https://doi.org/10.1038/s41583-023-00725-6

The hypothesis of fundal cognition

Understanding how the brain organizes information into functional representations and networks that support flexible cognitive behaviour is a major goal in neuroscience. In a 1994 paper, Markowitsch and Tulving identified a relationship between functional activations (observed by positron emission tomography (PET)) and the deepest points (fundi) in the indentations (sulci) of the human cerebral cortex (HCC). Many researchers probably associate Tulving with pioneering research differentiating semantic and episodic memory — and not with a hypothesis of fundal cognition. Indeed, while many of Tulving's papers and book chapters have been cited thousands of times, the paper discussing the fundal cognition hypothesis has been cited fewer than 30 times.

Markowitsch and Tulving conducted a meta-analysis of 30 studies and showed that 57% of PET loci activated during memory or problem-solving tasks occurred at (or were associated with) fundi. By contrast, a minority (30%) of such loci were associated with basic motor and sensory tasks. The authors concluded that there may be a correlation between deep, fundal points in the HCC and "computational complexity".

Some researchers questioned the accuracy of the mapping between coarse, stereotaxic coordinates of PET data and fundal points in average template space. The authors acknowledged these concerns in a section entitled "Are the findings real?" They wrote: "A number of experts in the field of PET who are aware of our "fundus story" have expressed serious doubts about its reality." Why the doubters? Well, as about 60–70% of the HCC is buried in sulci, a majority of functional neuroimaging activations should be buried in sulci. Nevertheless, it's important to remember that their hypothesis of fundal cognition was based not on the absolute percentages, but on the difference in the percentages of PET locus–fundus correspondences between more complex cognitive tasks and basic motor and sensory tasks.

Despite these doubts, the paper is important, as a growing body of work over the past three decades empirically supports a relationship between individual differences in sulcal morphology and individual differences in cognition and functional representations across age groups, species and different clinical populations. This relationship includes the deepest fundal points (known as sulcal pits or sulcal roots). For example, Régis et al. proposed the importance of deep sulcal points as roots for the functional organization of brain development (related to the popular 'protomap' model). Building on this proposal, and the fact that Markowitsch and Tulving admitted that their meta-analytic approach "overlooks developmental considerations," a major topic for future work could be to test the fundal cognition hypothesis longitudinally in the same individuals. A particular focus of future studies could be on tertiary sulci, which emerge late in gestation, continue to develop after birth and are often linked to human-specific aspects of cognition.

Of course, as many animal models in neuroscience have smooth, lissencephalic brains, an additional empirical goal could be to identify anatomical mechanisms that underlie the correspondence between deep fundal points and functional representations. Mechanistically, Markowitsch and Tulving proposed fundal points as convergence zones and "hubs of crosscortical traffic" on the basis of underlying anatomical features. For example, fundal points often differ from sulcal walls and gyral crowns in their microarchitecture and connectivity, as well as exhibiting sparse thalamocortical connections.

Altogether, although Markowitsch and Tulving admitted that "direct evidence for the hypothesis clearly is quite frail," there is growing evidence supporting a relationship between deep fundal points in some parts of the HCC and cognition. Of course, this is probably not always the case, and future studies will pinpoint where in the brain and when during development and life this relationship occurs. Finally, future tests of the fundal cognition hypothesis should aim to determine the combination of anatomical and functional mechanisms that underlie the complex relationship between fundal points and cognitive performance.

Kevin S. Weiner
Department of Psychology, Helen Wills Neuroscience Institute, University of California, Berkeley, Berkeley, CA, USA.
e-mail: kweiner@berkeley.edu

Acknowledgements
This research was supported by NSF CAREER 2042251 and NARSD 30738. I thank S. Bunge, B. Jagust and E. Willbrand for comments on previous versions of this Journal Club article.

Competing interests
The author declares no competing interests.

Original article: Markowitsch, H. J. & Tulving, E. Cognitive processes and cerebral cortical fundi: findings from positron-emission tomography studies. *Proc. Natl Acad. Sci. USA* **91**, 10507–10511 (1994)

Related article: Régis, J. et al. "Sulcal root" generic model: a hypothesis to overcome the variability of the human cortex folding patterns. *Neurol. Med. Chir. (Tokyo)* **45**, 1–17 (2005)