Coordination of brain activity across multiple timescales by excerpts of popular music

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Introduction

Tonal structure in music unfolds on multiple timescales. Our perception of it is influenced by local contexts generated by transitions from one chord/harmony to the next as well as more global contexts that provide a sense of key. I hypothesized that auditory, premotor, and cerebellar areas would be more responsive to the shorter timescales on which the details of harmonic sequencies and associated lyrics are better represented, and that ventromedial prefrontal cortex would be more responsive at longer timescales over which emotions associated with mode (major/minor) and patterns of tension buildup and release develop.

This study extends the analysis of tonality-tracking responses observed in a study of music-evoked autobiographical memories that identified the dorsal medial prefrontal cortex (MPFC) as a site at which music and memories are associated (Janata, 2009, Cerebral Cortex).

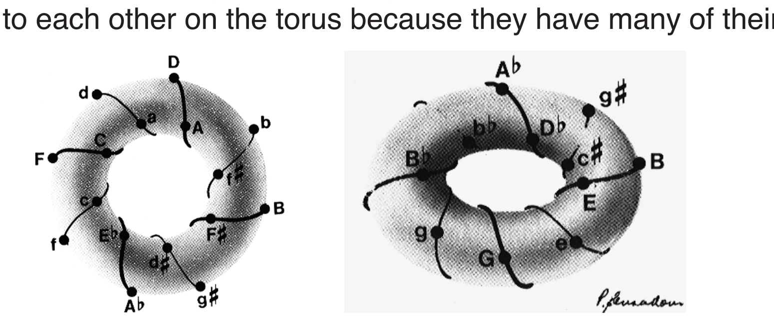
Methods

fMRI data acquisition and preprocessing

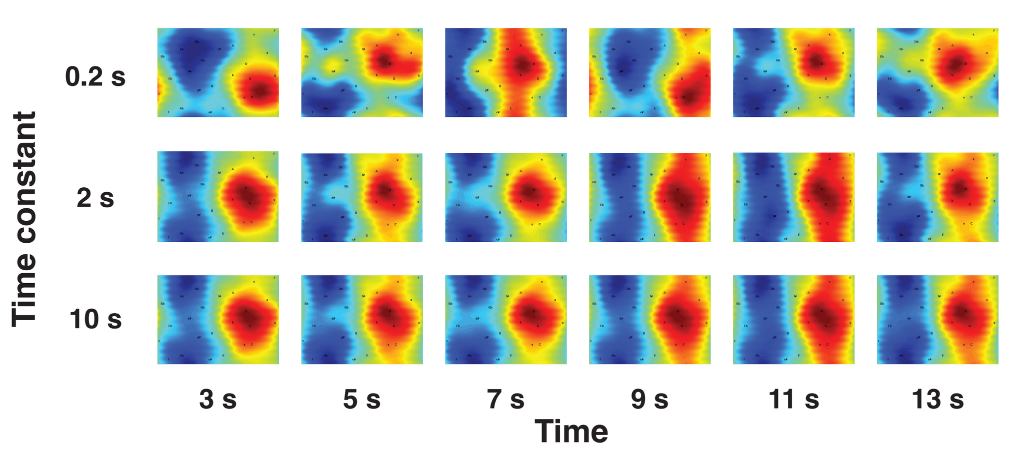
- 13 subjects (11 female)
- 30 stimuli across two scanning runs, selected at random from the Billboard Top 100 Pop and R&B charts from when the subject was between 7 and 19 years of age.
- Scan parameters: Siemens 3T Trio, 34 slices (4 mm thick, 0 skip), TR=2.0s, in-plane resolution: 3.4x3.4 mm.
- Analyses were performed using SPM5. Data were spatially normalized, and variance associated with estimated movement parameters and linear trends was removed prior to further model estimation.

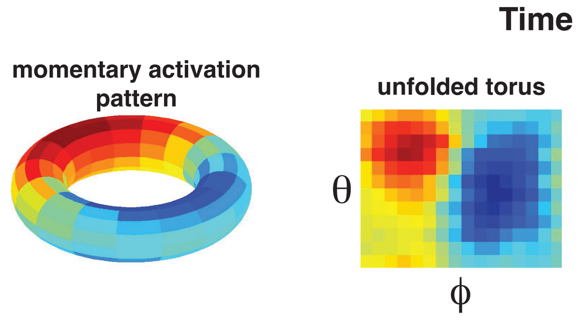
Modeling music's movement in tonal space

Converging evidence from music theory, cognitive psychology, and self-organizing neural networks indicates that the system of major and minor keys in Western tonal music can be represented on the surface of the torus (shown below labeled with major and minor keys). Each location on the surface represents a tonal center that is defined by a probabilitiy distribution of pitch classes (notes). Closely related keys are adjacent to each other on the torus because they have many of their notes in common.



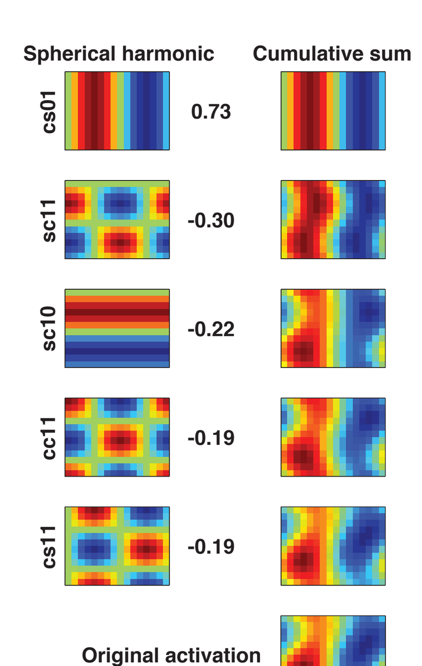
As a piece of music unfolds, the changing harmonies and chord progressions create a changing pattern of activity on the surface of the torus, providing a signature of a piece of music. Exactly what that pattern looks like depends on the time window (defined by a time constant) over which the distribution of notes is accumulated. Short time constants, e.g. 0.2 s, will emphasize individual chord changes whereas longer time constants, e.g. 10 s, will emphasize a more stable sense of key. In the plots below, red indicates stronger activation of a tonal region.



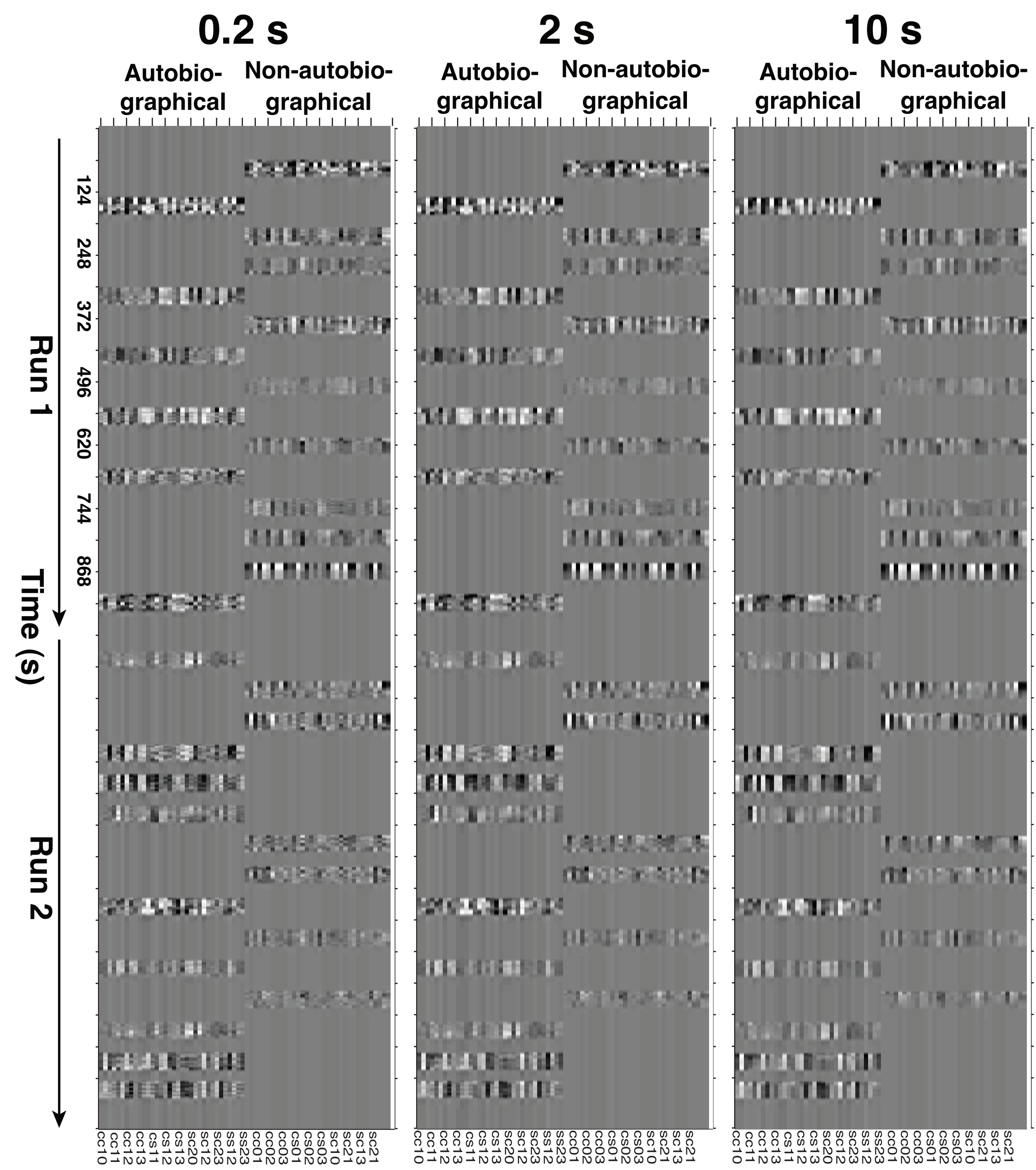


The activation pattern on the torus at any given moment in time can be described as a weighted-sum of a set of spherical harmonics (spatial frequencies) using the equation below and illustrated to the right.

$$f(\theta,\phi) = \sum_{m=0,n=0}^{M,N} a_{mn}^{cc}\cos(m\theta)\cos(n\phi) + \sum_{m=0,n=0}^{M,N} a_{mn}^{cs}\cos(m\theta)\sin(n\phi) + \sum_{m=0,n=0}^{M,N} a_{mn}^{sc}\sin(m\theta)\cos(n\phi) + \sum_{m=0,n=0}^{M,N} a_{mn}^{ss}\sin(m\theta)\sin(n\phi)$$



Design matrices modeling tonality-tracking at three timescales



Identification of tonality-tracking brain areas

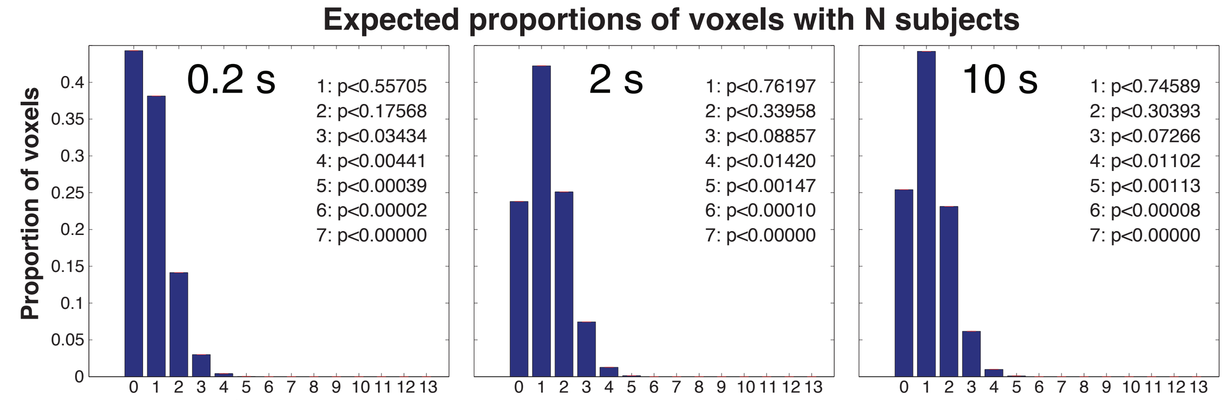
Tonality-tracking voxels were identified using time-varying coefficients of 34 spherical harmonic components, convolved with a canonical hrf, as illustrated above in the design matrices for one subject. Each patterned horizontal band represents one 30 s song excerpt.

If the probability of obtaining the residual variance of the veridical model, given the distribution of residual variances from 100 models in which the ordering of the songs was permuted was <5%, a voxel was said to exhibit tonality tracking.

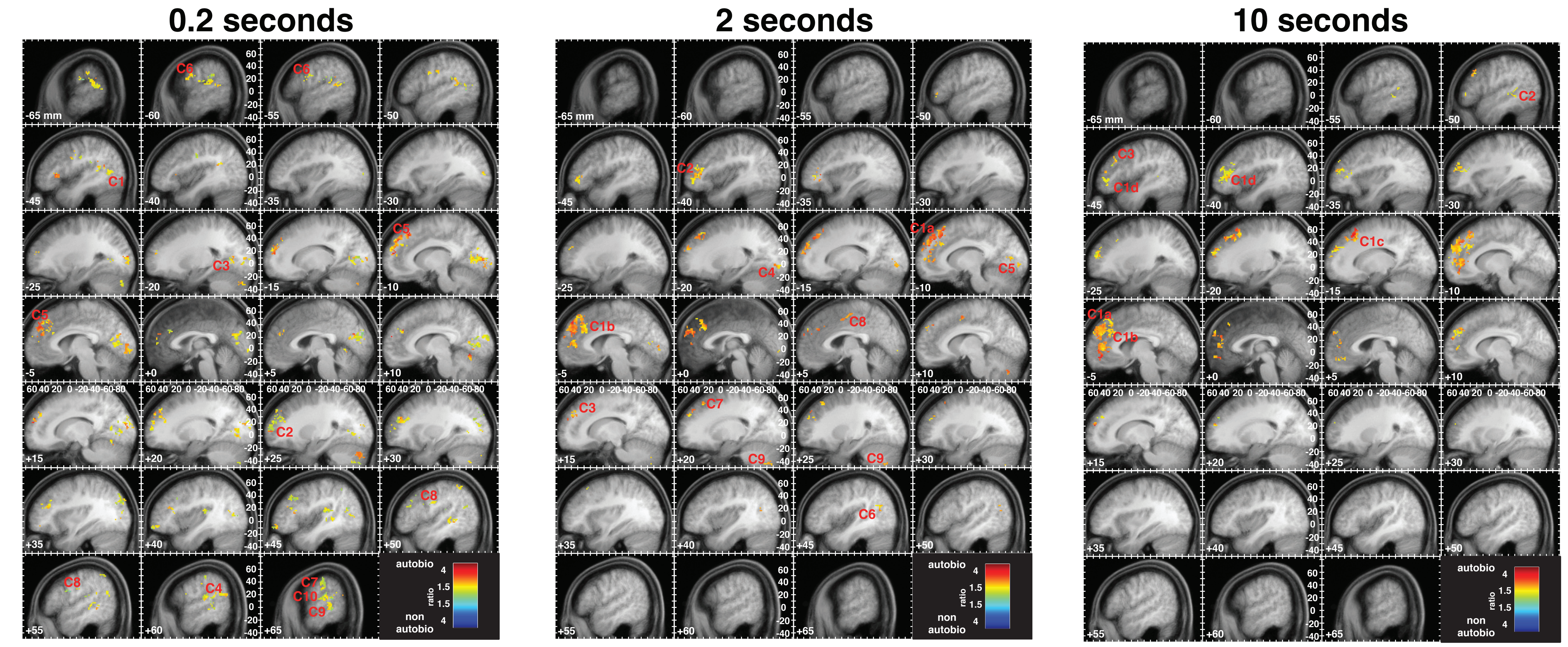
Group-level tonality-tracking maps were determined by a Monte-Carlo simulation in which all tonality-tracking voxels across all subjects were distributed randomly in the brain and the number of voxels showing activation by N subjects was tallied. This procedure was repeated 100 times to obtain the probability distributions shown below. Image thresholds were set at N=3, 4, and 4, for the 0.2, 2, and 10 s time-constant models, respectively. Extent threshold = 40 voxels.

For individual subjects, the tendency of a voxel to track the tonality of autobiographically salient pieces was determined by calculating the ratio of variance explained by the sets of Autobiographical and Non-Autobiographical regressors. The group tonality-tracking bias of each voxel was determined by averaging the bias ratios (on a logarithmic scale) across all of the individual subjects who showed significant tonality-tracking at that voxel.

Expected proportions of voxels with N subjects



Brain areas track tonal structure at one or more timescales and with differential sensitivity to autobiographical salience



Group maps of tonality tracking at three different timescales. Every voxel that showed siginificant tonality tracking in a greater number of subjects than would be expected by chance alone is rendered in a color that reflects the average tonality-tracking bias toward songs that evoked autobiographical memories across subjects who showed significant tonality tracking at that voxel. Voxels in green or light yellow exhibited little tonality tracking bias, and were observed primarily at the fastest timescale. Tonality tracking was biased strongly toward autobiographical songs primarily in medial prefrontal areas at longer timescales. Red labels refer to the clusters in the corresponding tables shown below.

Summary of tonality-tracking loci at each of the timescales

0.2 s

Cluster	Anatomical Location	Brodmann Area	#voxels in cluster	Location (mm) x	y	z	#subjects at peak	#subjects in cluster
1	Posterior superior temporal sulcus	39	482	-46	-64	10	5	13
2	Middle frontal gyrus	10	569	24	58	12	5	12
3	Retrosplenial, cuneus	30/17/18	1331	-24	-68	8	5	11
4	Superior temporal gyrus	22	159	56	-40	16	4	11
5	Superior frontal gyrus	8	458	-8	34	46	6	10
6	Precentral gyrus	6	174	-54	0	30	5	9
7	Central sulcus	3/4	123	68	-20	36	5	9
8	Precentral gyrus/sulcus	6/44	44	54	5	28	4	9
9	Superior temporal gyrus	22	210	62	-34	6	5	8
10	Superior temporal gyrus	42	131	62	-24	20	5	8

2 s

Cluster	Anatomical Location	Brodmann Area	#voxels in cluster	Location (mm) x	y	z	#subjects at peak	#subjects in cluster
1	Medial prefrontal cortex		1112					10
1a	Superior frontal gyrus	9		-10	52	32	7	
1b	Anterior cingulate	32		-4	28	34	6	
2	Lat. orbital gyrus Inferior frontal gyrus	47/45/46	219	-46	42	-2	6	10
3	Superior frontal gyrus	9/10	127	16	48	34	5	9
4	Lingual gyrus	18	104	-18	-86	-4	5	8
5	Cuneus	17	43	-10	-82	10	5	7
6	Post. sup. temporal sulcus Angular gyrus	39	55	42	-62	22	5	7
7	Superior frontal sulcus	8	60	18	32	52	5	7
8	Cingulate sulcus	24	53	8	-2	50	5	6
9	Cerebellum		61	26	-68	-48	5	6

10 s

Cluster	Anatomical Location	Brodmann Area	#voxels in cluster	Location (mm) x	y	z	#subjects at peak	#subjects in cluster
1	Medial prefrontal cortex		2082					13
1a	Superior frontal gyrus	9	295	-6	48	38	7	
1b	Anterior cingulate	32	70	-6	44	8	6	
1c	Superior frontal gyrus	8	60	-14	36	46	6	
1d	Superior frontal sulcus	10/46	51	-44	42	2	6	
2	Middle temporal gyrus Superior temporal sulcus	21/22	61	-52	-38	-2	5	9
3	Middle frontal gyrus	46	62	-42	30	30	5	8

Tonality-tracking at different timescales as a marker of intertwined perceptual, motoric, and mnemonic processes

Music and musical experiences can be characterized on multiple timescales. We perceive changing notes in melodies and chord progressions at a relatively fast timescale that roughly matches the timescale of words in language. The mental processes of covertly singing along with a piece of music or actively forming expectations for the next note or chord in a sequence are characteristic of this timescale. The observation of tonality-tracking in a set of regions that serve as a sensorimotor network for speech and music (Hickok et al., 2003, J. Cogn. Neuro.) may be interpreted in this way. Musical events occuring at fast timescales must be integrated into longer sequences (phrases). A variety of memory processes come into play, such as memory for a particular piece of music or autobiographical memories that are evoked by the music. A number of prefrontal areas are postulated to contribute to the structural integration of the musical events [lateral BA10 (C2, 0.2 s) and VLPFC (C2, 2 s; C1d, 10 s)], and the stitching together of memories and images associated with the music [MPFC and SFS (C5, 0.2 s; C1a,b, C7 2 s; C1a,c 10 s)]. The greater ventral extent of tonality-tracking in MPFC at longer timescales for autobiographical songs is consistent with the role of this region in emotional processing and the evolution of mood states across longer timescales.

The results indicate that analyzing BOLD data using models of the time-varying pitch distributions that characterize how individual pieces of music move in tonal space can facilitate our understanding of the music-brain interactions that underlie our multifaceted ways of engaging with and experiencing music.

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