

Keith Worsley
1951-2009



Legend has it that Keith's introduction to neuroimaging followed a chance encounter in a verdant corner of McGill University. One of us (Alan Evans) found Keith gathering maple leaves in the fond hope that variations in their shape would provide a useful source of data, against which to test his statistical ideas. This was in the late 80s when PET scanners had just started producing images of cerebral hemodynamics. It was suggested to Keith that there were more than enough data in functional neuroimaging for his machinations: A suggestion that Keith took seriously. This is one of the key events in the inception of modern imaging neuroscience; although probably not the best day for the study of maple leaves.

It is difficult to imagine human brain mapping without Keith's contributions. All mainstream inference in neuroimaging rests upon his ideas and the transcription of those ideas into understandable heuristics and pragmatic computational schemes. Basically, Keith invented a new sort of statistics. Before Keith Worsley, statistical inference in brain mapping was largely limited to discrete or single tests; for example, T-tests on activities in regions of interest. However, continuous image data called for a different sort of inference, based on significant topological features like peaks and excursion sets above some threshold. This should not be confused with spatial statistics of the more traditional sort that predated Keith's contributions, which dealt mostly with kriging and related techniques. Keith introduced a fundamentally different way of characterising interesting features in images that could not be described in terms of simple numbers. The trick was to appeal to differential geometry and topology, which provided a description of the probabilistic behaviour of image data under the null hypothesis in terms of special point processes. This description was in terms of topological features such as the number of blobs and holes induced by thresholding an image. The result was a very powerful and general framework for topological inference that was grounded in random field theory (Worsley et al., 1992, 1996, 2004). This approach has been at the heart of all mainstream inference in neuroimaging since the early 90s. It is an integral part of all the commonly used voxel-based analysis software and has placed our community at the forefront of statistical developments in this area. Keith's formulation of the problem and its solutions transcend brain imaging and are likely to reach much further in the fullness of time. Random field theory has been used in the analysis of continuous psychophysical data (Worsley et al., 2007), through to the analysis of foot pressure images in the clinic (Pataky and Goulermas, 2008); from astrophysics through to meteorology (Worsley, 2002) In short, Keith was responsible for a paradigm shift that enabled statistical inference to move from scalar statistics to statistical fields or images.

These advances were particularly important for neuroimaging and, in one sense, define its history. At the time that Keith was introducing random field theory, the first brain mapping experiments were starting to appear in the high profile literature. These reports were greeted with a high degree of scepticism from people in established fields like psychology and electrophysiology; largely because it was impossible to tell which of the visually appealing blobs in activation maps were significant or not. Topological inference finessed the multiple comparison problem and allowed one to assign P-values, not to the statistics subtending each blob but to the very occurrence of the blobs themselves. With this advancement, human brain

mapping became one of the most rigorous disciplines in neuroscience, in terms of its careful statistical characterisations and control of false-positive rates. This rigor was an essential component of integrating imaging neuroscience into the broader biological sciences. It is also interesting to reflect that the advent of functional magnetic resonance imaging coincided exactly with the introduction of topological inference and random field theory. The success of fMRI may, in part, reflect the ground-work pioneered by Keith in the analysis domain. One can quantify the impact Keith has had in terms of his explosive citation rates, since the inception of these procedures.

It is impossible to describe Keith's statistical contributions precisely in such little space, but they are an inspired mix of differential topology (Morse theory), integral geometry (intrinsic volumes and Kinematic formulae) and spatial point processes derived from smooth random fields (Rice–Kac formula). The main idea behind all topological inference is to compute the behaviour of a topological feature of the blobs called the Euler characteristic. The topologically deep results of Morse theory express the Euler characteristic in terms of the number of local maxima (minima and saddle points) contained in the blob. Another branch of geometry, integral geometry, is used to express integrals or averages of Euler characteristics in terms of intrinsic volumes that measure the size and curvature of the search region, in our case, the brain. The final result is a beautiful relationship between the P-value of a blob and the volume and surface area of the brain, characterised in terms of the unit-less quantities known as resells that Keith pioneered.

*Jonathan Taylor, Alan Evans, Karl Friston
Department of Statistics
Stanford University*

(Author's title given as of the time of writing)