Network Science: A New Method for Investigating the Complexity of Musical Experiences in the Brain

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Abstract

Network science is a rapidly emerging analysis method for investigating complex systems, such as the brain, in terms of their components and the interactions among them. Within the brain, music affects an intricate set of complex neural processing systems. These include structural components as well as functional elements such as memory, motor planning and execution, cognition and mood fluctuation. Because music affects such diverse brain systems, it is an ideal candidate for applying network science methods. Using as naturalistic an approach as possible, the authors investigated whether listening to different genres of music affected brain connectivity. Here the authors show that varying levels of musical complexity affect brain connectivity. These results suggest that network science offers a promising new method to study the dynamic impact of music on the brain.

Network science has emerged as a method that offers a useful framework for capturing and studying complex systems [1]. Based on graph theory, network science measures complex system properties and quantifies the relationships among network property components [2]. There is arguably no more complex biological system for investigation than the human brain. The brain exhibits characteristics of small-world connectivity with regional specificity manifesting through high local clustering and distributed information via short path-lengths. The ability to study how the brain behaves and functions as an integrated system offers the opportunity to pursue new research questions while advancing the knowledge of both structural and functional connectivity [3].

Brain Networks vs. Brain Activations

Using network methods to study the brain is different from traditional neuroscience imaging. In traditional neuroscience, scientists typically administer a task and measure specific activation areas within the brain relative to the given task: what turns "on" in the brain while performing the task. This method requires the experiment to be extremely narrow in scope to accurately measure activation site(s). However, the brain does not activate areas in static isolation. Rather, the brain functions as a cohesive whole and, therefore, as a network. We are interested in how the *entire brain network changes* across tasks. We also study the effects of each brain area on every other brain area within the network during a specific task.

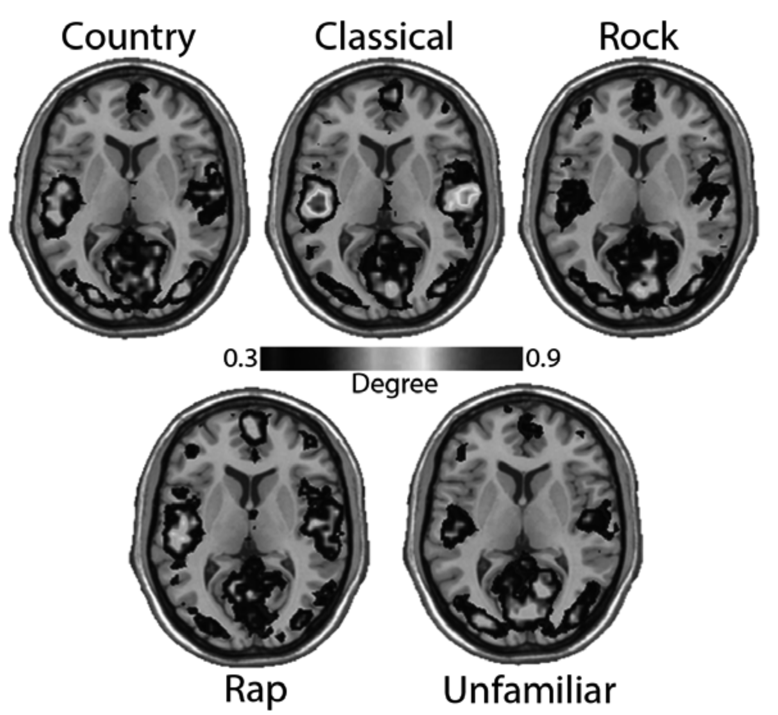
There are a multitude of metrics one can use to measure and analyze brain connectivity, e.g. degree distribution, community structure, local and global efficiency, centrality and path length. Each of these metrics provides a layer of information to help us determine brain connectivity. This kind of analysis may therefore help us understand how structural brain connectivity contributes to functional connectivity and reveal the *consistency of networks across people.*

We have chosen in this manuscript to focus on the network metric *degree*, often denoted *K.* Degree is the number of edges that connect to each node (i). Thus, the degree of a node is the number of connections that it has within the network. Network analyses can be used to determine the degree in every voxel in the brain. In the brain, when a node is said to have 'high degree', it functions similarly to what we might consider a brain communication center or "hub." Hubs are regions considered critical for network integrity. If damaged, these hubs dramatically alter information processing over the entire network [4]. Nodes ranked in the top 10-20% of the brain's node degree distribution within the network are generally considered hubs. Using this metric, one can determine how consistently brain hubs are represented across people, i.e the typical location or region of hubs. We report in this paper the consistency of brain hubs across people when undergoing different musical experiences.

The Human Musical Experience

Perhaps more than any other externally orchestrated stimuli, music remains singularly one of the most mysterious perceptive experiences within the complexity of the human mind. From the time of ancient Greek philosophers, such as Aristotle, to contemporary thinkers, speculations about why music exists, much less why humans of all cultures and throughout time, are willing to spend so much time engaged with music, continue to intrigue both the philosophic and scientific communities [5]. Researchers from such diverse disciplines as machine learning, physics, anthropology, and

Fig. 1: These images show the consistent location of hubs for each of the genres in the brain. An axial slice at the level of the auditory cortex is depicted.) (©Robin W. Wilkins[1])



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philosophy consider music to be one of the most complex aspects of the universal human experience [6-9].

Research has shown that music connects a diverse set of intricate neural processing networks within the brain. These include complex networks associated with sensory and motor processing, cognition, memory, and mood or emotional fluctuation [10]. Music has been revealed to influence speech and language development, brain plasticity, spatial reasoning, the mirror-neuron system and clinical health recoveries [11, 12]. Additionally, music has been included at the center of provocative questions surrounding the emergence of consciousness, emotions and theory of mind [13-15]. However, many questions remain. Research into the connections and potential contributions music offers for understanding these questions remains largely unexplored [16]. Studying how the brain is affected by music, as people actually experience it, has proved immensely challenging. Previous fMRI (functional magnetic resonance imaging) and PET (positron emission tomography) studies have often been structured around tones, chords or brief excerpts. These imaging experiments required time constraints for appropriate scientific analysis. However, music listening is more than a single or multi-second event. When people listen to music, their response occurs over time. Imaging studies are not able to account for that loss of valuable information. Now, with the grounding of network science methodology, metrics are available to apply and study promising questions within neuroscience. We sought to determine whether brain connectivity is altered when one listens to different genres of music. We studied network connectivity resulting from listening to a series of songs from different genres having varying musical complexity.

Brain Imaging Methodologies

We performed network generation and analysis using the fMRI time series data acquired from 21 subjects listening to music with their eyes closed. We selected songs that would be considered iconic within the music genre repertoire. Songs included Water, by Brad Paisley, (country), Movement I of Symphony No. 5 by Beethoven (classical), Rock and Roll All Nite by Kiss (rock), OMG by Usher (rap), and Spring Hall by the Chinese Jinna Opera Band (unfamiliar). Each of the songs was played continuously for five minutes and presented in pseudo-randomized order.

We evaluated whole-brain connectivity using graph theory methods on a voxel-by-voxel basis. Such analysis allows for each voxel (or node) to be counted and considered within the context of the overall brain network [17].

In brief, we first generated an adjacency matrix (A_{ij}), or whole-brain connectivity matrix, for each subject. This is a binary $n \times n$ matrix, where n = the total number of brain voxels, with each voxel representing a network node (~21,000 in this data). The matrix defines the presence or absence of a node connection between any two nodes (i and j). The adjacency matrix serves as the basis for most of the network analysis.

For the fMRI data, our determination of a connection between any two nodes (i and j) was performed using a time series regression analysis on spatially normalized brain images. To account for physiological noise associated with cardiac, respiratory and cerebrospinal fluid changes, our fMRI time series was first band-pass filtered (0.009-0.08 Hz). We then performed a full regression analysis including motion parameters as well as global, white matter and CSF covariate of no interest to further correct for physiological noise. This produced a cross-correlation matrix that contained the partial correlation coefficient representing the connectivity between each and every node [18]. An adjacency matrix was generated for each subject by thresholding the correlation matrix as described in [17].

Brain Imaging Network Results: Does Musical Genre Really Matter?

Our findings indicate that when listening to different genres of music, the brain exhibits different connectivity patterns and hub locations. Specifically, the brain exhibited a higher degree (K) within the auditory cortex when listening to classical music [Fig. 1] compared to the other musical genres. Interestingly, when listening to other musical genres, the auditory cortex was not as highly connected. This high degree of connectivity within the auditory cortex is arguably the result of the greater complexity within the structure of the classical music.

Future Directions

While the degree within the auditory cortex is different between the genres, the response within the overall brain network is likely affected by musical preference. Future analyses might reveal how brain connectivity is altered by *personal preference*, including whether overall personal preference, regardless of genre, affects brain connectivity. In addition, further network analyses on these data will use network methodology to identify brain network neighborhoods as a function of musical genre and musical preference.

References and Notes

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