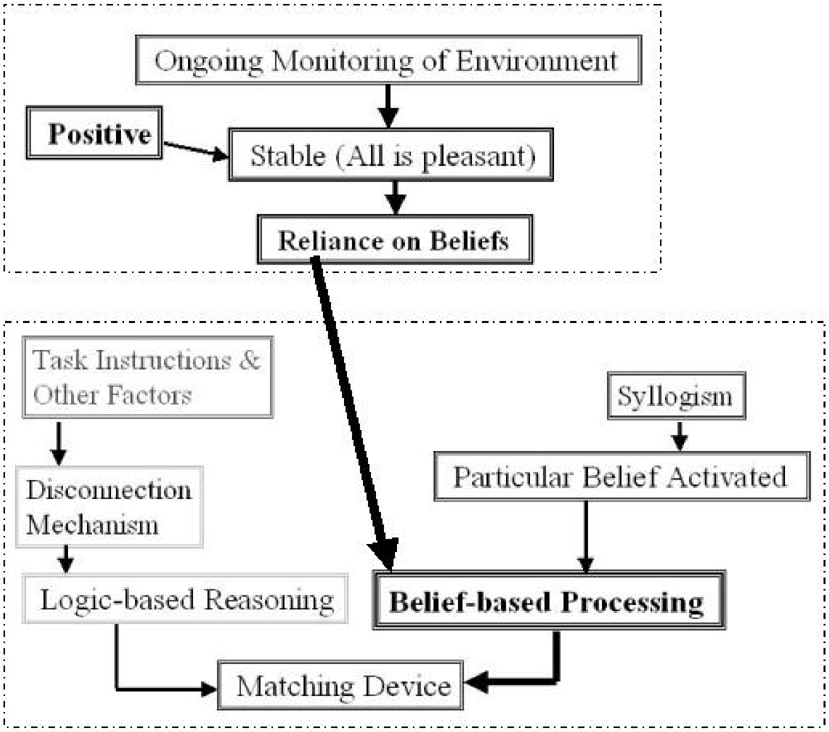

Figure 17. Basic components of the MIRE model showing the effect of positive emotion induction.

A mild or moderate perturbation of the environment does not trigger a change of strategy. A mild or moderate perturbation is not sufficient to trigger a change of strategy away from a reliance on the current belief. Perhaps it is treated as a one time occurrence (a blip) rather than as a signal that the organism's circumstances have changed. Perhaps it is tolerated, for instance as a nuisance that one can adjust to.

When a second task is introduced in these circumstances, people may be distracted by ongoing processing related to the perturbation, and therefore may not fully engage in the second task (see Figure 18).

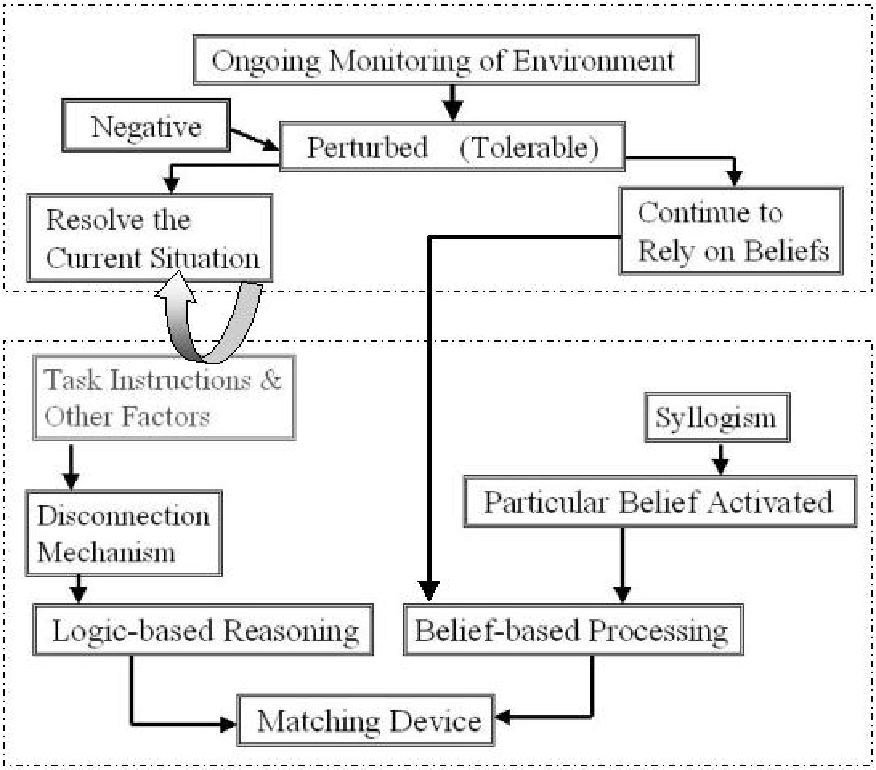

Figure 18. Basic components of the MIRE model showing the effect of negative emotion induction.

Triggering a change of strategy from belief-based to logic-based reasoning. A change of strategy could be triggered by a strong perturbation of the environment. In general, such a perturbation would signal that the current strategy is not sufficient to deal with the changed circumstances, and an alternative strategy must be found. In the syllogistic reasoning paradigm, the change of strategy would be a change from belief-based to logic-based reasoning (see Figure 19).

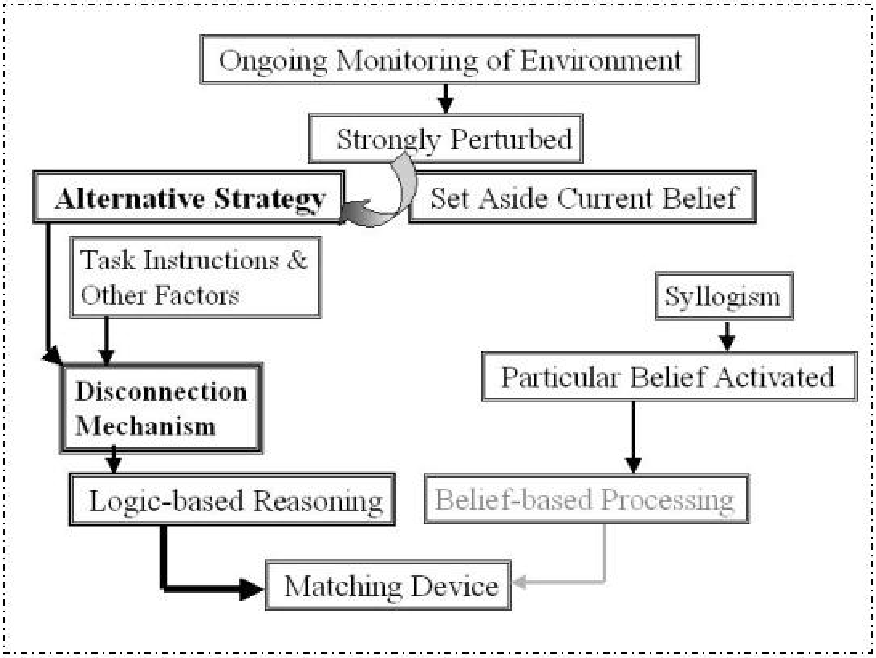

Figure 19. Basic components of the MIRE model showing the hypothesized effect of a strong perturbation of the environment.

Clearly, people can engage in logic-based reasoning in the absence of a strong perturbation of the environment; thus, there must be other mechanisms that could lead to a change of strategy. Three possibilities are suggested here, but there could be others as well. For example, a person may have explicit knowledge about using logic; however, it should be noted that, in experimental paradigms, participants are recruited from the general population, and are not provided with logic training. Secondly, the implicit task demand (as described above) may encourage people to search for a non-dominant or alternative strategy. Thirdly, a change of strategy may be triggered by noticing some incongruous feature or detail in the material being reasoned about; for instance, if a person notices the conflict between beliefs and logic in an incongruent syllogism, (s)he may engage in logic-based reasoning.

Regulating interference from another person's emotion. There are real situations in which someone is expressing emotion and the reasoner realizes that the emotion is not directed at the reasoner personally, or the reasoner needs to regulate his or her own emotion and focus on what needs to be done. Parents may have to help a crying child at the supermarket; psychotherapists need to guide clients who have become visibly upset. The reasoner might be listening to important information over the public address system in the subway and the announcer's voice might be conveying emotion. An employee might be called in to the manager, who is habitually emotional and directs this at the employee directly, but the employee can regulate the emotion's effect on him- or herself (see Figure 20).

Sadness and anger were induced concurrently with the syllogism task in the current tone of voice study. Oatley and Johnson-Laird (1987) proposed that there are discrete emotion modes; LeDoux (1996) proposed that there are separate neural emotion systems. The finding that sadness and anger were associated with different underlying neural activations is consistent with these models. In each condition, the effect of the emotion was regulated. As a result, in each condition, the rate of logical responding did not differ significantly from the non-emotional condition. Anger regulation tended to be more efficient than was regulation of sadness. This is demonstrated by the tendency for a higher rate of correct responses to all syllogisms, whether the logic and beliefs were congruent or incongruent, after anger induction than after either sadness or non-emotional tone of voice.

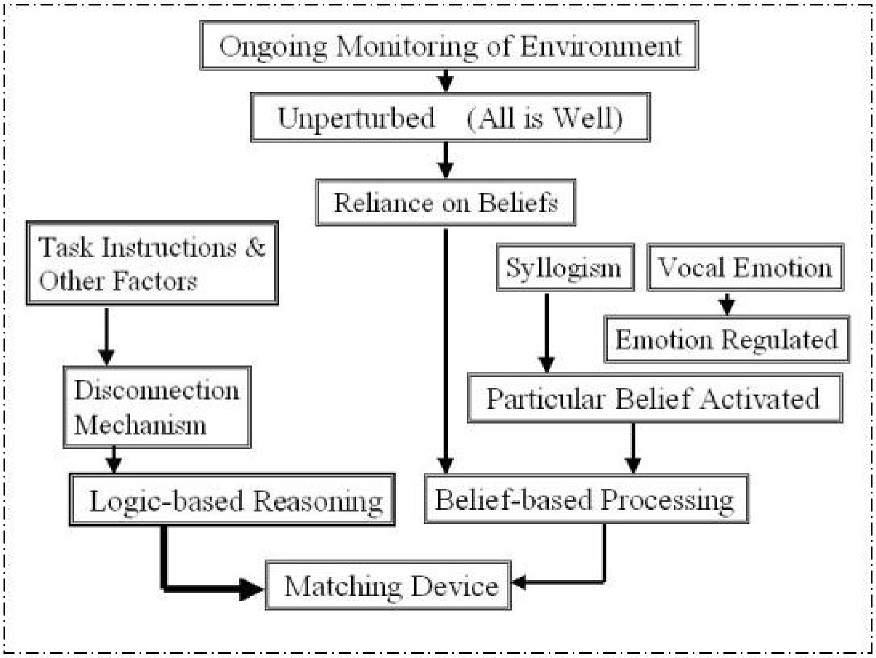

Figure 20. Basic components of the MIRE model showing the effect of vocal concurrent emotion induction.[36]

Responding to congruent syllogisms.[37] When the syllogism argument and the truth or falsity of the concluding statement are congruent, it is not possible to determine whether people were relying on belief-based processing or on logic-based reasoning.

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[36] Future research may show that sad voice signals a mild environmental perturbation, and that angry voice signals a strong perturbation. These predictions are presented in the discussion of the tone of voice study results.

[37] The reader is reminded that the evidence in support of the model is presented (p. 170-191) after the model has been explained; the evidence relating in particular to the theme of interaction with the external environment is presented on pp. 174-183.

However, the dissertation argues that belief-based processing is the default, and moreover, there could be many factors that may trigger logic-based reasoning.

An examination of the accuracy rate when responding to congruent syllogisms in the pictures study shows that accuracy in the positive condition did not differ from the rate in the neutral congruent condition. Following a positive induction, it is less likely that logic-based reasoning would be triggered; there is no reason to expect that logic was triggered any more in the positive than in the neutral condition.

In the negative condition, the perturbation from the negative pictures has not been strong enough to discard a reliance on beliefs; however, the negative material itself is the focus of ongoing processing even after the hypothetical situation (the syllogism) is subsequently presented. People are distracted by resolving some issue related to the negative pictures (see p. 104); this impedes the triggering of logic-based reasoning that one might expect from the conflict between beliefs and logic. In the congruent condition, logic-based reasoning may not have been triggered by any cause, just as it may not have been in the neutral condition. In the incongruent condition, ongoing distraction in the negative condition impedes noticing the belief/logic conflict that triggered logic-based reasoning in the neutral condition.

In the tone of voice study, the evidence shows that people succeeded in regulating the effects of emotional interference; this would be the case regardless of whether there was a conflict between logic and beliefs or not. In fact, it was shown that angry tone of voice tends to increase that efficiency, and this was observed in relation to the congruent and the incongruent conditions, in combination.

Logical reasoning entails a disconnection from the influence of beliefs. As previously mentioned, when a person encounters a syllogism (that has meaningful content), a belief will automatically be activated. Logic-based reasoning necessarily entails a temporary disconnection from the influence of that belief.

There may be more than one disconnection mechanism. As mentioned, a hypothesis presented for future research is that there may be more than one disconnection mechanism; that is, one type of disconnection mechanism may operate primarily as an inhibitory mechanism, another may be involved following conflict detection, and another may operate primarily by fostering a search for novel / non-dominant / alternative models.

A hypothesized role for a "processor" in logic-based reasoning. A second hypothesis presented for future research is that logical reasoning is *supported by* a mechanism (the "processor") for updating and integrating the *configuration* of argument terms as reasoning proceeds. A simple analogy is invoked to explain this: A baker makes a cake, using an equation (recipe) to determine which ingredients to include, and their parameter weights, and may recruit one or more preparation strategies (such as chopping, mixing, and dissolving), depending on the particular equation. However, the cake must go into the oven. The oven is a (crude) metaphor for the "processor".

Consultation of feelings, and simultaneous focus on external objects / internal feelings and thoughts. We can monitor our feelings and thoughts (which are conscious by definition). As well, there are situations in which we are simultaneously aware of some event/object in the external environment and our (conscious) feelings/thoughts in relation to that external stimulus.

The matching device. As mentioned above, the reasoning process (whether belief-based or logic-based) will produce a final configuration. That configuration is then mapped, by a matching device, onto the response choice ("valid" or "not valid").

Evidence in support of the model. Evidence in support of the MIRE model is organized according to four themes:

- Dual mechanisms: People can engage in logic-based reasoning. However, belief-based processing is the default. Logic-based processing requires disconnection from the influence of the belief. There is a matching device that maps the outcome of either type of processing onto the choice of response key.
- Interaction with the environment: There is a mechanism supporting ongoing monitoring of the *external* environment. A lack of perturbation is an indication that all is well and no change of strategy from belief-based processing is necessary. A mild or moderate perturbation is tolerated without a change in strategy. A strong perturbation triggers a change of strategy to logic-based reasoning. An indication, such as a positive event, that the stability of the environment has increased encourages greater reliance on beliefs. Regarding the monitoring of the *internal* environment, the model includes a role for consulting one's (conscious) feelings and thoughts, and for maintaining simultaneous focus on external stimuli and internal (conscious) feelings and processing strategies.

- Personal interactions: Interaction with an emotional person will activate the same emotion in the reasoner, who can regulate his or her own emotion and engage in reasoning.
- Hypotheses for future research: The first hypothesis proposed for future research is that there is a neural processor that supports logic-based reasoning. The second hypothesis is that the disconnection mechanism may be comprised of subregions with dissociable functions.

Evidence supporting the theme of dual mechanisms. The MIRE model proposes dual mechanisms, belief-based and logic-based, that may be recruited in syllogistic reasoning. This is by no means the first model to propose dual mechanisms. Epstein (1994) proposed that information processing in general could be carried out by means of an experiential system or an analytical system. Stanovich (2009) has proposed one type of information processing system (System 2) for rational thought, and another (System 1) to account for relatively automatic processes such as heuristics and biases. Goel et al. (2000) proposed that syllogistic reasoning involves a language-based associative system based in left hemisphere, when reasoning about syllogisms with meaningful content, and a separate, visuo-spatial reasoning system based in right hemisphere, when reasoning about abstract material (that is, about material with no meaningful content, such as syllogisms involving placeholder letters).

The MIRE model proposes that belief-based processing is the default processing mechanism. In syllogistic reasoning, there is a robust belief-bias effect (Evans, 2003; Goel & Dolan, 2003a). For example, in a behavioural reasoning study, syllogisms with meaningful content (as opposed to letters) were presented in 64 different configurations based on different quantifiers (such as "All" or "Some") and order of argument terms (based on subject and predicate of conclusion, and the third or middle term).

> Overall, just 52% of the responses were logically correct. Since subjects had...five responses to choose from, one would expect them to be correct 20% of the time purely by chance. One of the main themes in research has been an attempt to explain why people do so badly (Dirkstein, 1978, as cited in Evans, Newstead et al., 1993, p. 215).

In the current neuroimaging studies, the proportion of logical ("correct") responses to incongruent syllogisms in the non-emotional condition was 65.9% in the pictures study and 57.9% in the tone of voice study. These rates would suggest that the default response was logic-based; however, the syllogism forms themselves had been selected deliberately to include only those forms on which people's responses were logic-based in the Dirkstein study cited above. As well, there would have been an implicit task demand to engage in logic-based reasoning.

Beliefs might be congruent with facts, but not necessarily. Gazzaniga (2000) postulated that healthy normal individuals have "a propensity to try to find patterns in sequences of events, even when told the sequences are random" (Gazzaniga, p. 1316); this was discovered in work with split-brain patients, and the propensity is a characteristic of left but not right hemisphere processing.

The model proposes that logic-based reasoning requires disconnection from the influence of the belief. Stanovich (2009) proposes that a key aspect of hypothetical reasoning is that it provides the cognitive decoupling of a representation from its real-world application so that it can be manipulated in imagination without being permanently changed; Stanovich also states that cognitive decoupling is computationally expensive. Goel and Dolan (2003a) have demonstrated that when reasoners fail to detect an incongruence between beliefs and logic (or are unable to set beliefs aside), neural activation occurs in ventromedial prefrontal cortex (BA 11, BA 32); however, when they do succeed in noticing this conflict and engage logical reasoning instead of being swayed by beliefs, the accompanying neural activation occurs in the right lateral/ventrolateral prefrontal cortex (BA 45, BA 46). On this basis, Goel (2009) has proposed that logical reasoning necessarily involves an "uncertainty maintenance mechanism" (to prevent premature responding on the basis of beliefs), with the underlying neural mechanism being right ventrolateral prefrontal cortex.

Stanovich also proposes that there is a separate mechanism that "sends out a call to begin... hypothetical reasoning" (Stanovich, 2009, p. 61). The MIRE model does not propose any specific "call" mechanism, as disconnection could occur as the result of many circumstances.

The model proposes a matching device that maps the output of the reasoning process onto the response options. Using a memory paradigm, Badre and Wagner (2007) demonstrated that the left ventrolateral prefrontal cortex (VLPFC, specifically left BA 47) is activated when only a single representation has been retrieved from memory to base a response on, whereas left VLPFC (left BA 45) is activated when there are two or more such representations that have been triggered and the competition between them must be resolved. The paradigm was not a deductive reasoning paradigm. However, the finding supports the postulate that there is a matching device.

Evidence supporting the theme of interaction with the environment. The model proposes that there are neural mechanisms supporting ongoing monitoring of the external environment.

> A certain amount of processing must go on continuously, or almost continuously, to enable the system to *notice* when conditions have arisen that require ongoing programs to be interrupted. The noticing processes will be substantially in parallel with the ongoing goal-attaining program of the total system (Simon, 1967, p. 34).

A lack of perturbation is an indication that all is well and no change of strategy from belief-based processing is necessary. A mild or moderate perturbation is tolerated without a change in strategy. A strong perturbation triggers a change of strategy to logic-based reasoning.

Converging evidence supports the view that the neural region implicated in registering that the external environment is stable, or only mildly or moderately unstable but tolerable, is the orbitofrontal cortex (OFC).[38] The OFC produces a summed signal based on accumulation of activity of neurons in medial and lateral OFC (Hikosaka & Watanabe, 2000). The prevalent characterization of OFC signalling as being related to reward *versus*

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[38] The use of unstandardized terminology in the literature when referring to lateral orbitofrontal cortex (OFC) and right ventrolateral prefrontal cortex (VLPFC) may have led to misunderstanding about the role of the right VLPFC. This section will use a consistent terminology distinguishing between lateral OFC and right VLPFC. Readers who read the cited articles are advised to be aware of this terminology issue.

punishment (for example, Bechara, Damasio, & Damasio, 2000) is insufficient, as has been demonstrated by O'Doherty et al. (2001) and by Windmann et al. (2006).

The evidence from O'Doherty et al. (2001) demonstrates that right VLPFC is recruited when the current stimulus-contingency situation needs to be re-interpreted, but otherwise the signal emanates from OFC. While the reward value of a stimulus is being learned, rewards are associated with a signal in medial OFC, and small losses are associated with a signal in right lateral OFC; large losses during learning do *not* produce an OFC signal but are associated with activation in right ventrolateral prefrontal cortex (VLPFC, BA 44/45) instead. After the learning phase, a small loss when a large reward was expected is associated with a signal in right lateral OFC. A reward will not register a signal in OFC if the organism was expecting a much larger reward than was delivered; instead, such a contingency is once again associated with activation in right VLPFC (BA 44/45).

The work of Windmann et al. (2006) provides more conclusive support for the view that right VLPFC is recruited when the current strategy needs to be replaced. They found that rewards received in the context of ongoing reward/occasional losses were associated with signal in medial OFC, whereas rewards received in the context of ongoing loss were associated with activation in bilateral VLPFC (BA 47). Losses received in the context of ongoing reward were associated with activation in bilateral VLPFC (BA 47) whereas losses in the context of ongoing loss yielded no voxels surviving correction. The researchers' interpretation is that right VLPFC is recruited when the contingencies between stimulus and outcome are unstable. Furthermore, Windmann et al. discuss the role of right VLPFC in terms of risk seeking, an interpretation that would imply that this region could be recruited not only as a reaction to environmental perturbation but also in the context of a proactive intention by the organism.

OFC-lesioned patients, such as the well-known case of Phineas Gage, demonstrate socially inappropriate behaviours and have difficulty making decisions despite retaining normal functioning as assessed on other cognitive tests (Stuss, Gow, & Hetherington, 1992). Bechara et al. (2000) propose that the OFC plays an important role in implicating emotion in the decision-making process; their model (Damasio, 1994) has been influential in the field of emotion research, and is mentioned for that reason. Other laboratories have had difficulties in using their paradigm (the Iowa Gambling Task, or IGT) successfully with healthy participants (for examples, see Lawrence, Jollant, O'Daly, Zelaya, & Phillips, 2009; Lin, Chiu, Cheng, & Hsieh, 2008), whereas research with OFC-lesioned patients (Fellows & Farah, 2005; Manes et al., 2002) has challenged their model. However, when the terminology confusion is taken into account, these lesion-study findings can be interpreted as converging evidence supporting the view taken by the current dissertation model. This will be demonstrated next.

Fellows and Farah (2005) proposed that the deficit in OFC-lesioned patients is a deficit in reversal learning, rather than a deficit in decision-making *per se*; specifically they proposed that in the IGT (which is a stimulus-contingency paradigm involving four card decks), participants initially learn that the decks are rewarding and the patients cannot reverse that learning when unexpected losses occur later on. Fellows and Farah tested this by modifying the IGT so that all four decks produced initial losses. They found that OFC patients played advantageously on the modified version. As well, in the original version of the IGT, six of the nine patients made advantageous choices at a level greater than chance. Fellows and Farah concluded that their own hypothesis was supported; however, this conclusion may be premature. One notes that, as a group, the performance of OFC patients lagged 10% behind that of controls on both versions of the task. Moreover, there is an unexplained large improvement in performance, among both controls and patients, between playing the original and the modified version, and this cannot be explained as learning transfer, as the two versions were played between-subjects in the control-group condition.

Given the accumulated evidence, the dissertation offers the following interpretation of the findings reported by Fellows and Farah (2005): Participants draw cards from each of four decks and *invariably* incur a loss. This circumstance would not activate an OFC-driven system at all, but instead would activate a right-VLPFC system for re-interpreting the stimulus-contingency association. One notes that the OFC lesions[39] in Fellows and Farah mostly spare the right VLPFC, especially the posterior aspect (that is, sparing in BA 45, BA 44 but not necessarily in BA 47). Note that in O'Doherty et al. (2001), the neural region that sprang into action after an unexpected large loss was right VLPFC, specifically BA 44/45. This interpretation suggests that OFC-lesioned patients were able to perform the modified IGT (Fellows & Farah) because that task did not require recruitment of the OFC. Instead, the emotional experience of sudden loss recruited right VLPFC from the outset.

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[39] ...illustrated in radiologic convention: left side of image is right hemisphere (Fellows & Farah, 2005, p. 59, Figure 1a).

Manes et al. (2002) hypothesized that impaired performance by OFC-lesioned patients on the IGT could arise from impairments in one or more subcomponent processes including working memory, "reduced deliberation, poor learning of outcome probabilities, genuine preference for risky outcomes, and deficits in strategy acquisition and maintenance" (Manes et al., p. 625). Using the IGT and various other measures, Manes et al. tested patients with lesions restricted to OFC or to various other regions of prefrontal cortex. Contrary to what would be predicted from the work of Bechara et al. (2000), OFC patients' performance on IGT was comparable to that of normal controls. Their sole deficit was that they deliberated significantly longer before making decisions than did any other lesion group. Such results would seem to contradict the dissertation model. However, a close inspection of patient data indicates that most of these patients had lesions to left but not right OFC; that is, there was sparing in the OFC. Therefore, these patients may have had some decrement in environmental monitoring that might explain their slow decision-making but they did not have a complete loss of environmental monitoring. Moreover, Manes et al. (2002) report that the group with extensive frontal-lobe lesions was the only group that demonstrated difficulty with attentional set shifting, and this was specific to extra-dimensional set shifts (such as switching from the colour to the shape dimension). Thus, contrary to the prediction of Fellows and Farah (2005), deficits in reversal learning are not driving impaired performance on the IGT among OFC-lesioned patients.

Therefore, converging evidence supports the position taken in the dissertation model that right VLPFC is recruited when the contingencies between stimulus and outcome are unstable or when a novel strategy is being recruited. In contrast, the OFC is implicated when the current situation is stable, whether positive or mildly / moderately aversive (or neutral, in which case the summed signal is zero).

This interpretation is consistent with taking the view that OFC responds when an environmental stimulus either *matches expectations / beliefs* or delivers a mismatch that does not require a change of strategy. That interpretation can be applied to evidence presented by Elliott, Dolan, and Frith (2000), who report activation in medial OFC during the delayed match-to-sample paradigm when there is a match between the expected and the received outcome, but activation in lateral OFC when there is not a match. Keeping in mind that, in that paradigm, the consequences of responses do *not* accumulate from trial to trial, there is no requirement in that task to change strategy.

In summary, the MIRE model postulates that under ordinary (that is, unperturbed) circumstances, the ongoing monitoring of the external environment registers an OFC signal that is close to zero. Positive events are registered in medial OFC. A net signal indicating a moderate perturbation that is tolerable (perhaps because it is interpreted as a single event or "blip" rather than a changed set of circumstances) will be associated with activation in lateral OFC. However, *strong* perturbations emanating from the external environment, indicating that a change of strategy is required, do not involve OFC but are associated with activation in right ventrolateral prefrontal cortex. It is the right VLPFC that Goel (2009) has proposed as the "uncertainty maintenance mechanism" in logic-based reasoning; the MIRE model postulates that this region is the neural disconnection mechanism.

Although a mild or moderate perturbation of the environment will not trigger a change of strategy away from a reliance on beliefs, it may have other consequences. Evidence from the negative emotion condition of the current pictures study has been interpreted as support for the view that people attempted to engage in reasoning as usual but were distracted by continued contemplation (or at least, continued processing) regarding the negative images or the ratings chosen for those images. Behaviourally, the rate of logical (correct) responding to incongruent syllogisms[40] dropped significantly from 65.9% in the non-emotional control condition to 50.4% in the negative condition. Neuroimaging analysis of a) negative reasoning, after subtracting out neutral (non-emotional) reasoning (and the baselines of both conditions), and b) the reverse contrast favouring neutral (non-emotional) reasoning, indicated the following pattern: There was *not* a crossover interaction (or double dissociation) between negative reasoning and neutral reasoning. Instead, negative reasoning involved activation in neural regions *in addition to* those regions associated with neutral (non-emotional) reasoning.

This interpretation is consistent with (although not synonymous with) LeDoux's (1996) proposal that there is only one mechanism for conscious awareness, and inputs to awareness from emotion systems will displace inputs from the fact-based system. Secondly, Oatley and Johnson-Laird (1987) proposed that when an event occurs that is

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[40] An incongruent syllogism is a syllogism in which the logical argument would promote one response choice whereas a reliance on the beliefs in the conclusion would promote the other response choice; that is, there is an incongruence between the logical argument and one's beliefs about the content stated in the conclusion.

not served by the currently active processing mode, the brain responds by eliciting an emotion signal that interrupts processing in that mode and immediately sets the brain into the relevant emotion mode to respond quickly to the stimulus. It is not clear from their proposal whether a subsequent non-emotional reasoning task would restore processing to a non-emotional mode. The evidence from the negative condition of the pictures study suggests a slightly more complex interpretation: people can engage, to some extent, in a second, non-emotional, task, but the second task will not, itself, curtail the processing in the emotion mode.

This section of the discussion has been focusing on the theme of interaction with the external environment. One further aspect of this theme is the proposal that an indication of increased environment stability, such as the occurrence of a positive event, will bolster a reliance on beliefs. Evidence from the behavioural literature (Bless et al., 1992; Bodenhausen, Kramer et al., 1994; Schwarz & Clore, 1983) demonstrates that positive mood induction promotes heuristic rather than systematic cognitive processing. Schwarz and Bless (1991) suggest that a positive, heuristic, system can be considered adaptive in the overall context of an evolutionary account; specifically, they offer the interpretation that positive emotion is a signal that the current situation is safe and requires no action. However, one notes that this is expressed poorly: if an organism takes no action on the basis of a positive signal, that lack of action does not *confer* an adaptive advantage (of safety). The MIRE model clarifies that a positively-weighted signal is an indication that the current status of the environment is currently beneficial to the organism (and the neural mechanism will provide an update if there is any change), and for now, the organism can carry on with ordinary functioning.

The evidence from the pictures study demonstrated that responses to incongruent syllogisms were significantly less logical (more belief-biased) in the positive emotion condition than in the non-emotional condition. The patterns of neural activation in the crossover interaction comparing activation during the positive *versus* non-emotional reasoning time-window (after subtracting out the respective baseline activations) showed that neural mechanisms underlying cognitive processing in the positive reasoning time-window were *not* simply activations *in addition to* those in the non-emotional state; instead, there were *non-overlapping* mechanisms supporting each of the two conditions. The behavioural and neural findings, taken together, provide converging evidence that reasoning influenced by positive emotion is *more belief-based* than it is in the non-emotional condition. Thus, the evidence from the positive condition of the pictures study supports the view that positive emotion bolsters a reliance on beliefs.

Up to this point, the discussion on the theme of interaction with the environment has focused on signals from the *external* environment, associated with signal in OFC. The MIRE model proposes that (conscious) feelings that the organism is consulting (that is, in the *internal* environment) are associated with activation in dorsomedial prefrontal cortex (medial BA 9). When the organism is maintaining simultaneous focus on i) external stimuli and ii) (internal) feelings or (internal) cognitive processing strategies, there is activation in frontal pole (BA 10). When the focus is more on the external stimulus, activation is in medial frontal pole; when the focus is more on internal feelings or strategies, the activation is in lateral frontal pole. An example of simultaneous focus is as follows: A study participant concentrates on a positive picture while consulting his or her feelings to determine an intensity rating.

Support for including consultation of feelings in the model comes from the following evidence. When participants were rating the intensity of IAPS pictures as emotional (across valence) on the basis of the feelings (Northoff et al., 2004) or the feelings and thoughts they were having (Dolcos et al., 2004), neural activation was reported in dorsomedial prefrontal cortex (BA 9). Grimm et al. (2006) obtained activation in dorsomedial prefrontal cortex (BA 9) in only the passive picture-viewing condition; nonetheless, in their model, they postulated the role of this region to be attention to and judgment of the intensity. Ratings of the intensity of positive pictures in the current pictures study were associated with a tendency for activation in this region.

Support for including a role in the MIRE model for simultaneous focus on external stimuli and internal conscious processes comes from research by Gilbert et al. (2009) and by Simons et al. (2006). Their work supports their hypothesis that focus on the external environment (and with cuing coming from the external environment) while simultaneously noticing internal processing is associated with medial pole activation, whereas focus on internal processing (and with self-initiated cuing) while simultaneously noticing the external environment, is associated with lateral frontal pole activation.

Evidence supporting the theme of personal interactions. As mentioned above, the MIRE model postulates that interaction with an emotional person will activate the same emotion in the reasoner, who can regulate his or her own emotion and engage in reasoning. Evidence comes from the sad and angry emotion conditions of the current tone of voice study.

In that study, the sadness induction was successful. Liotti et al. (2000) had induced sadness in participants by means of autobiographical scripts; additionally, participants were instructed to visualize the memories to magnify the intensity of the emotion, and then to focus on their feelings. In Liotti et al., sadness was associated with activation in subgenual anterior cingulate and insula, whereas relative deactivation was reported in dorsolateral prefrontal cortex. On that basis, it was predicted that sadness induction in the current study would be associated with similar involvement of these neural regions. In fact, activation (in the Sad-Neutral contrast of the emotion-induction time-window) was found in subgenual anterior cingulate and insula; the relative activation rather than deactivation in frontal cortex in the current study was attributed to the fact that participants were learning the syllogism material concurrently with hearing the sadness in the voice.

In the tone of voice study, participants were able to regulate the effect of the sadness and engage in reasoning. This interpretation is supported by the data. The rate of logic-based responding to incongruent syllogisms was not significantly different between the sad and the non-emotional reasoning conditions. Furthermore, neuroimaging analysis revealed a crossover interaction; that is, there were at least partially different patterns of voxels associated with sad reasoning and with non-emotional reasoning, when these conditions were directly compared (after subtracting out the baselines) in favour of sad reasoning and then in favour of non-emotional reasoning.

In the current tone of voice study, the anger induction was successful. In a study by Sander et al. (2005), participants listened to the voice of an angry speaker while simultaneously performing a cognitive task (identifying the gender of the speaker on each trial). Activation was reported in bilateral superior temporal sulcus, left prefrontal cortex, and bilateral ventrolateral prefrontal cortex; these activations were associated with the emotion in the tone of voice rather than with low-level acoustic features (Grandjean et al., 2005). As predicted, these neural regions were implicated in the anger emotion induction condition of the current tone of voice study.[41]

In the tone of voice study, participants were able to regulate the effect of the anger and engage in reasoning. This interpretation is supported by the data. The rate of logic-based responding to incongruent syllogisms was not significantly different between the angry and the non-emotional reasoning conditions; overall, there was a tendency for a higher rate of correct (logic-based) responses to both the incongruent and the congruent syllogisms, considered together. Furthermore, neuroimaging analysis revealed a crossover interaction when angry reasoning and non-emotional reasoning were directly compared. The tendency for greater efficiency in reasoning in the angry than in the sad condition is interpreted as a result of heightened attention elicited by hearing the angry voice.

The results of the tone of voice study suggest questions for future research as to why the rate of logic-based responding was maintained at a level similar to that in the non-

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[41] In the current study, the activation in bilateral ventrolateral prefrontal cortex was noted as trends when the threshold was set at $p < .05$.

emotional condition. It could be that the vocal emotion induction was experienced as a strong enough perturbation of the environment to trigger a change of strategy towards logic-based responding; alternatively, it could be that the experience of being spoken to can, in certain circumstances, trigger a change of strategy from belief-based to logic-based responding. In either case, it seems that the triggering effect was tempered by the cost of regulating the emotion, with a net result of no significant change (behaviourally) in the level of responding from that in the non-emotional condition.

Evidence supporting the hypotheses proposing a) a processor supporting logic-based reasoning, and b) dissociable disconnection mechanisms. A hypothesis proposed for future research is that there is a neural processor that supports logic-based syllogistic reasoning. The proposed neural mechanism is the basal ganglia. Evidence in support of this hypothesis will be presented, next, in conjunction with further evidence supporting the role of right ventrolateral prefrontal cortex as the disconnection mechanism.

The Melrose et al. (2007) study may be the first to focus specifically on the role of the basal ganglia in deductive reasoning. These researchers used fMRI to assess the role of the caudate (part of the basal ganglia) in abstract reasoning involving deduction and application of a sequence rule, after subtracting out working memory effects. Results indicated that reasoning processes, after accounting for working memory effects, were associated with activation in the left caudate head and right VLPFC (BA 47), as well as other neural regions. There was significantly more activation in bilateral caudate body, as well as a trend for greater activation in left caudate head, during reasoning than during a control condition.

Prefrontal cortex recruitment in relational matrix reasoning might be explained specifically by the complex reasoning process of considering multiple relations simultaneously, rather than by task difficulty. This hypothesis (Christoff et al., 2001) was confirmed using fMRI. Moreover, in noting that the caudate nucleus was the only other neural structure activated solely by complex reasoning, the researchers comment that "there is converging evidence that the PFC and the caudate are major components of a neural system mediating complex reasoning" (Christoff et al., p. 1146).

It should be noted that the matrix reasoning tasks employed by Christoff et al. (2001) involved three levels of complexity. At the highest level of complexity, activation was noted in the basal ganglia. There is no mention of right VLPFC in that condition, nor is there mention of either basal ganglia or right VLPFC in the two less complex conditions. That is, when the lowest level was subtracted from the middle level, no voxels survived correction. One possible explanation, given that the middle level was similar to that used in Melrose et al. (2007), is that these regions were present in all conditions and therefore were subtracted out.

Activation was reported in basal ganglia and right dorsolateral and ventrolateral prefrontal cortex (BA 46/45) in syllogistic reasoning, when meaningful content was incongruent but not when it was congruent with the argument logic (Goel et al., 2000). Both the basal ganglia and right VLPFC were involved in reasoning in the neutral (right BA 47), angry (right BA 47), and sad (right BA 44) conditions of the tone of voice study. In the positive condition of the pictures study, where the belief-bias effect was enhanced, there was no activation reported in either basal ganglia or in right VLPFC. In the negative condition of the same study, where it is postulated that reasoners were distracted by ongoing reactions to the mixed negative stimuli, the involvement of right VLPFC (BA 45) was not accompanied by involvement of basal ganglia.

To investigate neural underpinnings of fluid reasoning ("decision-making on the fly")[42], Kalbfleisch et al. (2007) conducted an fMRI study in which participants were asked to perform a visual matrix reasoning task, but were given only 20% of the time normally needed to complete the task, on each trial. In the introduction of the study, the researchers noted that the role of basal ganglia and cerebellum had not been explored in reasoning studies. Neuroimaging analysis based on correct trials (which occurred at above-chance levels) revealed no involvement of basal ganglia,[43] although there was activation in many neural regions including cerebellum, bilateral precuneus and bilateral lingual gyrus, as well as left VLPFC. The lack of basal ganglia involvement when there is insufficient processing time is consistent with the observation of Christoff et al. (2001) that caudate is important in complex reasoning, which would normally involve a deep level of processing.

Thus, there is converging evidence of a correlation between functioning of right VLPFC and basal ganglia in syllogistic reasoning (as well as in matrix reasoning). Effective connectivity analyses could be performed to demonstrate whether these relations are more than correlational. However, such analyses require a between-subjects

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[42] Curiously, Kalbfleisch et al. (2007) assert that past reasoning studies have involved extensive pre-scan training; they include the Goel opus in that assertion but it is not clear how that misunderstanding arose.

[43] This lack of basal ganglia involvement was not commented on by the researchers.

design; the existing studies in the Goel opus involve within-subjects designs. One form of the hypothesis is that *if* the right VLPFC is necessary for logical reasoning, then the basal ganglia and right VLPFC form a fronto-striatal loop that underlies logical reasoning.

A second hypothesis for future research is that the disconnection mechanism, in right ventrolateral prefrontal cortex, has dissociable functions. The right ventrolateral prefrontal cortex is comprised of three subregions: BA 44, BA 45, and BA 47. As shown above, right BA 44 was implicated in reasoning in the sad condition of the tone of voice study. Right BA 45 has been associated with reasoning when syllogism logic is incongruent with beliefs (Goel et al., 2000; Goel & Dolan, 2003a) and was involved during the negative reasoning time-window of the current pictures study. Right BA 47 was associated with non-emotional reasoning in both the pictures study and the tone of voice study, and with reasoning in the angry condition of the tone of voice study.

Future research could explore whether these different subregions are supporting different ways in which disconnection might be characterized. Indirect evidence from other sources suggests this possibility. The role of right BA 44 is ubiquitous in response inhibition (Aron et al., 2004), including but not limited to the inhibition of episodic memories. In an fMRI study investigating auditory change detection (Opitz, Rinne, Mecklinger, von Cramon, & Schroger, 2002), bilateral superior temporal gyri and right ventrolateral frontal gyrus (BA 45) were implicated when auditory change was detected and led to the initiation of an involuntary switch in attention. The auditory change detection itself was associated with activation in the superior temporal gyrus, and the activation in right BA 45 ensued. Involvement of right BA 47 has been reported in transitive reasoning when alternative models of the relation among the syllogism terms could be constructed (Goel et al., 2009; Goel et al., 2007); an example of such an argument would be "The Earth is dimmer than the sun. The sun is brighter than Mars. The Earth is brighter than Mars" (which is invalid because there is insufficient information in the premises to determine whether the conclusion logically follows from them). In the literature beyond deductive reasoning, activation in right VLPFC (specifically right BA 47) has been noted in complex problem-solving tasks where a search for the non-dominant or alternative meaning is important to the task (Goel & Vartanian, 2005; Vartanian & Goel, 2005). Also, as mentioned in the earlier discussion on the roles of OFC and right VLPFC in the organism's interaction with the environment, it is the right VLPFC (right BA 47 in particular) that is recruited when a strong environmental perturbation indicates that the current strategy is not working and an alternative strategy must be adopted.

Stanovich (2009) proposed that there are three subtypes of cognitive decoupling: response override (that is, a suppression of belief-bias to engage in logical reasoning), a switching of focal bias (by which is meant a disengaging from one belief, only to end up substituting another belief in its place and continuing deliberation about that new belief), and cognitive simulation. Although it is not clear whether these particular types of decoupling would map onto the proposed dissociation, the Stanovich proposal is taken as support for the *principle* that disconnection may involve dissociable mechanisms.

The Relation of the MIRE Model to Theoretical Accounts in the Literature

The MIRE model is, of course, influenced by existing theoretical accounts. Stanovich (2009) demonstrated that two distinct subprocesses, reflection and algorithmic processing, characterize rational thinking. This conceptualization was not adopted in the model, which focuses on a particular type of reasoning, namely deductive reasoning. However, the distinction itself proved useful as inspiration for thinking of the neural model in terms of a processor (a neural algorithm of sorts) as being a separate contributor to a reasoning system.

The MIRE model proposes that there is a disconnection mechanism involved when reasoning is unencumbered by beliefs. Stanovich (2009) proposed a cognitive decoupler that takes cognitive processing "offline" during hypothetical thinking so that argument terms could be manipulated temporarily without leading directly to updating of existing knowledge or to action. Goel and Dolan (2003a) provided neural evidence of what the MIRE model refers to as the disconnection mechanism. Goel (2009) refers to it as an uncertainty maintenance mechanism, in the sense that a strong and obligatory call from left hemisphere to respond on the basis of prepotent belief is postponed. The MIRE model has chosen not to use this terminology because of the proposal that one type of disconnection promotes the use of novel strategies, such as for seeking non-dominant meanings or alternative models, and these might not be characterized primarily by inhibition.

LeDoux (1996) proposed that there are separate emotion systems at the neural level; this view is supported. An account of emotion as being based in the autonomic system is outdated; advances in knowledge contributed by neuroimaging studies (for examples, see Liotti et al., 2000; Sander et al., 2005) have shown that specific emotions have been associated with characteristic neural underpinnings.

Oatley and Johnson-Laird (1996) advanced the concept of distinct neural emotion systems by proposing separate emotion modes in which the organization of the brain is controlled, bodily resources for action are mobilized, attention is focused, appropriate biases of cognitive processing are recruited, and the triggering issue is made salient in consciousness. This concept can be accommodated within the structure of the MIRE model in the following way. Logic-based reasoning is characterized as involving disconnection and a processor; future research could explore whether reasoning about material within one particular emotion mode (such as reasoning about the loss of a loved one) might implicate a particular subtype of disconnection mechanism. There are clues from the tone of voice study data that are consistent with the Oatley and Johnson-Laird model: although the current syllogism material was *not* incorporated into a sad reasoning system or an angry reasoning system (perhaps because the material was not relevant to such a system), the two systems themselves were initially activated, and the mechanisms of regulation of their effects differed. Furthermore, it is predicted that a reasoning system will be characterized by additional components specific to that system; for instance, reasoning about grief may involve additional components related to episodic memories. As a general principle, this has already been foreseen by Epstein (1994) and by Goel (2009), as will be explained.

Epstein (1994) had described the richness in experiential processing, characterized as being variously heuristic, stereotypic, or narrative/parable-based. This general principle of richness is reflected in the concept that different neural emotion systems recruit different components. Goel (2009) has shown that (in the absence of emotion) analytical processing, too, is rich. The position taken in that model is that reasoning is subject to effects of belief-bias, of the presence or absence of meaningful content, and of the (in)determinacy of the logical argument. For example, in the absence of any meaningful content ("All Ps are Qs"), logic-based reasoning involves a visuo-spatial strategy associated with activation in parietal lobes (Goel et al., 2000) as well as (according to the MIRE model) the disconnection mechanism and processor. In this case, the MIRE model would predict that, since the disconnection mechanism is not recruited by a conflict with beliefs (as there are no beliefs in the experimental situation), its involvement is explained as follows: First, the basal ganglia (hypothesized as the processor) have been characterized as operating by means of loops involving the frontal lobes (for instance, see Chang, Crottaz-Herbette, & Menon, 2007; Seger, 2008); perhaps the frontal lobes are necessarily recruited as part of a fronto-striatal loop. Secondly, in a real situation, perhaps when people encounter situations for which their current beliefs are insufficient, a label (such as "thing" or "stuff") is applied (perhaps pre-reflectively), and this label itself needs to be set aside in order to engage in abstract reasoning.

Oatley and Johnson-Laird's (1996) concept of emotion modes as being states that the organism is in, is expanded to a broader perspective that was implicit in their model. That is, the MIRE model characterizes a default state of mundane functioning in which knowledge states (such as beliefs about infrastructure) and habits can be built up and relied upon. Meanwhile, neural mechanisms continually register the status of the organism with respect to the external environment. This averaged signal could sum to zero or it could indicate a perturbation. Perturbations could be valenced (and that view is consistent with the positive and negative valence characterized in Damasio's model); however, the MIRE model builds on evidence that it is the interaction of perturbation and valence that characterizes the averaged signal. The MIRE model does not specify whether the OFC signal is registered in consciousness or not. Damasio (1994) had postulated a somatic marker (gut feeling) as a signal to the organism and had linked that marker to OFC functioning; however, evidence to date is correlational (Bechara et al., 2000) and needs corroboration.

Evidence of the effects of positively valenced visual emotion induction (in the pictures study) has provided support for the view that the default state of mundane functioning is reinforced when the signal registers increased stability. An implication is that existing knowledge states, including beliefs, are relied on perhaps even more than usual during (cognitive) processing. This postulate is consistent with the view that this type of emotion induction exerts its effects on reasoning by means of influencing beliefs. It also provides an explanation for the finding (Blanchette, 2006; Blanchette & Richards, 2004) that positive emotion impairs logical reasoning by impacting beliefs in general and not just specific beliefs.

Evidence of the effects of negatively valenced visual emotion induction (in the pictures study) has provided support for the view that negative emotion distracts the reasoner, thus hindering engagement with a subsequent non-emotional task. The MIRE model does *not* propose that the negative emotion was linked to a strong perturbation of the environment leading to a change of strategy. A mild or moderate perturbation could signal that some issue needs to be resolved, even though a change of strategy is not called for; it may simply require additional attention, involving one's ongoing belief-based processing. Blanchette's finding (Blanchette, 2006; Blanchette & Richards, 2004) that negative emotion impairs logical reasoning by impacting beliefs in general and not just specific beliefs is consistent with this interpretation.

The MIRE model proposes that a strong perturbation will signal the need for a change of strategy, and that in the context of syllogistic reasoning, this would trigger a change from belief-based processing to logic-based reasoning. Such a view is consistent with the report of an increased rate of logic-based responses to terrorism-related material, but not to general negative material, provided by witnesses to a real terrorist attack but not by unaffected participants (Blanchette et al., 2007).

In the absence of an environmental perturbation, or in the case where the perturbation is merely mild or moderate (but not strong), the disconnection mechanism could be recruited by various means. Clearly, one means involves controlled use of critical thinking skills (referred to as "mindware" by Stanovich, 2009). Future research may show that one hypothesized triggering mechanism might include involuntary attention capture from detection of some anomaly such as a mispronounced word during auditory delivery of material. Perhaps such detection of anomaly would foster meta-awareness of the task environment and instructions. Perhaps it might be a direct effect of activation of a neural mechanism for anomaly detection (which might perhaps be the "non-propositional signal" proposed by Oatley & Johnson-Laird, 1996). Evidence has suggested that involuntary attention capture by auditory change detection is associated with activation in the superior temporal lobe, and further processing of the change is associated with activation in right ventrolateral prefrontal cortex (Opitz et al., 2002).

Limitations of the Current Neuroimaging Studies

The emotion inductions chosen for the pictures study were characterized by a mixture of emotions within each valence. However, different emotions of the same valence may have different effects on behaviour and on underlying neural mechanisms. Future designs should focus on a small number of particular emotions coded into separate conditions.

Secondly, the baseline trials involved reading sentences, and pressing the key to respond, in the usual way. Thus, during neuroimaging analysis, these features of the task could be separated from the reasoning activity itself. Of course, we cannot know what participants may have been thinking about during the baseline trials. Raichle et al. (2001) have shown that there is no true "resting state"; that is, in the absence of a task, there is ongoing neural activity. However, many studies in the Goel opus (for example: Goel et al., 2000; Goel & Dolan, 2003a) have employed the same "reasoning *minus* baseline" design; this has been accepted by reviewers, and permits some continuity of interpretation across the opus.

Thirdly, the criteria for rejecting or failing to reject hypotheses were based on converging evidence from neuroimaging interaction contrasts and behavioural data parsed by correct congruence/incongruence; these sources of evidence do not directly map onto each other. The main purpose of the two studies was to identify neural regions involved when people are given a reasoning task in the absence or presence of emotion inductions. Our interest was in capturing the neural activations that accompany whatever processes people engage in. Having succeeded in that goal, we could then use the further parsing of the behavioural data to determine what proportion of logic-based reasoning was associated with each of these conditions. This was a deliberate strategy. Our design strategy was based on wanting to compare two different types of emotion (positive *versus* negative, or sad *versus* angry) in each study, and we needed a control (neutral) condition as well. In order to analyse the neuroimaging data along the lines of "correct incongruent" trials it would have been necessary to create a design in which the reasoning factor was further divided into a 2 (Congruence) X 2 (Accuracy) factorial. Because such a design would have insufficient power to detect neural differences that may exist in nature, we would have had to alter our study purpose to achieve this. Goel and Dolan (2003a) did address the issue of correct incongruence at the neural level, directly, using fewer conditions and many more trials per condition. As well, there were four fundamental differences, other than the differences identified in the designs, between the two studies, and such differences preclude drawing comparisons about effects of emotion introduced prior to *versus* concurrently with the reasoning task. These differences are identified, in the next subsection, as questions that may generate further research.

Directions for Future Research

The pictures study and the tone of voice study may be the first experiments to explore neural underpinnings of deductive reasoning under the influence of emotion inductions unrelated to the syllogism content. There were at least four differences between these studies that could be the basis for a continued program of research into the effects of emotion on deductive reasoning. In the pictures study, the emotion induction was visual, syllogism material remained visible during the reasoning time-window, the syllogism was presented separately from the induction, and participants' attention was specifically drawn to the pictures by means of ratings. In the tone of voice study, the emotion induction was auditory, syllogism material had to be memorized/learned, the syllogism was presented embedded in the emotional tone of voice, and participants' attention was not drawn to the character of the voice by means of any instruction or explanation.

Converging evidence from a series of neuroimaging studies might be needed to disentangle these effects. None of these differences would provide a sufficient explanation of the results in the current studies, as in each study the two emotional conditions were characterized differently.

The visual *versus* auditory distinction has been noted in two reports from the same laboratory, although it is not clear whether the experiments themselves were within-subjects or separate.[44] Transitive inference was investigated in an auditory presentation (Fangmeier & Knauff, 2009) and in a visual presentation (Fangmeier et al., 2006) and the resulting neural patterns were different.

Regarding the issue of syllogism material remaining available *versus* being remembered, it is possible that the requirement to remember material would place a greater demand on cognitive resources in the tone of voice study than in the pictures study. Of course, within the tone of voice study itself, such an effect was controlled for by being equivalent across all conditions.

Regarding the issue of separate *versus* embedded emotion induction, evidence from the behavioural literature demonstrates similar effects of positive induction regardless of whether the task is concurrent with or follows the induction (Bodenhausen, Kramer, et

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[44] The demographic data are almost identical between the two reports.

al., 1994). Positive induction involved writing about a happy autobiographical event or, in a second experiment, listening to music, prior to the main task; in a third experiment, embedded positive induction involved a procedure from the approach/withdrawal literature (Strack et al., 1988) which was to hold an object between the teeth to activate facial muscles involved in smiling. Task performance was interpreted as being heuristic rather than based on the use of available evidence in all three experiments.

Regarding the issue of attending to *versus* ignoring the emotion induction, evidence from auditory paradigms is consistent: Mitchell et al. (2003) have shown neural activation differences between passive listening and task-related listening to sentences with emotional prosody. Neural activation associated with the angry emotion induction in the tone of voice study was shown to be consistent with auditory paradigms in which the angry aspect of the voice (Sander et al., 2005) or the vocal sounds (Meyer et al, 2005) were not being attended to.

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Appendix A: Reasoning Syllogisms Used in the Pictures study

Valid		Invalid	
Congruent	Incongruent	Congruent	Incongruent
All hawks are birds. Some hawks are pets. Some pets are birds.	All rabbits are fluffy. All fluffy creatures are tadpoles. All rabbits are tadpoles.	All dogs are pets. All poodles are dogs. No poodles are pets.	Some vegetables are not carrots. No strawberries are vegetables. No strawberries are carrots.
All doctors are respected. Some parents are not respected. Some parents are not doctors.	No holidays are unpleasant. All Mondays are unpleasant. No Mondays are holidays.	All paper is absorbent. All napkins are paper. No napkins are absorbent.	All horses are intelligent. No intelligent animals are fast. Some fast animals are horses.
All dogs are pets. All poodles are dogs. All poodles are pets.	All boys are curious. No curious people are smart. Some smart people are boys.	All boys have skinned knees. No girls have skinned knees. All girls are boys.	All flying birds are black. No swans are black. Some swans can fly.
All paper is absorbent. All napkins are paper. All napkins are absorbent.	All white birds can fly. No swans can fly. No swans are white.	Some jazz is very rhythmic. Some very rhythmic music is tuneful. All tuneful music is jazz.	Some Catholic nuns are not gentle. All Catholic nuns are women. Some women are gentle.
All gossip rags are popular. All Hello magazines are gossip rags. All Hello magazines are popular.	All married people have rings. Some husbands do not have rings. Some husbands are not married people.	Some circles are polygons. All circles are squares. Some squares are not polygons.	Some mammals are donkeys. All mammals are animals. Some animals are not donkeys.
All artists are creative. Some children are artists. Some children are creative.	All flying birds are black. No swans are black. No swans can fly.	All paper is absorbent. All napkins are paper. No napkins are absorbent.	Some women are mothers. All mothers are gentle. Some gentle people are not women.
No lovers are friends. Some sweethearts are friends. Some sweethearts are lovers.	All gentle pets are canines. Some kittens are gentle pets. Some kittens are canines.	No candies are made with meat. Some meats are not cooked foods. No cooked foods are candies.	All white birds can fly. No swans can fly. Some swans are white.
No poisons are sold at the grocers. Some mushrooms are sold at the grocers. Some mushrooms are not poisonous.	All horses are intelligent. No intelligent animals are fast. No fast animals are horses.	All hawks are birds. Some hawks are pets. No pets are birds.	All clergy are fat. No fat people are religious. Some religious people are clergy.
All professors are scholars. Some women are not scholars. Some women are not professors.	All clergy are fat. No fat people are religious. No religious people are clergy.	All crunchy tubers are vegetables. Some carrots are crunchy tubers. Some carrots are not vegetables.	All doctors are fathers. Some women are doctors. No women are fathers.

Appendix A: Reasoning Syllogisms Used in the Pictures study, *continued*

Valid		Invalid	
Congruent	Incongruent	Congruent	Incongruent
All priests are Catholics. Some people are not Catholics. Some people are not priests.	All doctors are fathers. Some women are doctors. Some women are fathers.	All good athletes are healthy. Some boxers are not healthy. No boxers are good athletes.	All carpenters are men. Some women are carpenters. No women are men.
Some Chimps are movie stars. All movie stars are primates. Some primates are Chimps.	All carpenters are men. Some women are carpenters. Some women are men.	Some mothers are patient. No fathers are mothers. No fathers are patient.	Some rock singers are guitarists. All guitarists can sing. Some rock singers cannot sing.
Some movie goers are men. All men are French. Some French are movie goers.	No fashion models need to eat. Some fashion models are people. Some people do not need to eat.	All flying birds have feathers. No people have feathers. Some people are flying birds.	No Catholic nuns are priests. Some women are Catholic nuns. No priests are women.
Some children are not Canadians. All children are people. Some people are not Canadians.	No children wear pigtails. All little girls are children. No little girls wear pigtails.	Some accountants are rich. All rich men have muscular bodies. All accountants have muscular bodies.	All wines are made from grapes. Some dry drinks are not made from grapes. Some wines are not dry.
All sensitive men are good lovers. Some impotent men are sensitive. Some impotent men are good lovers.	No golfers prefer the indoors. All card players prefer the indoors. No card players are golfers.	No unhealthy foods have cholesterol. Some unhealthy foods are fried. No fried foods have cholesterol.	Some girls do not have pony tails. All girls are pretty. Some pretty girls have pony tails.
Some soldiers are brave. All soldiers are men. Some men are brave.	Some children are not people. All children are Canadian. Some Canadians are not people.	All smokers have cancer. Some smokers are women. No women have cancer.	Some redheads are not freckled. No blondes are redheads. Some blondes are freckled.
All smokers have cancer. Some smokers are women. Some women have cancer.	No tailors are women. All barbers are tailors. No barbers are women.	No tailors are women. All barbers are tailors. All barbers are women.	No men are fathers. Some fathers are brave. Some brave people are men.
Some Italians are short. All Italians are Catholics. Some Catholics are short.	All rabbits are fluffy. All fluffy creatures are tadpoles. All rabbits are tadpoles.	Some automobiles are machines. No robots are automobiles. Some robots are not machines.	All French poodles are dogs. Some French poodles are small. Some small animals are not dogs.
All hawks are birds. Some hawks are pets. Some pets are birds.	All female horses are deaf. No deaf horses are fast runners. No fast animals are female horses.	All good athletes are healthy. Some boxers are not healthy. No boxers are good athletes.	No reptiles can grow hair. Some elephants can grow hair. No elephants are reptiles.

Appendix A: Reasoning Syllogisms Used in the Pictures study, *continued*

Valid		Invalid	
Congruent	Incongruent	Congruent	Incongruent
Some men are not Canadians. All men are skaters. Some skaters are not Canadians.	No Cambodian lizards are make-believe. Some Cambodian lizards are dragons. Some dragons are not make-believe.		All asthmatics cannot run marathons. Some football players are asthmatic. Some football players can run marathons.

Appendix B: Reasoning Syllogisms Used in the Tone of voice study

Neutral condition

Valid		Invalid	
Congruent	Incongruent	Congruent	Incongruent
Some chimps are movie stars. All movie stars are primates. Some primates are chimps.	All rabbits are fluffy. All fluffy creatures are tadpoles. All rabbits are tadpoles.	Some circles are polygons. All circles are squares. Some squares are not polygons.	No men are fathers. Some fathers are brave. Some brave people are men.
All artists are creative. Some children are artists. Some children are creative.	No golfers prefer the indoors. All card players prefer the indoors. No card players are golfers.	Some accountants are rich. All rich men have muscular bodies. All accountants have muscular bodies.	Some women are mothers. All mothers are gentle. Some gentle people are not women.
All young mammals are curious. Some young mammals are babies. Some babies are curious.	All carpenters are men. Some women are carpenters. Some women are men.	Some movie-goers are men. All men are French. No French are movie-goers.	Some redheads are not freckled. No blondes are redheads. Some blondes are freckled.
All interactions are meaningful. All relationships are interactions. Some relationships are meaningful.	No beautiful people are evil. All women are evil. No women are beautiful.	Some jazz is very rhythmic. Some very rhythmic music is tuneful. All tuneful music is jazz.	All carpenters are men. Some women are carpenters. No women are men.
Some soldiers are brave. All soldiers are men. Some men are brave.	No children wear pigtails. All little girls are children. No little girls wear pigtails.	Some Italians are short. All Italians are Catholics. All Catholics are short.	No apples are pears. All fruit are pears. Some fruit are apples.
All nurses are caring. Some funny people are nurses. Some funny people are caring.	All felines are fluffy. All cats are felines. All cats are fluffy.	All furniture is useful. All chairs are furniture. No chairs are useful.	No drug addicts have cancer. Some smokers are drug addicts. Some smokers have cancer.
Some nurses are mothers. All mothers are dedicated. Some dedicated women are nurses.	No deer are fast. All stags are deer. No stags are fast.	No unhealthy foods have cholesterol. Some unhealthy foods are fried. No fried foods have cholesterol.	Some girls do not have ponytails. All girls are pretty. Some pretty girls have ponytails.
	No tailors are women. All barbers are tailors. No barbers are women.	No candies are made with meat. Some meats are not cooked foods. No cooked foods are candies.	Some Catholic nuns are not gentle. All Catholic nuns are women. Some women are gentle.
	No holidays are unpleasant. All Mondays are unpleasant. No Mondays are holidays.	Some elderly have memories. Some elderly are men. No men have memories.	No tailors are women. All barbers are tailors. Some barbers are women.

Appendix B: Reasoning Syllogisms Used in the Tone of voice study, *continued*

Neutral condition, *continued*

Valid		Invalid	
Congruent	Incongruent	Congruent	Incongruent
	All boys are curious. No curious people are smart. No smart people are boys.		All dentists are women. Some men are dentists. No men are women.
	All wise people are experts. No young people are experts. No young people are wise.		Some elderly have memories. Some elderly are men. Some men have memories.
	All teachers are mothers. Some men are teachers. Some men are mothers.		No lovers are friends. Some sweethearts are friends. Some sweethearts are lovers.

Sad condition

Valid		Invalid	
Congruent	Incongruent	Congruent	Incongruent
No poisons are sold at the grocers. Some mushrooms are sold at the grocers. Some mushrooms are not poisonous.	All canines can detect subtle odours. No mammals can detect subtle odours. Some canines are not mammals.	All dogs are pets. All poodles are dogs. No poodles are pets.	Some rock stars are guitarists. All guitarists can sing. Some rock stars cannot sing.
All priests are Catholics. Some people are not Catholics. Some people are not priests.	All flying birds are black. No swans are black. No swans can fly.	All paper is absorbent. All napkins are paper. No napkins are absorbent.	No reptiles can grow hair. Some elephants can grow hair. No elephants are reptiles.
All gossip rags are popular. All Hello magazines are gossip rags. All Hello magazines are popular.	All white birds can fly. No swans can fly. No swans are white.	No fast insects are snails. Some fast insects are slimy. Some snails are not slimy.	No beautiful people are evil. All women are evil. Some women are beautiful.
Some movie-goers are men. All men are French. Some French are movie-goers.	All horses are intelligent. No intelligent animals are fast. No fast animals are horses.	All flying birds have feathers. No people have feathers. Some people are flying birds.	All French poodles are dogs. Some French poodles are small. Some small animals are not dogs.

Appendix B: Reasoning Syllogisms Used in the Tone of voice study, *continued*

Sad condition, *continued*

Valid		Invalid	
Congruent	Incongruent	Congruent	Incongruent
Some policemen are detectives. All detectives are competent. Some policemen are competent.	No Cambodian lizards are make-believe. Some Cambodian lizards are dragons. Some dragons are not make-believe.		No deer are fast. All stags are deer. Some stags are fast.
Some Italians are short. All Italians are Catholics. Some Catholics are short.			

Angry condition

Valid		Invalid	
Congruent	Incongruent	Congruent	Incongruent
No women are tailors. All barbers are women. No barbers are tailors.	No harmful substance is natural. All poisons are natural. No poisons are harmful.	No fruits are fungi. All mushrooms are fungi. Some mushrooms are fruits.	All mammals are mice. No whales are mice. All whales are mammals.
All furniture is useful. All chairs are furniture. All chairs are useful.	All clergy are fat. No fat people are religious. No religious people are clergy.	All crunchy tubers are vegetables. Some carrots are crunchy tubers. Some carrots are not vegetables.	All boys are curious. No curious people are smart. Some smart people are boys.
Some combat-trained pitbulls are pets. All combat-trained pitbulls are vicious. Some pets are vicious.	All doctors are fathers. Some women are doctors. Some women are fathers.	All hawks are birds. Some hawks are pets. No pets are birds.	All calculators are machines. All computers are calculators. Some machines are not computers.
All African animals can be obedient. Some African animals are fierce. Some fierce animals can be obedient.	All married people have rings. Some husbands do not have rings. Some husbands are not married people.	All good athletes are healthy. Some boxers are not healthy. No boxers are good athletes.	All teachers are mothers. Some men are teachers. No men are mothers.
	All gentle pets are canines. Some kittens are gentle pets. Some kittens are canines.	Some smokers have cancer. Some smokers are women. No women have cancer.	Some mammals are donkeys. All mammals are animals. Some animals are not donkeys.
		All priests are Catholics. Some people are not Catholics. No people are priests.	

Appendix C: Supplementary Behavioural Analyses from the Pictures Study

Main effect of task (reasoning / baseline). The percentage of logical (that is, correct) responses to the 1021 reasoning trials overall was 62.98% and to the 615 baseline trials overall was 97.24%. A paired *t*-test was conducted to compare the participants' mean reaction time to reasoning *versus* baseline syllogisms; participants responded significantly faster to baselines: $t(13) = 8.567$, $p = .001$. Mean reaction time was 4185 (*SD* 789) ms to reasoning, and 1874 (*SD* 456) ms to baseline syllogisms.

Simple effect of emotion on reasoning. The percentage of the 1021 reasoning syllogisms within each valence (using participants' ratings) was as follows: 40.6% positive, 25.9% neutral, 25.6% negative, and 7.9% no rating. Among the 615 baseline trials, 46.3% were positive, 26.3% were neutral, 19.8% were negative, and 7.6% had no rating.

The proportion of logical (correct) reasoning responses to the total number of reasoning trials was computed for each participant within each valence. For instance, one participant rated 20 of the pictures (on reasoning trials) as positive, and reasoned logically on 15 of those trials; thus, the proportion of logical responses on positively-valenced reasoning trials was .75 for that participant. Next, a repeated-measures analysis of variance (n= 13)[45] was conducted to test whether the valence rating affected logical reasoning. The independent variable was proportion correct reasoning (three levels: positive, neutral, negative), and the dependent variable consisted of the actual proportions. The result was not significant. Overall, the valence of the picture did not

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[45] The one participant who had not rated any pictures as neutral was excluded from this analysis.

significantly influence subsequent logical reasoning. The mean proportions of logical (correct) responses to reasoning syllogisms by valence ($n = 13$) were as follows: .629 positive (*SD* .166), .701 neutral (*SD* .165), and .644 negative (*SD* .224).

The mean reaction time on reasoning trials was computed, for each participant, for each valence (positive, neutral, negative, no rating) separately. A repeated-measures analysis of variance, using all four levels, demonstrated that the assumption of sphericity was violated. A repeated-measures analysis of variance, multivariate approach, was conducted, with three levels (positive, neutral, negative) of the independent variable. The result was not significant: there was no significant difference in mean reaction time to reasoning syllogisms by valence of picture rating.

The mean reaction time on reasoning trials was computed, for each participant, separately by logical / illogical (correct / incorrect) responding for each valence. A repeated-measures analysis of variance, multivariate approach, was conducted with one factor being Logic (logical, illogical response) and the other being Emotion (positive, neutral, negative). The dependent variable was mean reaction time on reasoning trials. This analysis was based on data from nine participants. There was no significant interaction and no main effect of emotion. The main effect of logic was significant: $F(1, 8) = 17.197$, $p = .003$, partial $\eta^2 = .683$. Participants responded significantly more slowly when their response was illogical (incorrect) than when it was logical (correct), regardless of the valence of the trial.

Since there were complete data from 13 participants if the neutral rating was omitted, the analysis was repeated. This time the factors were Logic (logical or correct, illogical or incorrect response) and Emotion (positive, negative). The dependent variable was mean reaction time on reasoning trials. There was no significant interaction and no main effect of emotion. The main effect of logic (accuracy) was significant: $F(1, 12) = 7.537$, $p = .018$, partial $\eta^2 = .386$. Participants reasoned significantly more slowly when their response was illogical (incorrect) than when it was logical (correct), regardless of whether the valence of the trial was positive or negative.

Mean reaction times ($n = 13$) when logical (correct) were 3571 ms (*SD* 528) on positive and 3703 ms (*SD* 393) on negative reasoning trials. Mean reaction times when illogical were 4179 ms (*SD* 944) on positive and 4180 ms (*SD* 1263) on negative trials.

In summary, the proportion of logical (accurate) responses on reasoning trials was not significantly different among the positive, negative, and neutral conditions, nor was mean reaction time. People did respond significantly more slowly when their reasoning was illogical (incorrect) than when it was logical (correct), regardless of valence.

Congruence (across all reasoning trials). For each participant, the proportion of [logical (correct) responses on congruent syllogisms] to [all congruent syllogisms] was calculated. The similar calculation was carried out for incongruent syllogisms. Overall, the mean proportion of correct congruent syllogisms was .7255 (*SD* .189) and the mean proportion of correct incongruent syllogisms was .5517 (*SD* .184). Analysis revealed that the proportion of logical responses was significantly worse on incongruent than on congruent syllogisms: *paired* $t(13) = -2.994$, $p = .01$. This result indicates that, overall, logical (accurate) reasoning was impaired when the logic of the argument was in conflict with (that is, incongruent with) the truth of the concluding statement. Of course, when there is no conflict, the reasoner might be basing their response on argument logic or on the truth of the facts; either strategy would yield the same outcome.

For each participant, the mean reaction time was calculated separately for congruent and incongruent reasoning trials (collapsed across accuracy). Overall mean reaction time to congruent syllogisms was 3981 ms (*SD* 796) and to incongruent syllogisms was 4383 ms (*SD* 836). Analysis revealed that responses were significantly slower when beliefs conflicted with the logical argument than when they did not: *paired t*(13) = 3.545, *p* = .004. This result suggests that, overall, belief-based processing is faster than is logic-based reasoning in the context of a conflicting belief. However, this result does not isolate reaction time when reasoning was, specifically, accurate or logical.

Therefore, for each participant, the mean reaction time was calculated separately for congruent and incongruent reasoning trials, this time for logical (correct) responses only. Mean reaction time when responding logically to congruent syllogisms was 3386 ms (*SD* 424) and to incongruent syllogisms was 3966 ms (*SD* 615). Analysis revealed that logical (correct) responses were significantly slower when beliefs conflicted with the logical argument than when they did not: *paired t*(13) = -5.026, *p* = .001. Therefore, logic-based (accurate) reasoning in the context of a conflicting belief is slower than is accurate responding in the absence of such conflict.

Mean reaction time (collapsed across accuracy) in the analysis of the interaction of congruence and emotion. Mean reaction time (collapsed across accuracy) was calculated for each participant, by congruence and emotion. A repeated-measures analysis of variance, multivariate approach, was conducted, with mean reaction time as the dependent variable. The factors were Congruence (congruent, incongruent) and Emotion (positive, neutral, negative). The interaction was not significant. There was a significant main effect of Congruence: $F(1, 12) = 8.173$, $p = .014$, partial $\eta^2 = .405$. Overall, participants responded significantly more slowly when their beliefs were in conflict with the logical argument of the syllogism, regardless of valence of picture rating and regardless of accuracy. Mean reaction times (collapsed across accuracy) were as follows ($n = 13$): (a) congruent positive: 3937 ms (*SD* 1202); (b) congruent neutral: 4043 ms (*SD* 752); (c) congruent negative: 4012 ms (*SD* 837); (d) incongruent positive: 4289 ms (*SD* 818); (e) incongruent neutral: 4301 ms (*SD* 1110); (f) incongruent negative: 4681 ms (*SD* 986).

Appendix D: Supplementary Behavioural Analyses from the Tone of Voice Study

Main effect of task (reasoning / baseline). The overall proportion of logical (correct) responses on the reasoning trials was .669; for baselines (where the expected response would always be "not valid"), the proportion of logical responses was .993. Mean reaction time on reasoning trials was 2211 ms (*SD* 1121), and on baseline trials was 472 ms (*SD* 112). This difference was significant: paired t (14) = -6.366, p = .001.

Simple effect of emotion on reasoning. For each participant, the proportion of [logical (correct): total responses] was calculated within each valence. A repeated-measures analysis was conducted, using the multivariate approach, with a linear contrast as a follow-up test. The omnibus test was significant: F (2, 13) = 4.084, p = .042. 38.6% of the total variance in the proportion of logical (correct) responses:total responses was accounted for by the treatment (aural delivery of reasoning syllogisms in neutral, angry, or sad tone of voice). The follow-up linear contrast, with conditions weighted as neutral (-1), sad (0), and angry (+1), was significant: F (1, 14) = 8.736, p = .01, indicating that the proportion of logical (correct):total responses increased as the tone of voice changed from neutral to sad to angry. 38.4% of the variance in logical (correct) responding was attributable to the effect of the varying tone of voice. Post-hoc tests indicated that the difference between the means for the neutral and angry conditions did not survive Bonferroni correction. Mean proportion logical (correct):total responses were as follows: neutral .644 (*SD* .149); sad .661 (*SD* .165); angry .726 (*SD* .167).

A repeated-measures analysis of mean reaction time along the Emotion factor could not be conducted because of a violation of the assumption of sphericity. A multivariate test indicated that there was no significant difference (*p* = .181) in mean reaction time across the Emotion factor. Mean reaction times were as follows: neutral 2277 ms (*SD* 1200); sad 1962 (*SD* 835); angry 2325 (*SD* 1365).

A repeated-measures analysis of response time when responding logically (correctly) was conducted across the Emotion factor. There was no significant difference among the means (*p* = .818). Mean reaction times were as follows: neutral 1599 ms (*SD* 480); sad 1626 (*SD* 672); angry 1671 (*SD* 573).

In summary, the rate of logical reasoning tends to improve when non-emotional syllogism material is delivered in an angry tone of voice, but appears to remain unaffected by the sad tone of voice, compared to neutral. Mean response times were not affected by tone of voice, overall or when responses were logical (correct).

Congruence (across all reasoning trials). Reasoning syllogisms had been balanced on the basis of congruence between beliefs and argument logic. Therefore, for each participant, the proportion of logical (correct): total responses was calculated, among congruent syllogisms and separately among incongruent syllogisms. Overall, the mean proportion of [logical (correct) congruent: total congruent] syllogisms was .7700 (*SD* .163) and the mean proportion of [logical (correct) incongruent: total incongruent] syllogisms was .5856 (*SD* .154). Analysis revealed that the proportion of logical (correct) responses was significantly lower on incongruent than on congruent syllogisms: *paired t*(14) = -6.741, *p* = .001. This result indicates that, overall, logical (accurate) reasoning was impaired when the logic of the argument was in conflict with (that is, incongruent with) the truth of the concluding statement. Of course, when there is no conflict, the reasoner could be basing their response either on argument logic or on the truth of the facts; either strategy would yield the same outcome.

For each participant, the mean reaction time was calculated separately for congruent and incongruent reasoning trials (collapsed across accuracy). Overall mean reaction time to congruent syllogisms was 1933 ms (*SD* 1002) and to incongruent syllogisms was 2438 ms (*SD* 1229). Analysis revealed that responses were significantly slower when beliefs conflicted with the logical argument than when they did not: *paired t*(14) = -5.813, *p* = .001. This result indicates that, overall, reasoning takes longer when a conflict is encountered between the argument logic and the belief about the content. However, this result does not isolate reaction time when reasoning was, specifically, accurate or logical.

Therefore, for each participant, the mean reaction time was calculated separately for congruent and incongruent reasoning trials, this time for logical (correct) responses only. Mean reaction time when responding logically to congruent syllogisms was 1395 ms (*SD* 443) and to incongruent syllogisms was 1904 ms (*SD* 583). Analysis revealed that logical (correct) responses were significantly slower when beliefs conflicted with the logical argument than when they did not: *paired t*(14) = -5.385, *p* = .001. This result demonstrates that logical (correct) reasoning takes significantly longer when a conflict is encountered between the argument logic and the belief about the content.

Mean reaction time (collapsed across accuracy) in the analysis of the interaction of congruence and emotion. The mean reaction time, to reasoning syllogisms overall, was analysed for Congruence (congruent, incongruent) X Emotion (sad, neutral, angry) using a repeated-measures analysis (multivariate approach). The Congruence x Emotion interaction was significant: *F*(2, 13) = 3.845, *p* = .049. 37.2% of the total variability in mean response time is attributable to the dependence of the congruence effect on the tone of voice in which the syllogisms were delivered. There was no main effect of Emotion (*p* = .218). However, the main effect of Congruence was significant: *F*(1, 14) = 41.742, *p* = .001. 74.9% of the total variability in mean response time is attributable to congruence, regardless of emotion. A follow-up linear contrast for mean response time among congruent trials was significant, indicating that reaction time to congruent syllogisms (collapsed across accuracy) became faster as the tone of voice changed from neutral to angry to sad; *F*(1, 14) = 8.601, *p* = .011. 38.1% of the total variability in mean response time to congruent syllogisms is attributable to the effect of the tone of voice condition. The difference in mean reaction time between the neutral and sad condition did not survive Bonferroni correction. A similar test among incongruent trials was not significant.

Mean reaction times (collapsed across accuracy) were as follows: (a) congruent sad: 1664 ms (*SD* 827); (b) congruent neutral: 2102 ms (*SD* 1136); (c) congruent angry: 1934 ms (*SD* 1132); (d) incongruent sad: 2267 ms (*SD* 929); (e) incongruent neutral: 2394 ms (*SD* 1268); (f) incongruent angry: 2717 ms (*SD* 1643). This analysis includes incorrect responses, for which there could be explanations other than the effect of beliefs.