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Review

Dopamine, cognitive biases and assessment of certainty: A neurocognitive model of delusions

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ABSTRACT

This paper examines the evidence that delusions can be explained within the framework of a neurocognitive model of how the brain assesses certainty. Here, 'certainty' refers to both low-level interpretations of one's environment and high-level (conscious) appraisals of one's beliefs and experiences. A model is proposed explaining how the brain systems responsible for assigning certainty might dysfunction, contributing to the cause and maintenance of delusional beliefs. It is suggested that delusions arise through a combination of perturbed striatal dopamine and aberrant salience as well as cognitive biases such as the tendency to jump to conclusions (JTC) and hypersalience of evidence-hypothesis matches. The role of emotion, stress, trauma and sociocultural factors in forming and modifying delusions is also considered. Understanding the mechanisms involved in forming and maintaining delusions has important clinical implications, as interventions that improve cognitive flexibility (e.g. cognitive remediation therapy and mindfulness training) could potentially attenuate neurocognitive processes.

1. Delusional beliefs

Delusional beliefs are defined as highly improbable beliefs that are held with strong conviction and are not modified in the face of evidence to the contrary (American Psychiatric Association, 2013). Delusions are cardinal symptoms of psychosis and present in schizophrenia spectrum disorders, mania and psychotic depression, but may also occur in other presentations such as Alzheimer's disease, obsessive compulsive disorder and within the nonclinical population (Cowen, Harrison, & Burns, 2012). While innocuous delusions are relatively common within the 'normal' population (Johns & Van Os, 2001), in clinical populations delusions are associated with lower levels of wellbeing (Broyd, Jolley, & Johns, 2016; Freeman et al., 2014) and are often accompanied by significant distress, depression and anxiety (Smith et al., 2006), particularly if they are persecutory in nature (Freeman, Garety, Kuipers, Fowler, & Bebbington, 2002). In such cases, people can become highly preoccupied with their beliefs, and they can impact significantly on their personal, social and occupational functioning (Freeman, 2007).

People with delusions often report highly compelling subjective experiences (Chapman, 1966), even though their beliefs are, by definition, at odds with the environment they have actually encountered (Moritz & Woodward, 2006a). This suggests underlying interference in a range of metacognitive and neurocognitive systems involved in perception, reasoning, belief formation and the appraisal of one's experiences. In this article we will examine the evidence that delusions can be explained within the framework of neurocognitive models of how the brain assesses the certainty of perceptions, beliefs and thoughts. We will consider the empirical evidence for these neurocognitive models and their limitations. Finally, based on the existing evidence base, we propose a model explaining how alterations in the brain systems responsible for assigning certainty contribute to the cause and maintenance of delusional beliefs.

2. Assigning certainty

Although 'assigning certainty' can be interpreted as a unitary confidence judgment (Fleming, Dolan, & Frith, 2012; Insabato, Pannunzi, Rolls, & Deco, 2010; Rolls, Grabenhorst, & Deco, 2010), here it will refer to two different but related processes (see White, Engen, Sorensen, Overgaard, & Shergill, 2014). Firstly, it will refer to the ability to assign certainty to objective information provided by a stimulus, event, behaviour or cognitive state. This involves a 'low-level'

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inference based on the perceived characteristics of a stimulus. Secondly, assigning certainty will refer to the subjective confidence or feelings of conviction associated with a particular belief or experience. This constitutes a 'high-level' (conscious) judgment that relies on metacognitive ability (reasoning or beliefs about one's own cognitions) (Sandberg, Timmermans, Overgaard, & Cleeremans, 2010). Subjective feelings of conviction (or certainty) in one's beliefs will therefore rely both on the quality of perceptual information received (e.g. consistent stimulus and lack of interfering brain processes) as well as the capacity to self-scrutinise one's inference.

3. Bottom-up and top-down processing

The ways in which the brain perceives, attends to and processes perceptual information can be considered either a 'top-down' or a 'bottom-up' process (for review see Theeuwes, 2010). Bottom–up attentional control is stimulus-driven, i.e. attention is spontaneously oriented towards an incoming stimulus. Our *high-level* beliefs can therefore be conceptualised as being influenced by our *low-level* environmental perceptions through bottom-up processing. In contrast, top–down attentional control is intentional and cognitively driven, i.e. directed by knowledge, expectation and current goals (Desimone & Duncan, 1995). Top-down processing can conversely be conceptualised as our pre-existing high-level beliefs and knowledge exerting an influence on low-level perceptions of the environment. In simple terms, bottom-up processing leads us to believe what we perceive and top-down processing leads our perceptions to be biased or altered in line with what we already believe. Importantly, top-down and bottom-up processes represent overlapping organizational principles, and interact to optimize attentional performance (Sarter, Givens, & Bruno, 2001) but are associated with different brain networks (Corbetta & Shulman, 2002).

Perceptions therefore arise from an interaction between 'top-down' functions (e.g. learned expectations, hypotheses and reasoning) and objective stimulus data (Delorme, Rousselet, Macé, & Fabre-Thorpe, 2004; Mechelli, Price, Friston, & Ishai, 2004). According to such a model, it is possible for 'top-down' goals to influence the perception of one's environment (Theeuwes, 2010). A classic example of this is the slower and less accurate recognition that arises when an object presented in a particular scene violates the surrounding contextual information or is of an inappropriate size or location (e.g. a fire extinguisher sitting directly on top of a post box in a street scene) (Biederman, Mezzanotte, Rabinowitz, & Scene perception: Detecting and judging objects undergoing relational violations, 1982). This seems to indicate that contextual cueing or 'priming' can influence perception in a top-down fashion.

4. Theoretical accounts of delusions

A number of theoretical accounts have been put forward to explain delusions. As they are theoretical frameworks, they do not require evidence of empirical association with the severity of delusions. However, as will be addressed below, some have been tested empirically.

4.1. Aberrant perceptions

It has been suggested that delusional beliefs arise as a secondary response to aberrant or erroneous perceptions (Escher, Romme, Buiks, Delespaul, & van Os, 2002; Krabbendam et al., 2004). For example, Maher (Maher, 2005, 2006) argues that "bizarre" or delusional interpretations are a rational response to anomalous but genuine sensory experiences such as auditory or visual hallucinations that are also common in psychosis (Nayani & David, 1996). This account is consistent with the idea that certainty judgments can be erroneous at a basic low-level perceptual inferences level, which, then alter subjective high-level interpretations (i.e. arising through bottom-up processes). This seems consistent with the experiences of people with highly specific or 'monothematic' delusions. One such example is the 'Capgras delusion', which involves the highly compelling and specific belief that a friend or family member has been replaced by an imposter (in the absence of psychosis elsewhere) (Ellis, Young, Quayle, & De Pauw, 1997). The Capgras delusion has been explained through disconnection between an intact face recognition system and an intact autonomic nervous system. According to this account, the delusion arises from the patient attempting to explain the anomalous experience of recognising a familiar face in the absence of the usual affective response associated with that face (Coltheart, Langdon, & McKay, 2007; Coltheart, Menzies, & Sutton, 2010; Davies, Breen, Coltheart, & Langdon, 2001). This leads familiar faces to be perceived as strangers through dysfunctional bottom-up processes. However, a purely bottom-up explanation of delusions does not seem to account for delusional beliefs in the absence of perceptual disturbance (e.g. hallucinations), fails to account for the experiential qualities of delusions, and equally fails to explain why some unusual experiences and perceptions do not develop into delusions (Bell, Halligan, & Ellis, 2008; Hohwy, 2004; Langdon & Coltheart, 2000).

An alternative account proposes that pre-existing beliefs and reasoning/attentional biases may exert a 'top-down' influence to alter one's perception of sensory information (Adams, Stephan, Brown, Frith, & Friston, 2013; Fletcher & Frith, 2009). For example, Campbell (2001) disagrees that monothematic delusions arise through bottom-up processes, arguing instead that beliefs such as the Capgras delusion would not occur without a disruption of the top-down loading of one's fundamental beliefs influencing one's perceptual experience. For example, feelings of familiarity and memories associated with a particular person may be impaired at higher levels, which could alter perceptions of the person in a top-down fashion (Bayne & Pacherie, 2004). This account would suggest that delusions may arise through high-level certainty judgments influencing sensory experiences in a top-down way, although there is no convincing empirical evidence to support that monothematic delusions arise in this way.

4.2. Predictive coding

An influential account of delusions posits that they arise from a single core abnormality in updating beliefs and inferences in a Bayesian (or probabilistic) fashion (Adams et al., 2013; Fletcher & Frith, 2009; Hohwy, 2013). This account rests on the premise that the biological (neural), cognitive and experiential features of delusions are all explained through a unitary abnormality in predictive coding. Predictive coding refers to a brain process that aims to maximise cognitive efficiency by using prior experience to predict incoming sensory information. 'Surprise' (or 'prediction error') may occur when a person's learned expectations conflict with objective sensory input. Cognitive resources are then preferentially allocated to processing this novel information (Fletcher & Frith, 2009). This means that novel experiences that are consistent with pre-existing beliefs may be ignored or receive less attention due to their predictability, while those that are inconsistent with beliefs (and therefore 'surprising' or interesting) may be preferentially attended to and/or acted upon.

In delusions, 'false' prediction error signals may arise at lower levels in the brain and, through cognitive attempts to reduce the prediction-error signal (which indicates that pre-existing beliefs are not adequately accounting for the perceived input), adjustments will then be made at higher cognitive levels in order to minimise this discrepancy. Therefore false prediction error signals are thought to 'propagate up a belief hierarchy' (a 'Bayesian hierarchy') to form delusions. Within a framework of assigning certainty, the predictive coding account can be conceptualised as an inability to assign certainty at the low/perceptual level, which through bottom-up propagation can influence high-level certainty/beliefs. By definition, delusions are fixed false beliefs, so