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The role of effective connectivity between the task-positive and task-negative network for evidence gathering [Evidence gathering and connectivity]

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ABSTRACT

Reports linking a 'jumping-to-conclusions' bias to delusions have led to growing interest in the neurobiological correlates of probabilistic reasoning. Several brain areas have been implicated in probabilistic reasoning; however, findings are difficult to integrate into a coherent account. The present study aimed to provide additional evidence by investigating, for the first time, effective connectivity among brain areas involved in different stages of evidence gathering. We investigated evidence gathering in 25 healthy individuals using fMRI and a new paradigm (Box Task) designed such as to minimize the effects of cognitive effort and reward processing. Decisions to collect more evidence ('draws') were contrasted to decisions to reach a final choice ('conclusions') with respect to BOLD activity. Psychophysiological interaction analysis was used to investigate effective connectivity. Conclusion events were associated with extensive brain activations in widely distributed brain areas associated with the task-positive network. In contrast, draw events were characterized by higher activation in areas assumed to be part of the task-negative network. Effective connectivity between the two networks decreased during draws and increased during conclusion events. Our findings indicate that probabilistic reasoning may depend on the balance between the task-positive and task-negative network, and that shifts in connectivity between the two may be crucial for evidence gathering. Thus, abnormal connectivity between the two systems may significantly contribute to the jumping-to-conclusions bias.

Introduction

The jumping-to-conclusions bias (JTC) is a tendency to make inferences based on scarce evidence. It is typically assessed using probabilistic reasoning tasks such as the 'beads task' (Huq et al., 1988), in which participants are presented colored beads (e.g. red and blue) drawn in succession, and are asked to infer which of two jars containing beads in opposite color ratios (e.g. 85:15 and 15:85) the presented beads originate from. In such tasks, decisions based on very few pieces of evidence (typically, one or two 'draws'), are considered an index of JTC bias. JTC belongs to a group of higher-order reasoning styles, termed 'cognitive biases', that lead to a distorted integration and interpretation of incoming information. Its interest for research lies in its link to delusions as a clinical symptom of psychotic disorders, as patients with delusions and predisposed individuals have been observed to consistently gather less evidence than healthy individuals before arriving to a decision in JTC tasks (Ross et al., 2015; Dudley et al., 2016; McLean et al., 2016). Thus, research into the neurobiological bases of the JTC bias might provide useful hypotheses to test in clinical populations.

Although variants of the beads task have been widely used in behavioral studies, few studies have focused on their neuroimaging correlates. Functional magnetic resonance imaging (fMRI) studies comparing probabilistic reasoning to control tasks in healthy subjects have reported activations across widely distributed brain areas including the prefrontal, parietal, medial temporal cortex and the insula (Esslinger

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et al., 2013; Krug et al., 2014a,b). However, the block design used in these studies is not ideal for studying the brain structures involved in JTC, as it does not differentiate between draw events (i.e., when participants choose to see more evidence) and decision events (i.e., when a conclusion regarding the majority color is made). Thus, the above activations may be quite unspecific, reflecting, to an unknown extent, general cognitive demands posed by JTC tasks on e.g., attention or working memory. Moreover, similar activations have been reported by studies investigating non-probabilistic decision making under risk or uncertainty (e.g. Volz et al., 2003; Huettel et al., 2005; Grinband et al., 2006; Krain et al., 2006; Basten et al., 2010).

Studies using event-related designs and analyses have provided insights into more specific aspects of probabilistic reasoning: *Conclusion* events appear to be associated with greater activations in the medial prefrontal (mPFC) and dorsal anterior cingulate cortex (dACC), insula, parietal cortex and thalamic/striatal areas (Furl and Averbeck, 2011; Esslinger et al., 2013). In contrast, *draw* events have been associated with activations in the posterior cingulate cortex (PCC), but also lateral prefrontal and visual areas, and the temporoparietal junction (Furl and Averbeck, 2011). The subjective experience of *uncertainty* (reflected in response confidence) has been linked to activations in inferior frontal regions such as the ventromedial (Stern et al., 2010) and orbitofrontal cortex (Demanuele et al., 2015), while *probability updating* has been suggested to be mediated by the dACC (Stern et al., 2010; Whitman et al., 2013; Demanuele et al., 2015) and possibly also the dorsolateral prefrontal cortex (DLPFC) (Whitman et al., 2013; Demanuele et al., 2015). Finally, inferior parietal areas around the intraparietal sulcus are associated with increased evidence seeking under conditions of higher uncertainty or risk, and have been suggested to be associated with *willingness to seek more evidence* before arriving to a conclusion (Furl and Averbeck, 2011) –a central concept in the definition of JTC.

However, the above results are not always easy to reconcile in a coherent account of probabilistic reasoning. For example, dACC and DLPFC are implicated in probability updating (draw events) (Stern et al., 2010; Whitman et al., 2013; Demanuele et al., 2015), but also to trigger the final conclusion (decision events) (Esslinger et al., 2013; Whitman et al., 2013). Moreover, the aforementioned inferior parietal areas associated with increased evidence seeking (Furl and Averbeck, 2011) would be expected to be more active during draw than during decision events; however, the opposite is the case, raising the possibility that these areas are related to decision confidence rather than increased willingness to seek evidence. The above make it difficult to infer the neural correlates of JTC. One possible reason is that all existing studies have focused only on activations of brain areas, without taking into account how these areas may interact with each other during the various stages of evidence gathering. This latter point is particularly important in light of the current trend of the neuroimaging literature to move beyond the search for individual brain areas as loci of specific cognitive functions, and focus instead on the functional integration of brain areas into networks (Bressler and Menon, 2010; Sporns, 2014). This focus has proven advantageous for the study of complex functions such as emotion processing or memory, and has provided novel insights into psychiatric disorders such as schizophrenia. In this context, we assumed that the evidence gathering process may result from the dynamic interaction between two brain networks: A network responsible for evidence updating, possibly including the dACC, and another network that keeps track of uncertainty and might include areas such as the inferior parietal cortex or inferior frontal areas. According to our conceptualization, connectivity changes between the two hypothesized networks might determine when evidence accumulation is completed and a final conclusion is reached. The present study aimed to investigate this hypothesis by using fMRI to investigate not only brain activity, but also functional connectivity patterns during probabilistic reasoning in healthy individuals.

Material & methods

Participants

Participants were 27 healthy individuals (16 male) aged 23–54 years (mean 34.7 ± 9.7), who were recruited through postings on university recruitment sites and local media. Exclusion criteria were any past or current psychiatric (including substance use) or neurological disorder, a history of schizophrenia or bipolar disorder in a first degree relative, a history of cranio-cerebral trauma or serious medical conditions, and IQ lower than 70; moreover, the usual exclusion criteria for MRI studies (such as presence of metal parts or devices sensitive to magnetic fields) applied.

The Mini International Neuropsychiatric Interview (MINI; Sheehan et al., 1998) was used to screen for past or current psychiatric disorders, and eligibility criteria were assessed by means of a structured checklist. The study was approved by the Ethics Committee of the Psychological Association Hamburg, and was performed in accordance with the most recent version of the Declaration of Helsinki ethical standards. All participants provided written informed consent before participating in the study, and were reimbursed with 20 EUR for their participation.

Because the probabilistic reasoning paradigm implemented in the MRI scanner does not provide a cut-off for jumping-to-conclusions, the presence or absence of the latter was assessed with the Fish Task (Moritz et al., 2010), a well-established computerized variant of the Beads task, in which beads and jars have been replaced by fish and lakes. JTC was defined as decisions made after 1 or 2 draws.

Probabilistic reasoning paradigm

We used an fMRI-adapted version of the Box Task (Andreou et al., 2015; Balzan et al., 2017) to assess probabilistic reasoning. The Box Task is based on the Information Sampling Task (IST) of the CANTAB (Clark et al., 2006), but all elements of the IST related to feedback and reward have been removed in order to isolate the effects of evidence gathering to the best possible extent. The validity and reliability of the Box Task have been confirmed in previous studies (Andreou et al., 2015; Moritz et al., 2017).

In each trial, participants were presented with a 5×5 array of grey boxes on the screen, which opened one by one to reveal their color, corresponding to one of two colors displayed on two large panels at the bottom of the screen (see Supplement, Figure S1). Each trial started with a fixation display (4–20 s) and a display of the color ratio (either 80:20 or 60:40) for 2 s. After a jittered interval of 1–3 s, one box opened. After further 2 s, a question mark appeared between the two color panels at the bottom of the screen; this was the cue for the participant to indicate whether they were satisfied that they knew which color was in the majority (by pressing the left or right button on an fMRI-compatible response box to select the left or right color panel, respectively), or whether they wished to see more boxes open (by pressing the middle button on the response box). If the participant wished to see more evidence, another box opened after a jittered interval of 1–3 s; if they selected one of the two colors, the trial was terminated and a new trial started after a fixation display.

The duration of the fixation display varied between 4 and 20 s in an inverse relation to the total duration of the last trial, in order to prevent participants from prematurely terminating trials to speed up the task. All opened boxes remained visible throughout the trial to minimize working memory load. The task consisted of 3 blocks of 14 trials each (7 for each color ratio); trials of the same color ratio were presented in succession within each block, and ratio order was randomized across blocks. The distribution of colors across boxes and the order in which they opened was randomized in each trial. Because of that, and of the possibility to open a total of 25 boxes, the Box Task allows for greater flexibility than classical data-gathering paradigms regarding the presented sequences.