Nonoptimal Component Placement, but Short Processing Paths, due to Long-Distance Projections in Neural Systems

by Kaiser and Hilgetag (2006)

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Introduction

- Optimal component placement (wire length minimization) is a dominant hypothesis regarding the wiring of the neural systems.
- If things are optimal, any kind of rearrangement of component location will increase total wiring length.
- Rearrangement of Macaque visual cortical areas and *C. elegans* neural network resulted in dramatic decrease in total wiring length, suggesting otherwise.
- Reduction mostly due to the existence of long-range connections.
- Role of such long-range connections?: Decrease shortest-path length.

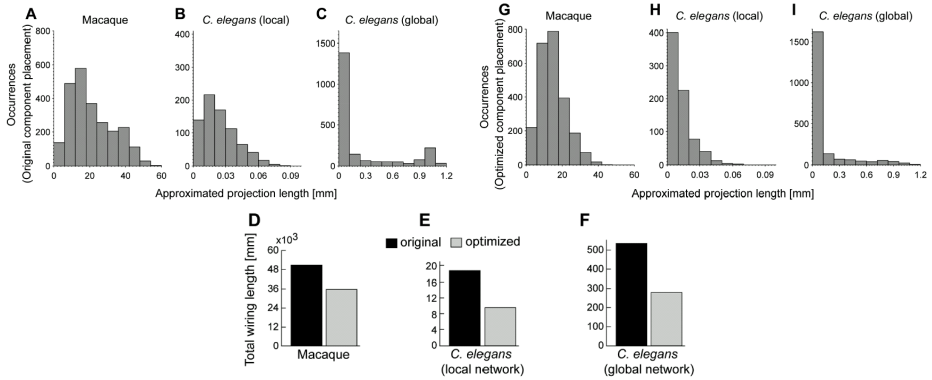
Organization of Neural Systems

- Multiple constraints: physical and chemical laws.
- Hypothesis regarding metabolic cost of neural connections and resultant minimization of wiring length.
- However, there are also long-distance projections.
- Other variants include component placement optimization (CPO).

Approach

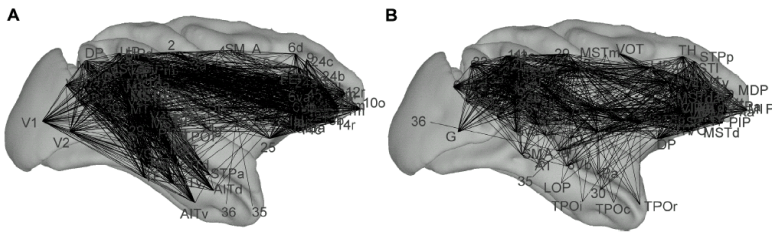
- Use simulated annealing optimization to rearrange neural elements, to reduce total wiring length.
- If it does decrease, original placement was not optimal.

Change in Connection Distribution Due to Component Rearrangement



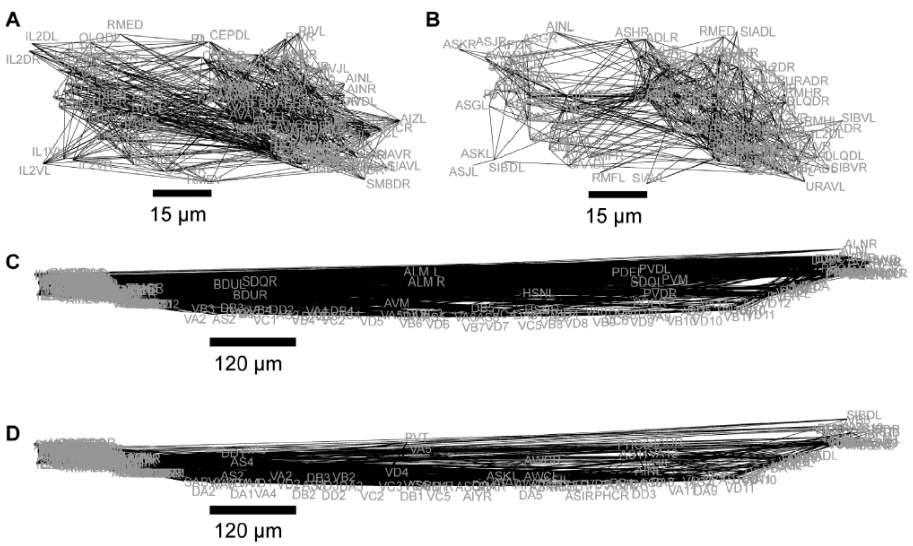
- Wiring length distribution before rearranging; wiring length distribution after rearranging.
- Reduction in total wiring length.

Rearranged Macaque Cortical Networks

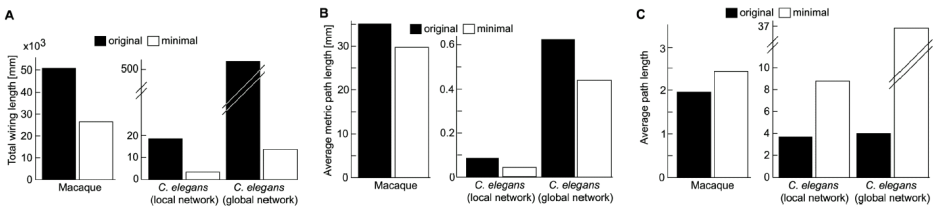


- Some factors: these are connectivity between “regions”, not neurons, so area of each region needs to be taken into account.
- White matter volume (and fiber tract diameter/volume) may also be a factor, but data is not complete. These are important to estimate the number of individual connections within those projections.

Rearranged *C. elegans* Neural Networks

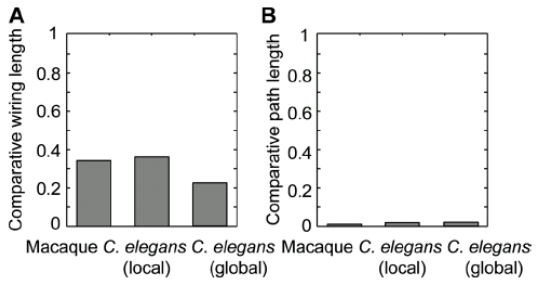


Minimally Rewired Networks



- Component position and number of connection fixed.
- Connectivity changed to prefer close neighbors connecting to each other.
- Wiring length reduced, but path length increased.

Relative Comparison



- Actual total wiring length in experimental data relative to the minimum wiring length (0.0) and maximum wiring length networks (1.0).
- Average shortest path length in experimental data to the shortest (0) and longest path length networks (1.0).

Discussion

- Wiring length minimization may not be a predominant constraint on the design of neural networks at all levels.
- Addition of long-distance connections may reduce the number of processing steps (although it is not optimal in terms of wiring length minimization).
- "The importance of network shortcuts ... has been pointed out before. The present study adds a spatial perspective ... by demonstrating that network shortcuts are formed mainly by long-distance connections. This conclusion, while intuitive, is not trivial, as one could also imagine alternative scenarios in which network shortcuts arise from short-distance connections. The coincidence of long-diatance connections with network shortcuts hints at a close match between the spatial layout and topology of neural networks. It will be an interesting task for future studies to explore more fully the developmental and evolutionary reasons for this coincidence."

References

Kaiser, M., and Hilgetag, C. C. (2006). Nonoptimal component placement, but short processing paths, due to long-distance projections in neural systems. *PLoS Computational Biology*, 2:805–815.