Network constraints on learnability of probabilistic motor sequences

Ari E. Kahn (arikahn@seas.upenn.edu)
Department of Neuroscience, University of Pennsylvania
Philadelphia, PA 19104 USA

Elisabeth A. Karuza (ekaruza@sas.upenn.edu)
Department of Psychology, University of Pennsylvania
Philadelphia, PA 19104 USA

Jean M. Vettel (jean.m.vettel.civ@mail.mil)
Human Research and Engineering Directorate, U.S. Army Research Laboratory
Aberdeen, MD 21001 USA

Danielle S. Bassett (dsb@seas.upenn.edu)
Department of Bioengineering, University of Pennsylvania
Philadelphia, PA 19104 USA

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Human learners are adept at grasping the complex relationships underlying incoming sequential input. As early as infancy, humans reliably detect the probabilities with which one stimulus transitions to another (transition probabilities, such as one syllable following another in speech) and the frequencies with which stimuli co-occur (Saffran, Aslin, & Newport, 1996). Evidence suggests that, depending on context, learners can extract both adjacent and non-adjacent dependencies between stimuli (Cleeremans & McClelland, 1991; Gómez, 2002). Indeed, recent work has shown that temporal ordering of visual stimuli can convey the organizational principle of modularity (Schapiro, Rogers, Cordova, Turk-Browne, & Botvinick, 2013). This observation opens up the possibility of studying whether certain broad-scale organizational structures might best facilitate learning (Karuza, Thompson-Schill, & Bassett, 2016). In the present work, we formalize complex relationships as graph structures derived from temporal associations in motor sequences (Karuza, Kahn, Thompson-Schill, & Bassett, 2017). Next, we explore the extent to which learners are sensitive to key variations in the topological properties inherent to those graph structures. Participants performed a probabilistic motor sequence task in which the order of button presses was determined by the traversal of graphs with modular, lattice-like, or random organization. Graph nodes each represented a unique button press and edges represented a transition between button presses. Results indicate that learning, indexed here by participants' response times, was strongly mediated by the graph's meso-scale organization, with modular graphs being associated with shorter response times than random and lattice graphs. Moreover, variations in a node's number of connections (degree) and a node's role in mediating long-distance communication (betweeness centrality) impacted graph learning, even after accounting for level of practice on that node. These results demonstrate that the graph architecture underlying temporal sequences of stimuli fundamentally constrains learning, and moreover that tools from network science provide a valuable framework for assessing how learners encode complex, temporally structured information.

References

Cleeremans, A., & McClelland, J. L. (1991). Learning the structure of event sequences. *Journal of Experimental Psychology: General*, *120*(3), 235–253. doi: 10.1037/0096-3445.120.3.235

Gómez, R. L. (2002, sep). Variability and Detection of Invariant Structure. *Psychological Science*, *13*(5), 431–436. doi: 10.1111/1467-9280.00476

Karuza, E. A., Kahn, A. E., Thompson-Schill, S. L., & Bassett, D. S. (2017). Process reveals structure: How a network is traversed mediates expectations about its architecture. *Scientific Reports*, *7*(1), 1–9. doi: 10.1038/s41598-017-12876-5

Karuza, E. A., Thompson-Schill, S. L., & Bassett, D. S. (2016). *Local Patterns to Global Architectures: Influences of Network Topology on Human Learning* (Vol. 20) (No. 8). doi: 10.1016/j.tics.2016.06.003

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical Learning by 8-Month-Old Infants. *Science*, *274*(5294), 1926–1928. doi: 10.1126/science.274.5294.1926

Schapiro, A. C., Rogers, T. T., Cordova, N. I., Turk-Browne, N. B., & Botvinick, M. M. (2013, feb). Neural representations of events arise from temporal community structure. *Nature Neuroscience*, *16*(4), 486–492. doi: 10.1038/nn.3331