Neuroscience and Biobehavioral Reviews 37 (2013) 1724–1737

Contents lists available at ScienceDirect

Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

Review

A revised limbic system model for memory, emotion and behaviour

Marco Catani [a,*], Flavio Dell'Acqua [a,b,c], Michel Thiebaut de Schotten [a,d,*]

[a] Natbrainlab, Department of Forensic and Neurodevelopmental Sciences, Institute of Psychiatry, King's College London, UK
[b] Department of Neuroimaging Sciences, Institute of Psychiatry, King's College London, UK
[c] NIHR Biomedical Research Centre for Mental Health at South London and Maudsley NHS Foundation Trust and Institute of Psychiatry, King's College London, UK
[d] UMR_S 975; CNRS UMR 7225, Centre de Recherche de l'Institut du Cerveau et de la Moelle épinière, Groupe Hospitalier Pitié-Salpêtrière, 75013 Paris, France

ARTICLE INFO

Article history:
Received 27 November 2012
Received in revised form 15 May 2013
Accepted 1 July 2013

Keywords:
Limbic system
Tractography
White matter connections
Brain networks
Emotion
Memory
Amnesia
Dementia
Antisocial behaviour
Schizophrenia
Depression
Bipolar disorder
Obsessive–compulsive disorder
Autism spectrum disorder

ABSTRACT

Emotion, memories and behaviour emerge from the coordinated activities of regions connected by the limbic system. Here, we propose an update of the limbic model based on the seminal work of Papez, Yakovlev and MacLean. In the revised model we identify three distinct but partially overlapping networks: (i) the Hippocampal-diencephalic and parahippocampal-retrosplenial network dedicated to memory and spatial orientation; (ii) The temporo-amygdala-orbitofrontal network for the integration of visceral sensation and emotion with semantic memory and behaviour; (iii) the default-mode network involved in autobiographical memories and introspective self-directed thinking. The three networks share cortical nodes that are emerging as principal hubs in connectomic analysis. This revised network model of the limbic system reconciles recent functional imaging findings with anatomical accounts of clinical disorders commonly associated with limbic pathology.

Contents

* Corresponding authors at: Natbrainlab, Department of Forensic and Neurodevelopmental Sciences, Institute of Psychiatry, 16 De Crespigny Park, London SE5 8AF, UK.
E-mail addresses: m.catani@iop.kcl.ac.uk (M. Catani), michel.thiebaut@gmail.com (M. Thiebaut de Schotten).

0149-7634/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.neubiorev.2013.07.001

1. Introduction

The limbic system is a group of interconnected cortical and subcortical structures dedicated to linking visceral states and emotion to cognition and behaviour (Mesulam, 2000). The use of the term 'limbic' has changed over time. Initially introduced by Thomas Willis (1664) to designate a cortical border encircling the brainstem (limbus, Latin for 'border') (Fig. 1) the term has been used in more recent times to indicate a progressively increasing number of regions dedicated to a wide range of functions (Marshall and Magoun, 1998; Mega et al., 1997). Paul Broca (1878) held the view that 'le grand lobe limbique' was mainly an olfactory structure common to all mammalian brains, although he argued that its functions were not limited to olfaction (Fig. 2). After Broca's publication the accumulation of experimental evidence from ablation studies in animals broadened the role of the limbic structures to include other aspects of behaviour such as controlling social interactions and behaviour (Brown and Schäfer, 1888), consolidating memories (Bechterew, 1900), and forming emotions (Cannon, 1927).

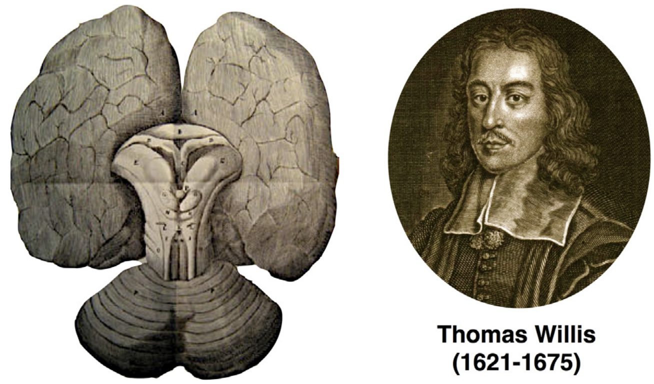

Fig. 1. The limbic system described for the first time by Thomas Willis (1664) to indicate cortical regions located around the brainstem.

Anatomical and physiological advancements in the field led Christfield Jakob (1906) (Fig. 3) and James Papez (1937) (Fig. 4) to formulate the first unified network model for linking action and perception to emotion. According to Papez emotion arises either from cognitive activity entering the circuit through the hippocampus or from visceral and somatic perceptions entering the circuit through the hypothalamus. In the case of emotion arising from cognitive activity, for example, '*incitations of cortical origin would pass first to the hippocampal formation and then down by way of the fornix to the mammillary body. From this they would pass upward through the mammillo-thalamic tract, or the fasciculus of Vicq d'Azyr, to the anterior nuclei of the thalamus and thence by the medial thalamocortical radiation [or anterior thalamic projections] to the cortex of the gyrus cinguli [. . .] The cortex of the cingular gyrus may be looked on as the receptive region for the experiencing of emotion as the result of impulses coming from the hypothalamic region [or the hippocampal formation][. . .] Radiation of the emotive process from the gyrus cinguli to other regions in the cerebral cortex would add emotional colouring to psychic processes occurring elsewhere* (Papez, 1937)'

A decade later, Paul Yakovlev (1948), proposed that the orbitofrontal cortex, insula, amygdala, and anterior temporal lobe form a network underlying emotion and motivation (Fig. 5). In two seminal papers published in 1949 and 1952, Paul. MacLean crystallised previous works by incorporating both Papez and Yakovlev view into a model of the limbic system that has remained almost unchanged since (MacLean, 1949, 1952). MacLean concluded that the limbic cortex, together with the limbic subcortical structures, is a functionally integrated system interconnected by short- and long-range fibre bundles (Fig. 6).

The development of tracing methods for studying long axonal pathways added details to the anatomical model of the limbic system (Crosby et al., 1962). These methods allowed, for example, the description of long and short connections of the cingulate cortex in animals. Further, the combination of anatomical methods with experimental procedures was used to demonstrate a direct link between specific limbic structures and behavioural response (e.g. amygdala and aggressive response). Unfortunately, axonal tracing could not be applied to human anatomy for the study of the biological underpinnings of those abilities that characterise human mind (e.g. emotions; empathy). Also animal models were not suitable for studying anatomical differences in psychiatric conditions such as autism and schizophrenia.

In the 1990s the use of functional neuroimaging methods (e.g. PET, fMRI) and later diffusion tractography offered the possibility of studying the functional anatomy of the limbic system in the living human brain. A major finding that emerged initially from PET studies and later confirmed with fMRI was the identification of a 'default network', consisting of a set of regions that activate under resting-state condition and deactivate during task-related functions (Buckner et al., 2008; Raichle et al., 2001; Raichle and Snyder, 2007; Shulman et al., 1997) (Fig. 7). The most medial regions of the default network correspond to the most dorsal portion of the Papez circuit and are interconnected through the dorsal cingulum.

Diffusion imaging is an advanced MRI technique based on optimised pulse sequences, which permits the quantification of the diffusion characteristics of water molecules inside biological tissues (Le Bihan and Breton, 1985). Given that cerebral white matter contains axons, and that water molecules diffuse more freely along axons than across them (Moseley et al., 1990), it is possible to obtain in vivo estimates of white matter fibre orientation by measuring the diffusivity of water molecules along different directions (Basser et al., 1994). By following the orientation of the water

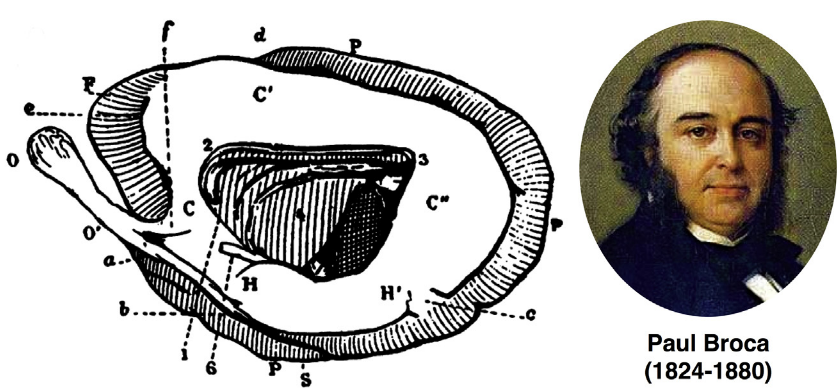

Fig. 2. Paul Broca (1878) identified the limbic system as mainly an olfactory structure of the mammalian brain.