Investigating Along - Track Decomposition Methods in DTI – Based Tractography

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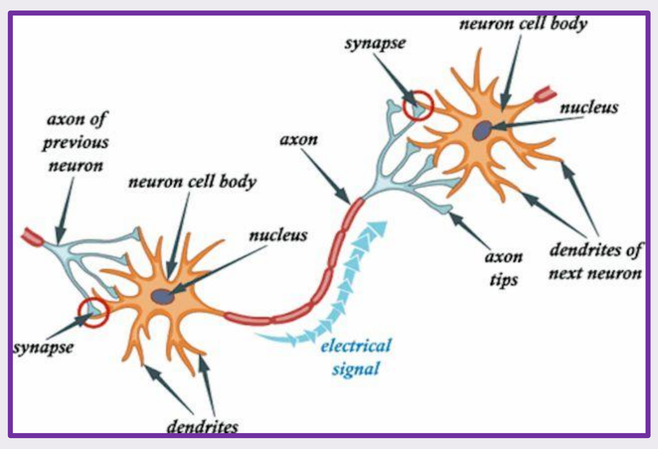
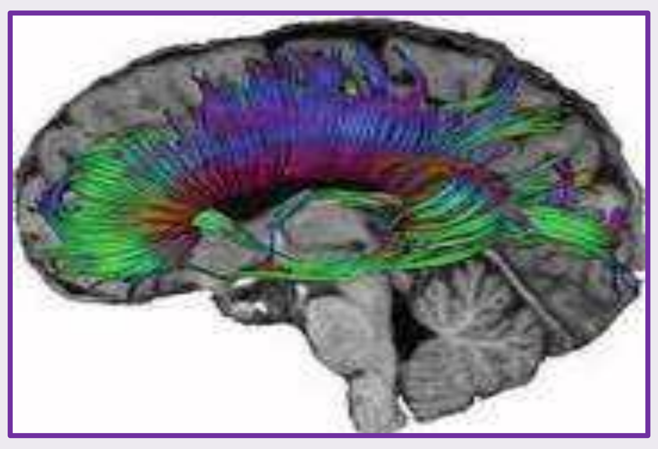
Introduction

The human brain consists of millions of neurons that transmit information from one region of the brain to another.



A schematic representation of neurons in the brain [10].



A set of fibers of the corpus callosum using diffusion tractography [11].

These regions are connected by the "axons" of these neurons and can be damaged when accidents (traumatic brain injury) occur, during the course of a degenerative disease or the course of aging.

Aims of study

- **To investigate two decomposition methods (on a realistic sequence of along-track properties) in order to ascertain which was more sensitive to detecting the aforementioned damages (represented as "outliers" in signal) along the white matter (WM) tract of the brain which would impede information from travelling successfully across the brain.**
- **To see which method works better in the presence of increasing noise which is always associated with such data.**

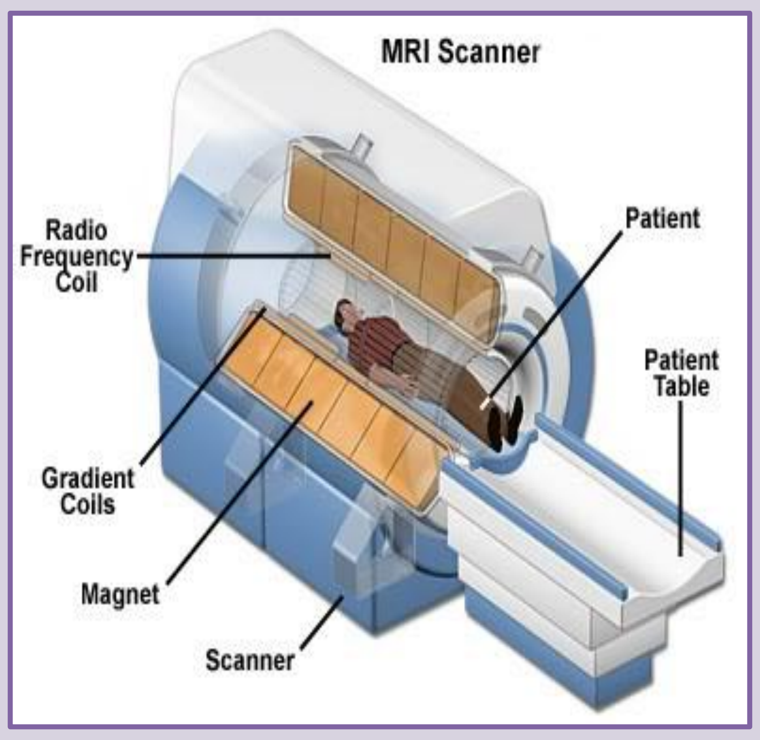
Relevance

- **Diffusion-based MRI is used to non-evasively study white matter of the brain.**
- **It provides in vivo information about connections and their properties across the brain.**
- **We can use track decompositions to investigate developmental stages of growth and diseases or disorders.**
- **May provide useful information for clinical diagnosis.**

The Process of Data Acquisition

1) **Magnetic Resonance Imaging (MRI)**

- **There is an abundance of hydrogen (H) in the body, whose magnetic moments can be excited in a magnetic field.**
- **H absorbs energy when radio-frequency pulse is applied.**
- **Releases the absorbed energy when radio-frequency is turned off.**
- **Released energy is converted to a picture of the internal organs of the body.**
- **Tissue contrast originates in differing local magnetic relaxation properties.**



An MRI Machine, [9].

2) **MRI modality: diffusion tensor imaging (DTI)**

- **Principle: directionality of major diffusion shaped along local white matter (WM).**
- **Measuring anisotropy of diffusion determines location and orientation of WM tracts.**
- **Diffusion weighted imaging (DWI):**

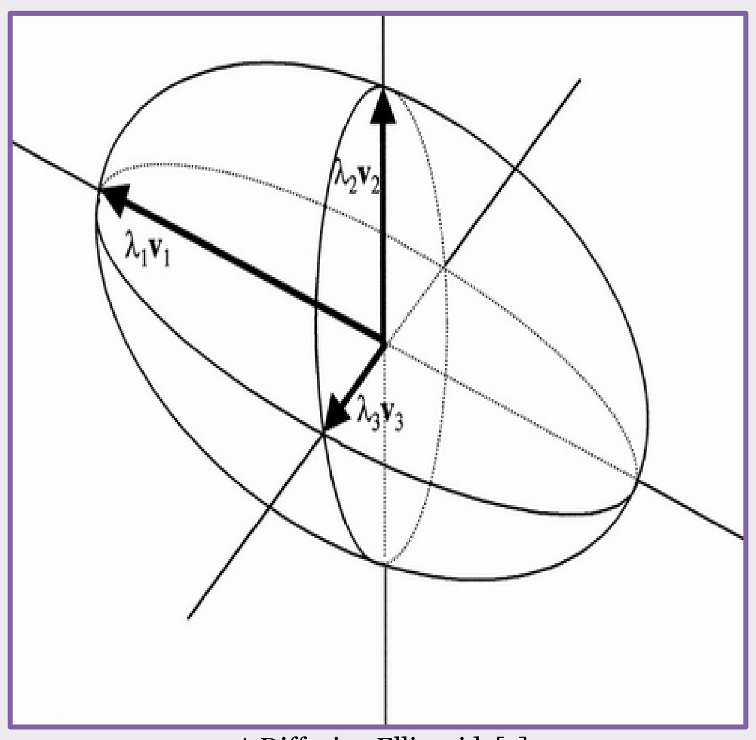
Stejskal and Tanner provided an early description of DW sequence by using a spin-echo t2 weighted pulse sequence with two extra gradient pulses that were equal in magnitude and opposite in direction, this enabled the measurement of net water movement in one direction at a time expressed as: [2].

$$SI = SI_0 \times \exp(-b \times ADC)$$

where SI_0 is the signal intensity of weighted images, (when **b**=0), **b**, is the diffusion sensitivity factor and **ADC**, the apparent diffusion coefficient.

- **Diffusion tensor acquisition and reconstruction:**

In the WM, diffusion is characterized by the shape of a fitted ellipsoid whose coefficients are described by a tensor (3x3) symmetric matrix, diagonalization of the diffusion tensor yields a basis for the diffusion ellipsoid [6].



A Diffusion Ellipsoid, [7].

- **Scalar DTI measures:**

Rotationally invariant scalar measures from estimated diffusion tensor at each voxel quantifies diffusion properties/direction.

E.g. Fractional anisotropy (FA) calculated as a scaled standard deviation of obtained eigenvalues characterizes the degree of diffusion anisotropy of the diffusion ellipsoid [3].

- **De-noising acquired data:**

The presence of noise in DTI data resulting from breathing, heartbeat etc. during measurement results in incorrect parameters from the diffusion tensor which is usually corrected using linear least-squares fits method [3].

3) **Tractography**

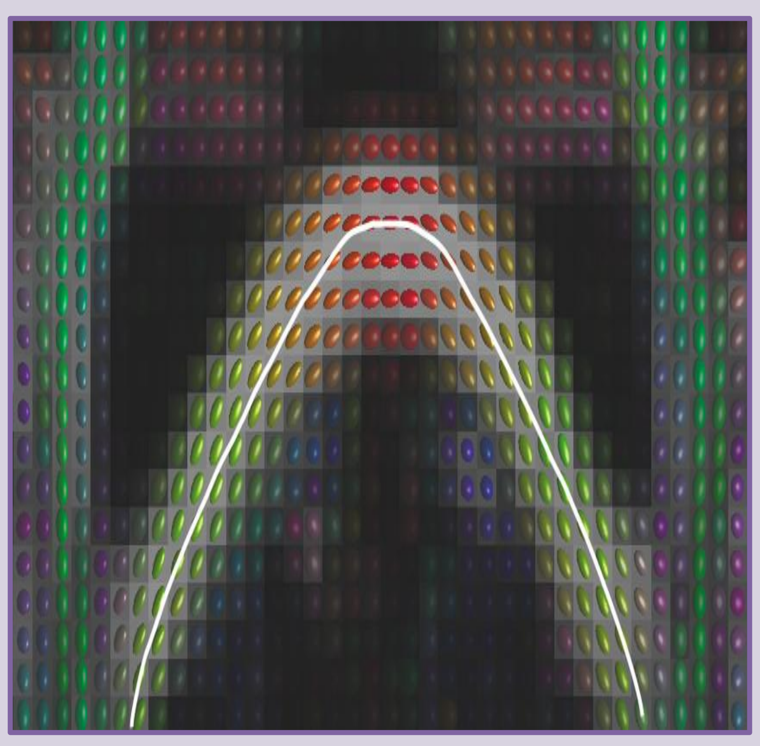
- **"Tractography" is estimating the locations of connecting WM fiber bundles that connect regions of the brain.**
- **It is a technique that uses DTI information to estimate pathways of anatomical connections in the brain. E.g., [12].**
- **The decomposition of properties is how we detect location of possible damage.**

1-D Sequence Decomposition

Two methods were implemented:

1. **Hilbert-Huang Transform (HHT).**
2. **Haar Wavelet Transform (HWT).**

Motivation: Both methods are suitable for complicated signals that are "Non-Stationary and Non-Linear"



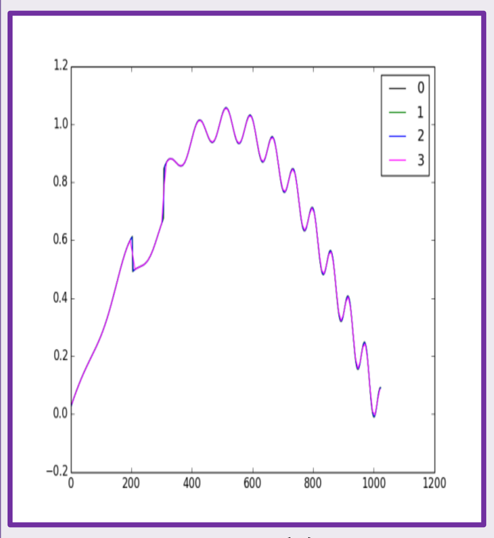
A tracked fiber, example (white line) on a background field of diffusion ellipsoids (colored by local orientation) [8].

Implementation and Results

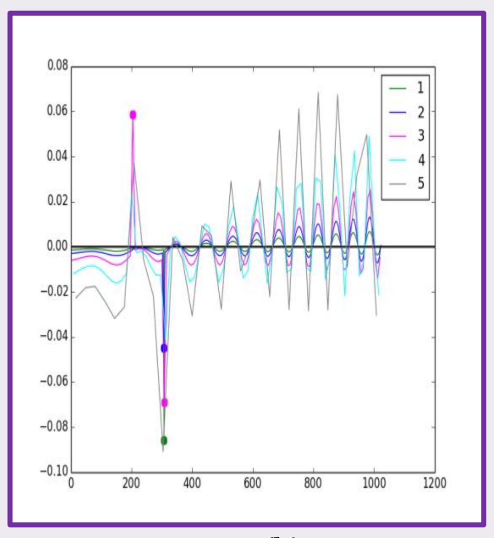
- **Programming language used: Python**

4) Haar Wavelet Transform

- **Wavelet Transforms**
- Provide local frequency information across time.
- Many wavelet based filters have properties such as time-invariance and linearity.
- Decomposes a signal successively to find increasingly low frequencies.
- **Haar Wavelet Filter (HWF)**
  - The HWT makes use of scale-varying basis functions.
  - Moving averaging filter (low pass filter).
  - Moving differencing filter (high pass filter).
  - Successive averaged and differenced signal results in a scaled transformed spectrum of the signal [5].

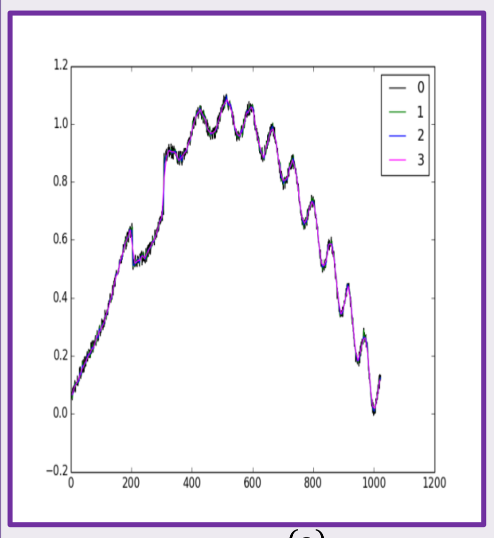


(a)

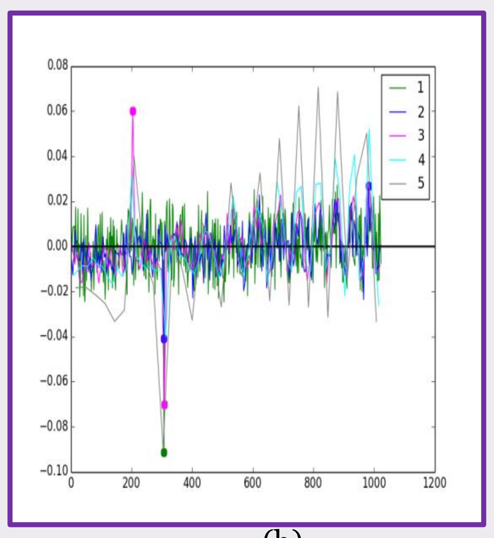


(b)

Noise level = 0

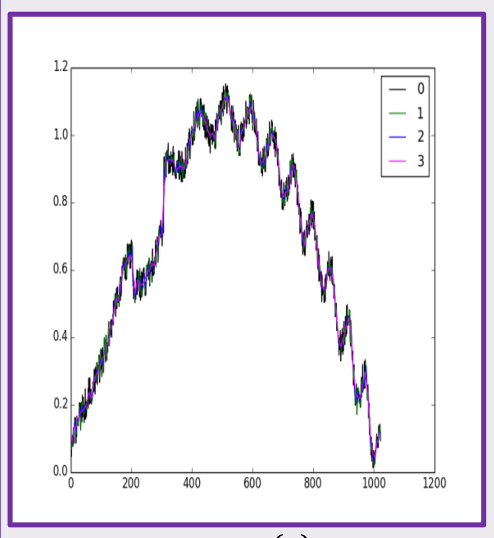


(a)

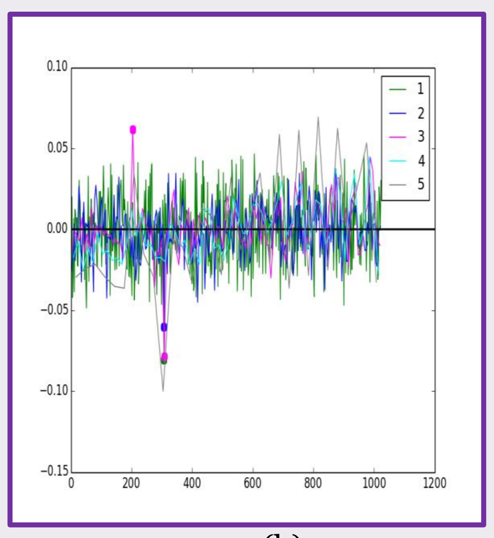


(b)

Noise level = 0.05



(a)



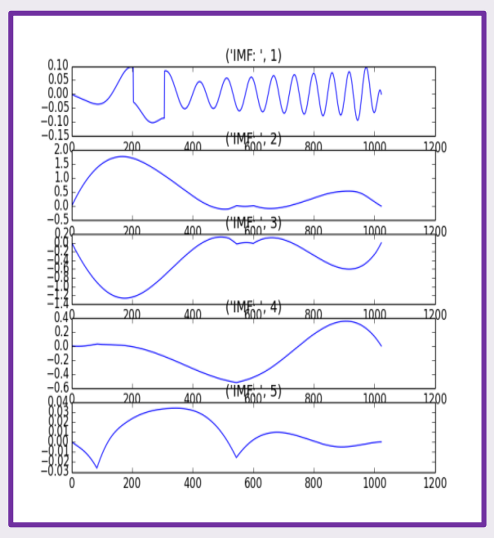
(b)

Noise level = 0.1

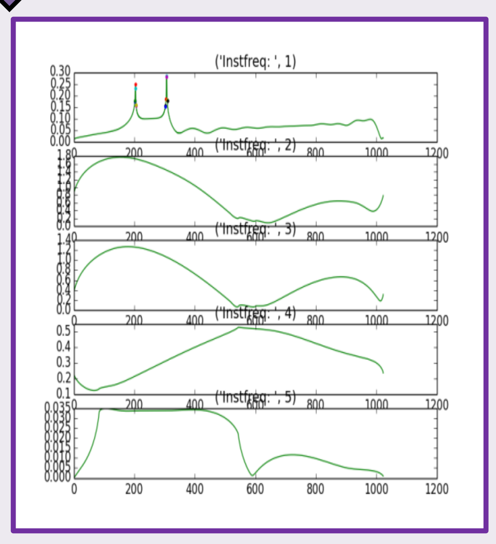
Panels (a) represent the original synthesized sequence at different noise levels, with 20% reduction in values (i.e., modelling local injury) between X and Y. Colored lines represent decomposition levels (0 = original) in each decomposition, outliers (jumps) are calculated to estimate the boundaries of the "injury", which are highlighted by dots.

5) Hilbert - Huang Transform

- **Emperical Mode Decomposition (EMD)**
- Algorithm to decompose a signal into finite sets of functions called ***"Intrinsic mode function (IMFs)"***
- Achieved by repeated "sifting": separating a moving average mean from local, higher frequency fluctuations [4].
- **Hilbert Spectral Analysis**
  - The analytic function (signal) that the HHT process seeks allows us to calculate both amplitude and phase functions locally in the sequences [4].
  - This is useful in looking for changes in local pattern (structure) of a signal.
  - calculate instantaneous frequency (which represents momentary changes in the signal).

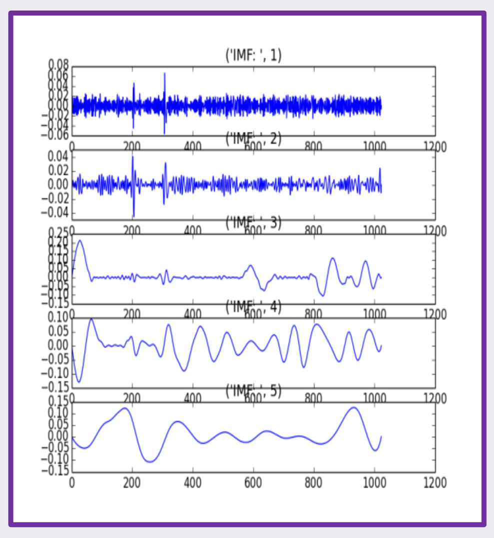


(c)



(d)

Noise level = 0



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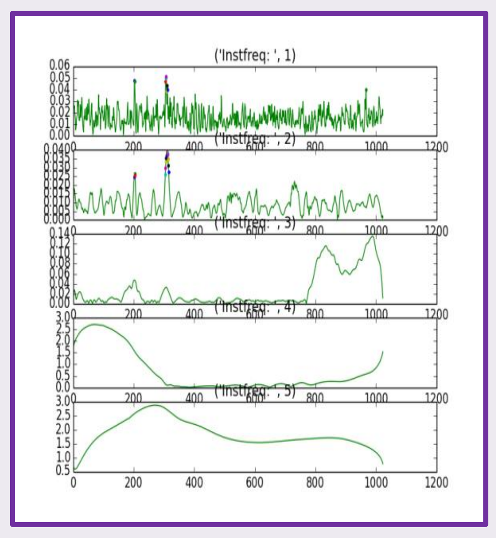
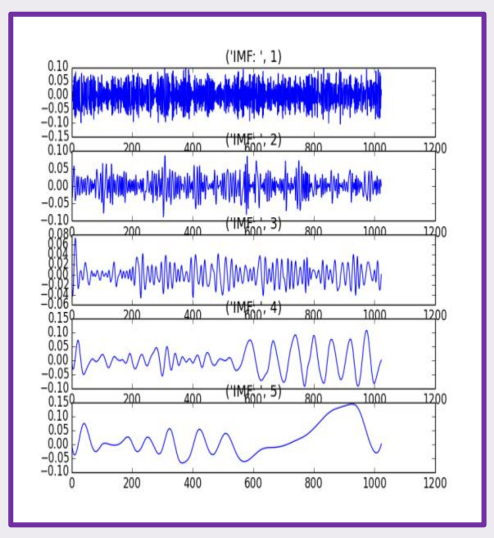


(d)

Noise level = 0.05



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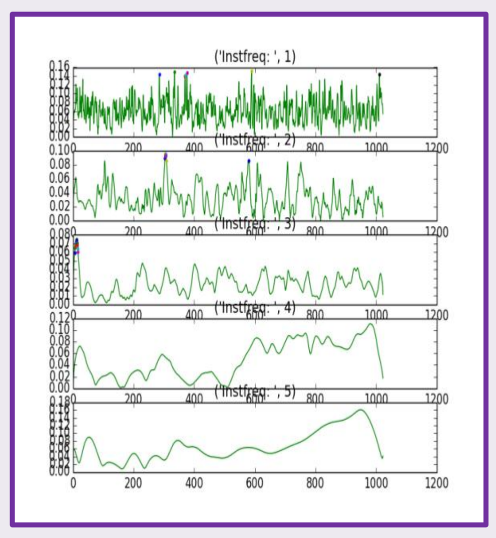

(d)

Noise level = 0.1

For the same synthesized curves in (a), five levels of HHT decomposition are shown in terms of IMFs (c) and instantaneous frequencies (d). Outliers in frequency are highlighted with dots.

Conclusion

From applying these decomposition methods to our signal, the Haar wavelet decomposition appeared more sensitive to detecting these aforementioned "jump in properties" and the boundaries in which they occur signifying damaged regions along the signal. This method also proved effective in the presence of increasing noise level. On the other hand, the method based on HHT did not appear to be as sensitive as that of Haar in detecting these sudden jumps as the noise level was increased [1].

References

[1] Gloria D. Sarki, Paul A. Taylor, *"Investigating Along-Track Decomposition Methods in DTI - Based Tractography"*, (2014). **[2]** J. O'Donnell Lauren and Westin Carl-Fredrick, *Introduction to Diffusion Tensor Imaging Analysis.* **[3]** Peter B. Kingsley, *Introduction to diffusion tensor imaging mathematics: Part ii & iii.* **[4]** Norden E. Huang, *Hilbert Huang Transform and its Applications*, (2005). **[5]** Amara Graphs, *An Introduction to Wavelets*, (1995). **[6]** Do Tromp, Rodrigo Perea, and Samuel A. Hurley, *Diffusion ellipsoids*, (2012). **[7]** American Society of Neuroradiology, *Arrows and eigenvectors*, (2014). **[8]** Human Connectome, *Ellipsoids*, (2002). **[9]** Mike Puddephat, *States of precessing h atom*, (2014). **[10]** Hawaii Electric Light Company, *Neuron*, (2002). **[11]** Shock M.D., *Resilience*, (2010). **[12]** Nathan Hangman, *Diffusion tensor imaging and applications*, (2012).

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