

# Functional Organization of Auditory and Reward Systems in Aging

Alexander Belden<sup>1</sup>, Milena Aiello Quinci<sup>1</sup>, Maiya Geddes<sup>2</sup>,  
Nancy J. Donovan<sup>3</sup>, Suzanne B. Hanser<sup>4</sup>, and Psyche Loui<sup>1</sup> 

## Abstract

■ The intrinsic organization of functional brain networks is known to change with age, and is affected by perceptual input and task conditions. Here, we compare functional activity and connectivity during music listening and rest between younger ( $n = 24$ ) and older ( $n = 24$ ) adults, using whole-brain regression, seed-based connectivity, and ROI–ROI connectivity analyses. As expected, activity and connectivity of auditory and reward networks scaled with liking during music listening in both groups. Younger adults show higher within-network connectivity of auditory and reward regions as compared with older adults, both at rest and during music listening, but this age-related difference at rest was reduced during music listening, especially in individuals who self-report high musical reward.

Furthermore, younger adults showed higher functional connectivity between auditory network and medial prefrontal cortex that was specific to music listening, whereas older adults showed a more globally diffuse pattern of connectivity, including higher connectivity between auditory regions and bilateral lingual and inferior frontal gyri. Finally, connectivity between auditory and reward regions was higher when listening to music selected by the participant. These results highlight the roles of aging and reward sensitivity on auditory and reward networks. Results may inform the design of music-based interventions for older adults and improve our understanding of functional network dynamics of the brain at rest and during a cognitively engaging task. ■

## INTRODUCTION

The process of aging is characterized by changes in a variety of brain functions that underlie motivated behavior (Mather, 2016). One set of age-related changes involves a loss of connectivity in functional network dynamics of the brain (Grady, Sarraf, Saverino, & Campbell, 2016; Sala-Llonch, Bartrés-Faz, & Junqué, 2015; Tomasi & Volkow, 2012). The default mode network (DMN), for example, shows decreased connectivity in normal aging (Persson, Pudas, Nilsson, & Nyberg, 2014; Hafkemeijer, van der Grond, & Rombouts, 2012; Tomasi & Volkow, 2012) as well as in age-related cognitive decline (Hafkemeijer et al., 2012; Sheline et al., 2010; Buckner et al., 2005). Other networks too have shown age-related changes: The auditory network shows age-related dedifferentiation, both in activity and in connectivity within itself and with other networks (such as DMN and salience network; Onoda, Ishihara, & Yamaguchi, 2012; Hwang, Li, Wu, Chen, & Liu, 2007). This age-related decline is observed in normal-hearing older adults (OAs), but is also associated with age-related hearing loss (Fitzhugh, Hemesath, Schaefer, Baxter, & Rogalsky, 2019; Onoda et al., 2012; Hwang et al., 2007). The dopaminergic reward system shows decreased density with age in both striatal and

extrastriatal regions (Li & Rieckmann, 2014; Erixon-Lindroth et al., 2005). Age-related decrease in dopaminergic function is linked to behavioral changes in a variety of cognitive and affective tasks. Cognitive changes include age-related declines with working memory capacity and maintenance (Klostermann, Braskie, Landau, O'Neil, & Jagust, 2012; Landau, Lal, O'Neil, Baker, & Jagust, 2009), as well as with reward learning from prediction errors (Samanez-Larkin, Worthy, Mata, McClure, & Knutson, 2014; Chowdhury et al., 2013). Reward learning is particularly of interest as it lies at the intersection of cognitive and affective tasks: The ability to form representations of predictions and prediction errors, which is fundamental to reward learning (Schultz, Dayan, & Montague, 1997), may be thought of as a cognitive process. On the other hand, the ability to represent valence and arousal of stimuli to be learned, and to form value-based representations of rewards more generally, may be considered more affect-based processing (Mather, 2016). Although age-related decline has been observed for both cognitive and affective aspects of reward learning (Yee, Adams, Beck, & Braver, 2019; Samanez-Larkin et al., 2014; Eppinger, Nystrom, & Cohen, 2012; Bäckman, Lindenberger, Li, & Nyberg, 2010), some studies have also shown no age-related differences in activity of the reward network, such as during the processing of monetary incentives (Geddes, Mattfeld, de los Angeles, Keshavan, & Gabrieli, 2018; Spaniol, Bowen, Wegier, & Grady, 2015), whereas other works have shown a more pronounced age-related

<sup>1</sup>Northeastern University, Boston, MA, <sup>2</sup>McGill University, Montréal, Québec, Canada, <sup>3</sup>Brigham and Women's Hospital and Harvard Medical School, Boston, MA, <sup>4</sup>Berklee College of Music, Boston, MA

decline in the memory-based, more cognitive aspects of reward learning, but a relative sparing of its more affective aspects (Geddes et al., 2018; Samanez-Larkin et al., 2014). At a behavioral level, OAs have also been reported to show more positive affect overall (Kessler & Staudinger, 2009), as well as less cognitive engagement during emotion-regulation tasks (Scheibe, Sheppes, & Staudinger, 2015).

Given these findings, it would be of great interest to learn how age-related changes in functional network dynamics interact with reward responses to cognitively and affectively engaging sensory stimuli. In that regard, music has a unique power to elicit moments of intense emotional and physiological responses (Harrison & Loui, 2014), experiences that are intrinsically rewarding for most people (Zatorre, 2015). Although music listening habits are known to be linked to psychological well-being in late adulthood/or late life (Laukka, 2007), the relationship between aging and the reward response to music is not well understood. On one hand, music-based interventions are hypothesized to be more enjoyable than other, non-musical cognitive training programs for OAs (Sutcliffe, Du, & Ruffman, 2020). Active music training in old age, such as through learning to play a musical instrument, could be a means to mitigate cognitive decline by facilitating auditory processes as well as more central processes such as cognitive reserve (Ai et al., 2022; Alain et al., 2014; Zendel & Alain, 2013). On the other hand, OAs show less sensitivity to reward (Eppinger et al., 2012), as subserved by differences in the reward system during gambling tasks (Geddes et al., 2018). Behavioral studies have also shown that sensitivity to musical reward, as assessed by self-report through the Barcelona Music Reward Questionnaire (BMRQ; Mas-Herrero, Marco-Pallarés, Lorenzo-Seva, Zatorre, & Rodríguez-Fornells, 2013), is lower in OAs than in younger adults (YAs; Cardona, Ferreri, Lorenzo-Seva, Russo, & Rodríguez-Fornells, 2022; Belfi, Moreno, Gugliano, & Neill, 2021). Addressing these gaps in our understanding of age-related differences in reward and functional network dynamics will have implications for the design of music-based interventions for healthy aging, as various strategies employed during music listening, even among receptive music-based interventions (e.g., listening for relaxation, imagery, or engagement), may cater to distinct brain networks that are differentially impacted by advancing age (Wheeler, 2015).

Cross-sectional functional neuroimaging studies may help shed light on the intrinsic and task-related differences in music reward sensitivity in YAs and OAs. During music listening, regions involved with auditory processing, including but not limited to superior temporal gyrus (STG) and Heschl's gyrus (HG), coactivate with multiple areas over and above their intrinsic activity and connectivity at rest, resulting in a richly connected task-based network for music listening that covaries with liking and familiarity (Quinci et al., 2022; Ellis, Bruijn, Norton, Winner, & Schlaug, 2013; Loui, Zamm, & Schlaug, 2012; Koelsch, 2005). Coactivated areas include lateral

prefrontal networks important for auditory–motor and linguistic processes, as well as emotion and reward-associated brain structures, including ventral portions of the medial prefrontal cortex (mPFC), orbitofrontal cortex, and the dorsal and ventral striatum (Ferreri et al., 2019; Gold et al., 2019; Salimpoor et al., 2013; Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011). The STG receives input from primary auditory regions (Kaas & Hackett, 2000; Yeterian & Pandya, 1998). It is structurally and functionally connected to the inferior frontal gyrus (IFG) and anterior insula (Wang, Belden, Hanser, Geddes, & Loui, 2020; Loui, Alsop, & Schlaug, 2009; Frey, Campbell, Pike, & Petrides, 2008), the latter of which also plays a role in reward system processing (Ai et al., 2022; Sachs, Ellis, Schlaug, & Loui, 2016). The STG also shows structural and functional connectivity to the nucleus accumbens (Loui et al., 2017; Martínez-Molina, Mas-Herrero, Rodríguez-Fornells, Zatorre, & Marco-Pallarés, 2016). The latter connects to regions including the mPFC, caudate, and substantia nigra, together constituting the reward system (Karlsgodt et al., 2015). Auditory connections to the reward system are hypothesized to encode hedonic responses to music (Belfi & Loui, 2020; Zatorre, 2015).

Despite our understanding of the reward system, much is still not known about the driving factor behind state- and trait-level differences in musical reward processing. Neuroimaging studies have found that individual differences in reward sensitivity to music listening are related to differences in white matter connectivity to and engagement of areas in the dopaminergic systems, specifically in the striatum (Martínez-Molina, Mas-Herrero, Rodríguez-Fornells, Zatorre, & Marco-Pallarés, 2019; Loui et al., 2017; Sachs et al., 2016; Zatorre, 2015; Salimpoor et al., 2011). Although the case of musical anhedonia represents an extreme lack of sensitivity to musical reward, music listening preferences also vary in the general population by the listener and for different situations (e.g., Rentfrow, Goldberg, & Levitin, 2011; North, Hargreaves, & Hargreaves, 2004). Even within the same individual, differences in musical reward processing can arise based on the listener's past experience with the piece, autobiographical memories related to the piece, and one's overall appreciation for the intentionality of the performer or composer (Aydogan et al., 2018; Alluri et al., 2017; Pereira et al., 2011; Janata, 2009). Agency in music listening also impacts the processing of musical information, with self-selection of musical stimuli leading to more active engagement for listeners (Quinci et al., 2022), possibly because of predictive processes that can be more strongly engaged when listening to self-selected music (Vuust, Heggli, Friston, & Kringelbach, 2022).

Here, we compare the functional connectivity of auditory and reward networks in a sample of OAs ( $n = 24$ ; aged 54–89 years) and YAs ( $n = 24$ ; aged 18–23 years). We do this using a combination of resting-state fMRI and fMRI collected during a music listening task. Our hypotheses are threefold. First, we expect well-liked music to elicit greater activity from auditory processing and reward-associated

brain regions. We expect this to be true for both YAs and OAs, and for differences in activity to arise between the two age groups. Second, we expect music listening to increase functional connectivity within and between auditory processing and reward-associated brain regions as compared with rest. We expect this to be true of both YAs and OAs, and that these connections will be particularly strong while listening to well-liked musical stimuli. Third and finally, we expect that connectivity within and between auditory and reward-associated regions will vary with age. Although we expect this effect to be present during both rest and music listening, we expect that age will modulate the connectivity of auditory and reward-associated regions in response to music, resulting in an Age  $\times$  Task interaction effect.

We test these hypotheses through a combination of whole-brain linear regression, seed-based connectivity, and ROI-based (ROI-to-ROI) connectivity approaches. Whole-brain linear regression is used to test our first hypothesis, providing a metric for general metabolic activity during music listening. Seed-based and ROI-to-ROI connectivity measures are used to test our second and third hypotheses. Whereas seed-based connectivity is intended as a more global method for determining functional connectivity, determining how auditory and reward networks (taken as a whole) may connect to the rest of the brain, ROI-to-ROI connectivity is intended as a more hypothesis-driven approach to determining the connectivity among and between known hubs of the auditory and reward networks.

## METHODS

### Participants

We recruited equal samples of OAs and YAs guided by median sample sizes of neuroimaging studies published in top neuroimaging journals in 2017 (23 participants) and 2018 (24 participants; Szucs & Ioannidis, 2020). Twenty-four adults between the ages of 18 and 23 years ( $M = 18.58$  years,  $SD = 1.21$  years) were recruited as the young adult group through the Northeastern University student population (20 identified as female, 3 as male, 1 as nonbinary). They had to meet the following inclusion criteria: (1) were 18 years of age or older, (2) had normal hearing, and (3) pass an MRI screening.

Twenty-eight OAs were recruited as part of a longitudinal study (Quinci et al., 2022). Recruitment for the OAs took place through community outreach as well as online recruitment engines such as including craigslist.org and BuildClinical.com. Participants were prescreened by telephone before participation and were included if they (1) were over 50 years old, (2) had normal hearing, (3) passed the Telephone Interview for Cognitive Status with a score of  $\geq 31/41$  indicating no cognitive impairment, and (4) passed MRI screening. Participants were excluded if they (1) changed medications within 6 weeks of screening,

(2) had a history of psychotic or schizophrenic episodes, (3) had a history of chemotherapy within the past 10 years, or (4) experienced serious physical trauma or were diagnosed with a serious chronic health condition requiring medical treatment and monitoring within 3 months of screening. Of the screened participants, four were unable to complete the MRI portion of the study, resulting in a final sample of 24 OAs (13 identified as male, 11 as female) between the ages of 54 and 89 years old ( $M = 66.67$  years,  $SD = 7.79$  years).

Participants were compensated for their time through either payment or course credit. This study was approved by the Northeastern University institutional review board. This study is preregistered at <https://osf.io/zxd42>.

### Procedure

All participants completed a prescreening phone call before being enrolled to ensure they met the inclusion/exclusion criteria described above. All participants were also asked to provide the researcher with the names of six of their favorite songs.

The young adult group was recruited from Northeastern University for a single-session study in return for course credit. The OA group was recruited as part of a longitudinal music-based intervention study that included an MRI, blood draw, battery of neuropsychological tests, and series of surveys (as described separately in Quinci et al., 2022). For the present analyses, we used fMRI data from the OAs that was collected before the music-based intervention took place. All participants filled out an online version of the BMRQ (Mas-Herrero et al., 2013) to assess individual differences in reward sensitivity. The BMRQ is a 20-item questionnaire in which participants rate on a 5-point scale the extent to which they agree with statements indicating their degree of musical reward across five dimensions: musical seeking, emotion evocation, mood regulation, sensory-motor, and social reward.

### Special Considerations because of COVID-19

For the YAs, data collection occurred exclusively during the COVID-19 pandemic, between October 2021 and March 2022. Data collection for OAs began in July 2019 and finished in November 2021, with nine participants completing their visits during the pandemic.

For the collection of human subject data during the COVID-19 pandemic, data collection followed a Resumption of Research Plan that was developed and approved in consultation with the institutional review board of Northeastern University (for more details on special considerations because of COVID-19, see Quinci et al., 2022).

### fMRI Task

The fMRI task consisted of 24 trials altogether. In each trial, participants were first presented with a musical stimulus

(lasting 20 sec) and then they were given the task of rating how familiar they found the music to be (familiarity rating lasted 2 sec), and how much they liked the music (liking rating also lasted 2 sec). Musical stimuli for the MRI task consisted of 24 different audio excerpts, each of which was 20 sec in duration. Each audio stimulus was from one of the following three categories: participant self-selected music (6/24 stimuli), researcher-selected music including well-known excerpts spanning multiple musical genres (10/24 stimuli), and novel music spanning multiple genres (8/24 stimuli). Stimuli were presented in a randomized order, and participants made ratings of familiarity and liking on the scales of 1–4: for familiarity: 1 = *very unfamiliar*, 2 = *unfamiliar*, 3 = *familiar*, 4 = *very familiar*; for liking: 1 = *hate*, 2 = *neutral*, 3 = *like*, 4 = *love*. Participants made these ratings by pressing a corresponding button on a button-box (Cambridge Research Systems) inside the scanner. Participants wore MR-compatible over-the-ear headphones (Cambridge Research Systems) over musician-grade silicone ear plugs during MRI data acquisition. The spatial mapping between buttons and the numerical categories of ratings were counterbalanced between participants to reduce any systematic association between ratings and the motor activity resulting from making responses.

### Behavioral Data Analysis

The proportion of each liking rating (hate, neutral, like, love) was averaged across participants for each group (YAs, OAs). A chi-square test was run on the  $2 \times 4$  matrix relating the frequency of each liking rating (hate, neutral, like, love) for each group (YAs, OAs). Familiarity ratings are not separately analyzed for this manuscript, as the relationship between liking and familiarity is investigated in a separate report in the laboratory (Kathios, Sachs, Zhang, Ou, & Loui, 2023) and the general similarity between liking and familiarity on brain activity during music listening has been demonstrated (Pereira et al., 2011). The effects of both ratings in the auditory and reward systems have also been shown in a separate report in our laboratory (Quinci et al., 2022).

### fMRI Data Acquisition

Images were acquired using a Siemens Magnetom 3 T MR scanner with a 64-channel head coil at Northeastern University. For task fMRI data, continuous acquisition was used for 1440 volumes with a fast repetition time (TR) of 475 msec, for a total acquisition time of 11.4 min. Forty-eight axial slices (slice thickness = 3 mm, anterior to posterior,  $z$  volume = 14.4 mm) were acquired as EPI functional volumes covering the whole brain (TR = 475 msec, echo time = 30 msec, flip angle =  $60^\circ$ , field of view = 240 mm, voxel size =  $3 \times 3 \times 3$  mm<sup>3</sup>). The resting-state scan followed the same parameters and included 947 continuous scans, for a total scan length of

approximately 7.5 min. T1 images were also acquired using a magnetization prepared rapid gradient echo sequence, with one T1 image acquired every 2400 msec, for a total task time of approximately 7 min. Sagittal slices (0.8 mm thick, anterior to posterior) were acquired covering the whole brain (TR = 2400 msec, echo time = 2.55 msec, flip angle =  $8^\circ$ , field of view = 256, voxel size =  $0.8 \times 0.8 \times 0.8$  mm<sup>3</sup>; as described in Quinci et al., 2022).

### fMRI Data Analysis

#### Preprocessing

Task and resting-state fMRI data were preprocessed using the Statistical Parametric Mapping 12 (SPM12) software (Penny, Friston, Ashburner, Kiebel, & Nichols, 2011) with the CONN Toolbox (Whitfield-Gabrieli & Nieto-Castanon, 2012). Preprocessing steps included functional realignment and unwarp, functional centering, functional slice time correction, functional outlier detection using the artifact detection tool, functional direct segmentation and normalization to Montreal Neurological Institute (MNI) template, structural centering, structural segmentation and normalization to MNI template, and functional smoothing to an 8-mm Gaussian kernel (Friston et al., 1995). Denoising steps for seed-based connectivity analyses included white matter and cerebrospinal fluid confound correction (Behzadi, Restom, Liu, & Liu, 2007), motion correction, global signal regression, and bandpass filtering to 0.008–0.09 Hz.

#### Univariate Whole-brain Analyses

Behavioral responses from the fMRI task were imported into R Studio (Posit), and onset values were extracted for each trial based on the liking rating participants awarded each stimulus (hate, neutral, like, love). For each participant, data were converted from 4-D to 3-D images, resulting in 1440 scans. The model was specified using the following criteria: interscan interval = 0.475 sec, microtime resolution = 16, microtime onset = 8, duration = 42 as to only include data from when the participant was listening to music. First-level main effects of each liking rating were obtained using the SPM12 toolbox. Second-level main effects were analyzed for each group (YAs and OAs) for each liking rating (hate, neutral, like, love) using a one-sample  $t$  test. Between-groups contrasts (YAs vs. OAs) were also run for each liking rating. Results were corrected at the voxel and cluster threshold of  $p < .05$  (false discovery rate [FDR]-corrected). Second-level results were visualized using the CONN Toolbox (Whitfield-Gabrieli & Nieto-Castanon, 2012).

#### ROI–ROI Analyses

ROI–ROI analyses were performed using 18 auditory network ROIs and 18 reward network ROIs derived from the CONN default atlas. The auditory network seed consisted

of all subdivisions of bilateral STG, middle temporal gyrus (MTG), inferior temporal gyrus, and HG, and the reward network seed consisted of anterior cingulate, posterior cingulate, bilateral insular cortex, frontal orbital cortex, caudate, putamen, pallidum, hippocampus, amygdala, and nucleus accumbens, as defined by Wang and colleagues (2020). Preprocessed ROI timeseries data were extracted from participants' first-level SPM.mat files using the Marsbar Toolbox (Brett, Anton, Valabregue, & Poline, 2002). Values associated with each liking rating (hate, neutral, like, love) were separated for each participant and averaged across all stimuli with that particular rating. For each liking rating, ROI time-series data were correlated across all auditory regions (auditory–auditory), across all reward regions (reward–reward), and between auditory and reward regions (auditory–reward).

Follow-up analyses of ROI–ROI connectivity included a repeated-measures multivariate analysis of covariance (MANCOVA) for participants who used all four liking ratings during the music listening task ( $n = 20$  OA, 18 YA), comparing groups in auditory–auditory, auditory–reward, reward–reward, auditory–mPFC, auditory–posterior cingulate cortex (PCC), reward–mPFC, and reward–PCC connectivity across our four levels of musical liking. Covariates included gender, self-reported musical reward, and within-group age.

### Seed-based Connectivity Analyses

Seed-based connectivity analysis was performed using the CONN Toolbox (Whitfield-Gabrieli & Nieto-Castanon, 2012). Above defined auditory and reward network ROIs were combined, resulting in one seed for each network. For both seeds, contrasts were drawn between task (task > rest), age groups (YA > OA), and interactions between age and task. Further contrasts determined linear and quadratic effects of music liking (as determined by in-scanner ratings) and selection. Finally, to rule out any confounding effects of within-group age differences, gender, and musical reward as measured by the BMRQ, direct subject effect contrasts of these metrics were performed for each condition and seed effect. Main effect contrasts of group, task, selection, and liking were also repeated using within-group age and BMRQ as covariates of no interest, and relevant differences to the main contrasts are presented when applicable.

## RESULTS

### Behavioral Results: BMRQ

The BMRQ was higher in YAs ( $M = 83.2$ ,  $SD = 7.28$ ) than in OAs ( $M = 72.3$ ,  $SD = 9.97$ ), as confirmed by an independent-samples  $t$  test,  $t(46) = 4.34$ ,  $p < .001$ , indicating that YAs experience greater self-reported music reward, replicating previous reports (Cardona et al., 2022; Belfi et al., 2021; Mas-Herrero et al., 2013).

### Frequency of Liking Ratings per Group

Although both groups used all liking ratings, OAs used more extreme ratings: A chi-squared test showed a significant association between group (YAs vs. OAs) and proportion of liking ratings for,  $\chi^2(3) = 12.7$ ,  $p = .005$ . Table 1 shows the proportion of each liking rating given by YAs and OAs, respectively.

### Univariate Whole-brain Results: Loved Music Activates Auditory and Reward Networks

For both YAs and OAs, music rated as hated, neutral, liked, and loved all activated auditory regions including the HG, planum temporale, planum polare, STS, STG, and MTG, as well as some regions outside the auditory network, specifically the hippocampus. For YAs, music rated as hated and liked also activated the parahippocampal gyrus, and music rated as liked additionally activated the brainstem. When listening to loved music, several additional regions became active in both groups: the mPFC, paracingulate gyrus, posterior cingulate cortex, precuneus, orbitofrontal cortex, and lateral occipital cortex (LOC). Also during loved music, YAs showed activity in the superior frontal gyrus, parahippocampal gyrus, brainstem, and SMA, whereas OAs showed activity in the ventral striatum/nucleus accumbens, brainstem, and cerebellum (see Table 2 and Figure 1).

YAs and OAs both showed a significant linear effect of liking rating (hate, neutral, like, love [ $-3 -1 1 3$ ]) on activity across a broad range of regions, including auditory cortex, mPFC, PCC, and striatum (Figure 1A–B, bottom row). Although linear-liking effects were present in both groups, OA showed larger clusters of significance spanning a greater portion of the brain, whereas YA showed

**Table 1.** Liking Rating Frequencies by Group

	Rating			
	Hate	Neutral	Like	Love
Young Adults				
% Within group	13.80%	32.50%	23.20%	30.50%
% Within rating	43.60%	57.90%	46.30%	48.90%
% Of total	6.90%	16.20%	11.60%	15.30%
OAs				
% Within group	17.80%	23.50%	26.80%	31.90%
% Within rating	56.40%	42.10%	53.70%	51.10%
% Of total	8.90%	11.80%	13.40%	16.00%
Total				
% Of total	15.80%	28.00%	25.00%	31.20%

**Table 2.** Univariate Whole-brain Results

<i>Region(s)/Clusters</i>	<i>Hemisphere</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>k</i>
<i>Young Adults</i>					
<i>Hate</i>					
STG/STS/MTG/HG	Right	54	-6	-3	455
Planum temporale/polare	Left	-51	-18	3	302
Parahippocampal gyrus	Left	-12	-9	-27	20
Hippocampus	Right	21	-15	-24	12
Brainstem	Left	-3	-33	-66	11
		-18	-78	-45	10
<i>Neutral</i>					
STG/STS/MTG/HG	Right	48	-18	6	506
Planum temporale/polare	Left	-48	-15	0	378
Parahippocampal gyrus	Right	15	-15	-24	12
<i>Like</i>					
STG/STS/MTG/HG	Right	63	-21	6	493
Planum temporale/polare	Left	-48	-18	0	366
Brainstem	Left	-18	-81	-48	14
Parahippocampal gyrus Hippocampus	Right	18	-12	-24	11
<i>Love</i>					
STG/STS/MTG/HG	Left	-48	-15	0	1064
Planum temporale/polare	Right	63	-24	6	918
Paracingulate gyrus mPFC	Left	-6	57	-9	333
Hippocampus	Right	12	-30	-12	147
Superior frontal gyrus	Left	-21	24	39	52

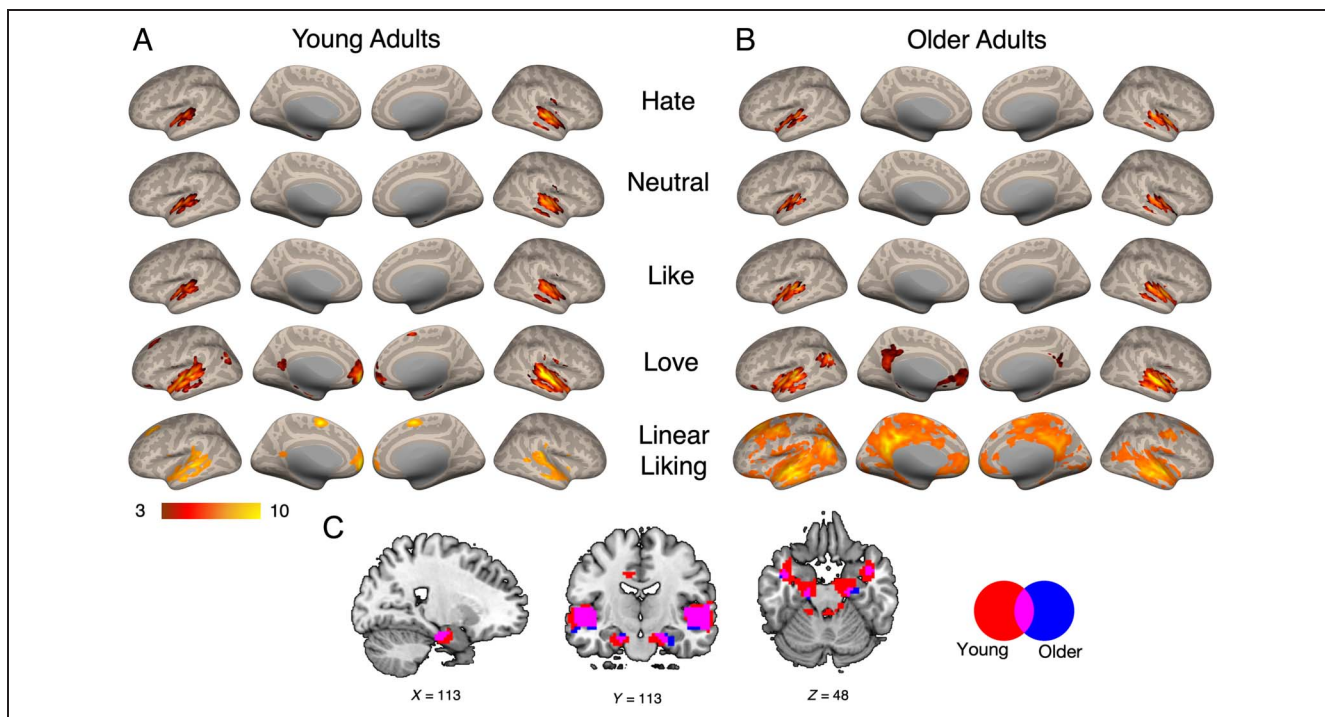
**Table 2.** (continued)

<i>Region(s)/Clusters</i>	<i>Hemisphere</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>k</i>
LOC	Left	-36	-78	33	34
Precuneus Posterior cingulate cortex	Left	-9	-54	12	34
Brainstem	Right	9	-48	-42	32
Parahippocampal gyrus	Left	-18	-36	-21	19
Orbitofrontal cortex	Left	-30	33	-12	14
SMA	Right	6	6	63	12
OAs					
<i>Hate</i>					
STG/STS/MTG/HG	Right	63	-24	0	320
Planum temporale/polare	Left	-54	-18	3	254
<i>Neutral</i>					
STG/STS/MTG/HG	Right	51	-6	-3	316
Planum temporale/polare	Left	-51	-18	3	284
<i>Like</i>					
STG/STS/MTG/HG	Right	48	-12	0	557
Planum temporale/polare	Left	-51	-18	3	490
Hippocampus	Right	18	-15	-21	31
	Left	-18	-12	-21	20
<i>Love</i>					
STG/STS/MTG/HG	Right	51	-6	-3	644
Planum temporale/polare	Left	-45	-27	6	632
Precuneus Posterior cingulate cortex	Left	-6	-54	15	194

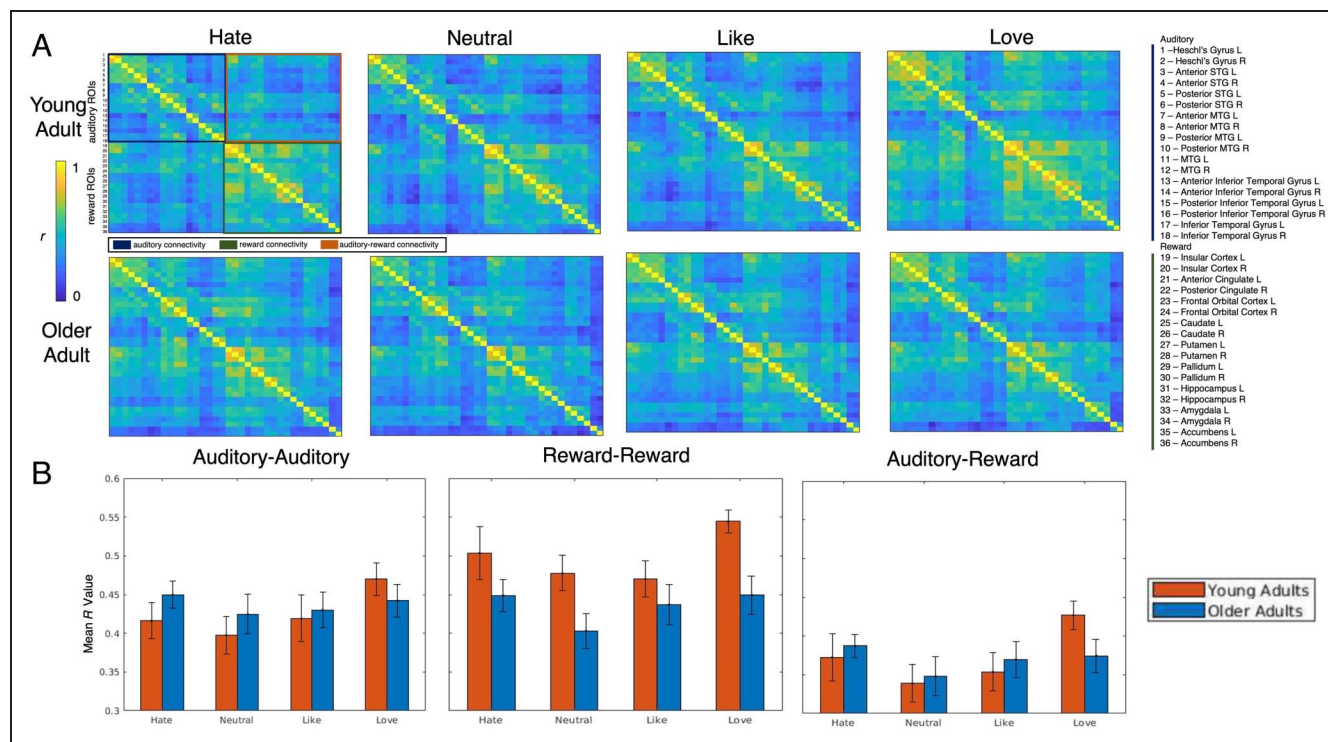
mPFC Paracingulate gyrus	Left	-3	51	-15	139
LOC	Left	-42	-72	33	103
Hippocampus	Right	21	-18	-21	47
	Left	-18	-21	-21	26
Brainstem	Right	3	-36	-12	38
Ventral striatum/nucleus accumbens	Left	-3	9	-12	33
Orbitofrontal cortex	Left	-36	30	-15	19
Cerebellum	Right	42	-69	-42	16

Voxel threshold:  $p < .05$  p-FDR corrected; cluster threshold:  $k > 10$  cluster size.





**Figure 1.** Functional activity across liking ratings. Univariate second-level results showing activity at each level of liking (rows 1–4) and linear contrast of liking (row 5) for YAs (A) and OAs (B) across liking ratings ( $p < .05$  p-FDR corrected for voxel height and cluster size). (C) Subcortical structures involved with listening to loved music for YAs (red), OAs (blue), and both (purple; voxel height  $p < .05$  p-FDR corrected; cluster size  $k > 10$ ).



**Figure 2.** Age-related differences in ROI-ROI connectivity for various levels of liking. (A) Correlation matrices showing the relationship between auditory and reward regions for different liking ratings for YAs and OAs. (B) Bar graphs depicting overall connectivity between auditory–auditory, reward–reward, and auditory–reward regions for YAs (orange) and OAs (blue) for hated, neutral, liked, and loved musical stimuli.

**Table 3.** Seed-based Connectivity Results

<i>Region</i>	<i>Hemisphere</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>k</i>	<i>Direction</i>
<i>YA(I) OA(-1); Rest; Auditory Network Seed</i>						
Precuneous	Bilateral	24	-72	32	20652	OA > YA
MFG	Right	34	42	38	713	OA > YA
MTG/STG	Left	-68	-18	-4	554	YA > OA
MTG/STG	Right	72	-28	0	479	YA > OA
MFG	Left	-36	50	26	427	OA > YA
LOC	Left	-38	-72	44	383	YA > OA
PostCG	Left	-48	-24	32	319	OA > YA
Caudate	Right	28	6	12	262	OA > YA
Putamen	Left	-20	6	14	221	OA > YA
PostCG	Right	58	-18	38	217	OA > YA
<i>YA(I) OA(-1); Music; Auditory Network Seed</i>						
Precuneous	Bilateral	-12	-78	2	22094	OA > YA
MFG	Left	-36	44	18	1321	OA > YA
MFG	Right	36	38	32	1285	OA > YA
PreCG	Left	-56	2	6	935	OA > YA
Insular cortex	Right	30	14	6	742	OA > YA
Thalamus	Right	30	-30	-12	489	OA > YA
STG/MTG	Right	68	-42	14	359	YA > OA
White matter	Left	-36	-46	12	313	YA > OA
Cerebellum	Right	30	-40	-42	283	OA > YA
Hippocampus	Right	12	-6	-24	221	YA > OA
AC	Bilateral	0	32	-4	214	YA > OA
mPFC	Bilateral	-2	20	-16	194	YA > OA
<i>YA(I) OA(-1); Rest; Reward Network Seed</i>						
Precuneous	Bilateral	22	-76	30	14053	OA > YA
AC	Bilateral	6	18	18	1531	YA > OA
HG	Right	58	-28	8	445	OA > YA
PreCG	Right	42	-10	42	415	OA > YA
SFG	Right	22	32	42	298	OA > YA
MFG	Right	40	14	42	244	OA > YA
HG	Left	-44	-34	8	189	OA > YA
PreCG	Left	-56	2	20	171	OA > YA
<i>YA(I) OA(-1); Music; Reward Network Seed</i>						
LG	Bilateral	-2	-70	0	1282	OA > YA
PreCG	Bilateral	-6	-24	74	760	OA > YA

**Table 3.** (continued)

<i>Region</i>	<i>Hemisphere</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>k</i>	<i>Direction</i>
IFG	Left	-38	44	-4	739	OA > YA
IFG	Right	42	42	-12	629	OA > YA
AC	Bilateral	-6	-4	30	437	YA > OA
PostCG	Right	36	-36	62	292	OA > YA
Precuneous	Bilateral	4	-72	38	245	OA > YA
PreCG	Left	-42	-12	30	208	OA > YA
PreCG	Right	46	-12	36	186	OA > YA
Pallidum	Left	-20	-6	-4	143	YA > OA
Pallidum	Right	18	2	-4	129	YA > OA
<i>YA; Music(1) Rest(-1); Auditory Network Seed</i>						
PostCG	Left	-42	-36	56	14668	Rest > Music
PostCG	Right	34	-54	60	6882	Rest > Music
LG	Left	-18	-52	8	5748	Music > Rest
STG/MTG	Left	-56	-16	2	3770	Music > Rest
STG/MTG	Right	52	6	-10	2841	Music > Rest
Cuneal cortex	Bilateral	-12	-88	36	2252	Music > Rest
mPFC	Bilateral	-2	50	-12	1883	Music > Rest
ITG	Right	54	-24	-22	1653	Rest > Music
OFusG	Right	24	-88	-12	739	Rest > Music
Brain stem	Bilateral	10	-18	-42	526	Rest > Music
Forb	Left	-48	42	-10	411	Rest > Music
FOrb	Right	24	32	-12	374	Rest > Music
Insular cortex	Right	36	-6	12	362	Rest > Music
ITG	Right	54	-10	-42	316	Rest > Music
LOC	Left	-42	-84	12	284	Music > Rest
PreCG	Right	64	12	20	248	Rest > Music
AG	Right	66	-50	26	233	Rest > Music
FOrb	Left	-24	30	-18	227	Music > Rest
OFusG	Left	-20	-88	-16	226	Rest > Music
<i>OA; Music(1) Rest(-1); Auditory Network Seed</i>						
PostCG	Left	-44	-18	44	7422	Rest > Music
PreCG	Right	28	-54	60	5459	Rest > Music
Precuneous	Bilateral	-6	-48	0	1182	Music > Rest
STG/MTG	Left	-66	-28	0	889	Music > Rest
STG/MTG	Right	52	-12	-10	726	Music > Rest
MTG	Left	-56	-52	2	458	Rest > Music
Thalamus	Bilateral	0	-4	0	211	Music > Rest

**Table 3.** (continued)

<i>Region</i>	<i>Hemisphere</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>k</i>	<i>Direction</i>
LOC	Left	-42	-72	36	187	Music > Rest
Cerebellum	Left	-8	-54	-30	158	Music > Rest
PreCG	Left	-54	2	24	138	Rest > Music
Insular cortex	Left	-36	-10	12	103	Rest > Music
LG	Left	-2	-66	-10	96	Music > Rest
ITG	Left	-44	2	-46	94	Rest > Music
<i>YA; Music(1) Rest(-1); Reward Network Seed</i>						
AG	Right	54	-58	18	119	Music > Rest
LOC	Left	-44	-72	14	95	Music > Rest
<i>All Participants; Self-Selected(1) Familiar Western(-1); Reward Network Seed</i>						
STG/MTG	Left	-50	-30	0	1958	SS > FW
STG/MTG	Right	48	-18	-4	1929	SS > FW
Forb	Left	-42	18	-10	108	SS > FW
<i>All Participants; Hate(-3) Neutral(-1) Like(1) Love(3); Auditory Network Seed</i>						
STG/MTG	Left	-62	-24	6	1142	
STG/MTG	Right	52	-18	-4	820	
<i>All Participants; Hate(-3) Neutral(-1) Like(1) Love(3); Reward Network Seed</i>						
STG/MTG	Right	46	-22	-4	42	

Voxel height threshold  $p < .05$ , FDR-corrected; cluster size threshold  $p < .05$ , FDR-corrected.

more regional specificity of the effect. Follow-up testing indicated no significant quadratic effect of liking (hate, neutral, like, love [1 -1 -1 1]) for either group, and whole-brain comparisons for young versus OA contrasts showed no significant effects of group at the  $p < .05$  FDR-corrected level.

### **ROI-ROI Connectivity: Linear and Quadratic Relationships with Liking and Effects of Age Group**

Results of our ROI-ROI analysis are summarized in Figure 2. Three repeated-measures ANOVAs were run to evaluate the main effects of Liking Ratings and Age and the Rating  $\times$  Age interaction for connectivity among auditory and reward regions, and between auditory and reward regions. We also ran linear and quadratic contrasts to further investigate the relationship between ratings and connectivity for the conditions listed above.

For connectivity among auditory regions, there was a significant main effect of Liking,  $F(3, 108) = 3.06$ ,  $p = .032$ ,  $\eta_p^2 = .078$ . Bonferroni-corrected pairwise comparisons revealed that beta-weights for stimuli rated as loved were significantly greater than those rated as neutral. There was no significant main effect of Age Group,  $F(1, 36) = 0.804$ ,  $p = .376$ ,  $\eta_p^2 = .022$ , and no significant Rating  $\times$  Age Group interaction,  $F(3, 108) = 0.807$ ,  $p = .492$ ,  $\eta_p^2 = .022$ . Although the linear contrast was only marginally significant,  $F(1, 36) = 3.42$ ,  $p = .073$ ,  $\eta_p^2 = .087$ , there was a significant quadratic contrast,  $F(1, 36) = 6.95$ ,  $p = .012$ ,  $\eta_p^2 = .162$ , suggesting that hated and loved music had greater functional connectivity compared with neutral and liked music.

For connectivity within reward regions, there was a significant main effect of Liking,  $F(3, 108) = 3.19$ ,  $p = .027$ ,  $\eta_p^2 = .081$ . Bonferroni-corrected pairwise comparisons revealed that beta-weights for stimuli rated as loved

were significantly greater than those rated as neutral and those rated as liked. There was a significant main effect of Age,  $F(1, 36) = 5.13, p = .030, \eta_p^2 = .125$ , suggesting that YAs have greater connectivity within reward regions compared with OAs. There was no significant Rating  $\times$  Age interaction,  $F(1, 108) = 1.43, p = .237, \eta_p^2 = .038$ . There was no significant linear contrast,  $F(1, 36) = 2.28, p = .139, \eta_p^2 = .060$ , but there was a significant quadratic contrast,  $F(1, 36) = 8.26, p = .007, \eta_p^2 = .187$ . Thus, hated and loved music had greater connectivity compared with neutral and liked music.

For connectivity between auditory and reward regions, there was a significant main effect of liking,  $F(3, 108) = 3.60, p = .016, \eta_p^2 = .09$ . Bonferroni-corrected pairwise comparisons revealed that beta-weights for stimuli rated as loved were significantly greater than those rated as neutral. There was no significant main effect of Age,  $F(3, 36) = 0.002, p = .962, \eta_p^2 < .001$ , and no significant Rating  $\times$  Age interaction,  $F(3, 108) = 1.49, p = .221, \eta_p^2 = .040$ . There was both a significant linear contrast,  $F(1, 36) = 4.20, p = .048, \eta_p^2 = .104$ , and a significant quadratic

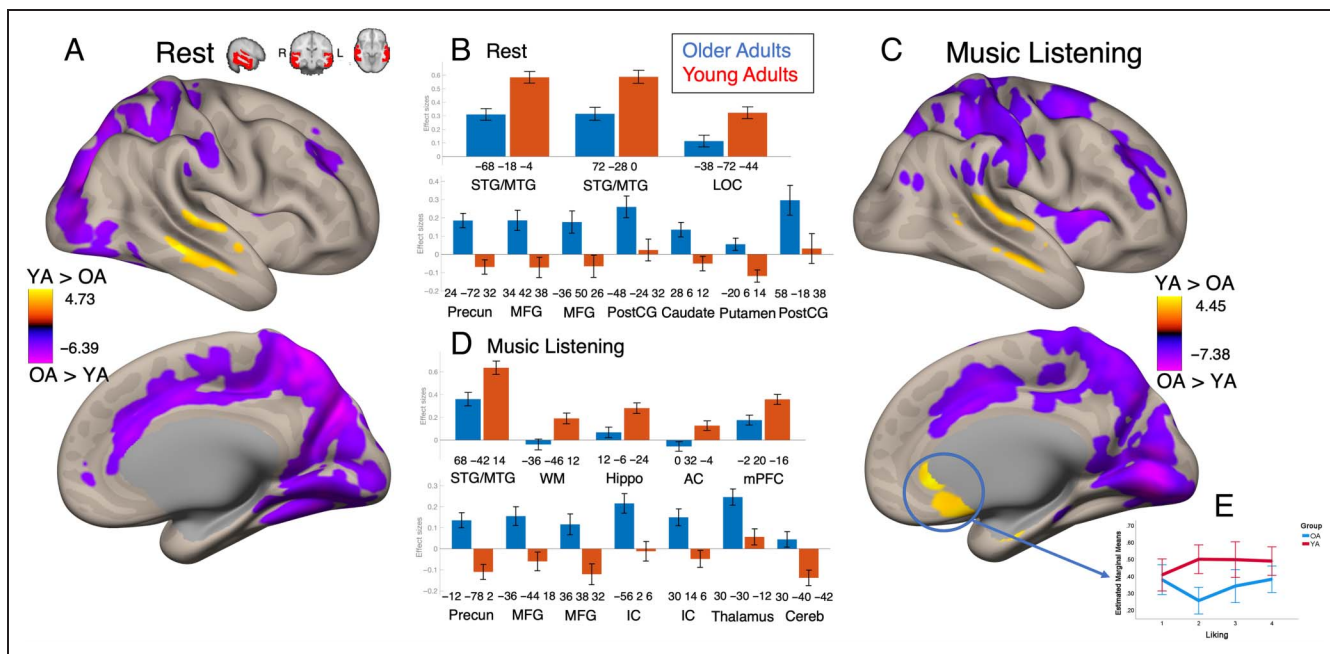
contrast,  $F(1, 36) = 7.28, p = .011, \eta_p^2 = .168$ ; in other words, auditory–reward connectivity scaled both with liking and with valence.

### Seed-based Connectivity: Age Group Differences in Auditory and Reward Network Connectivity

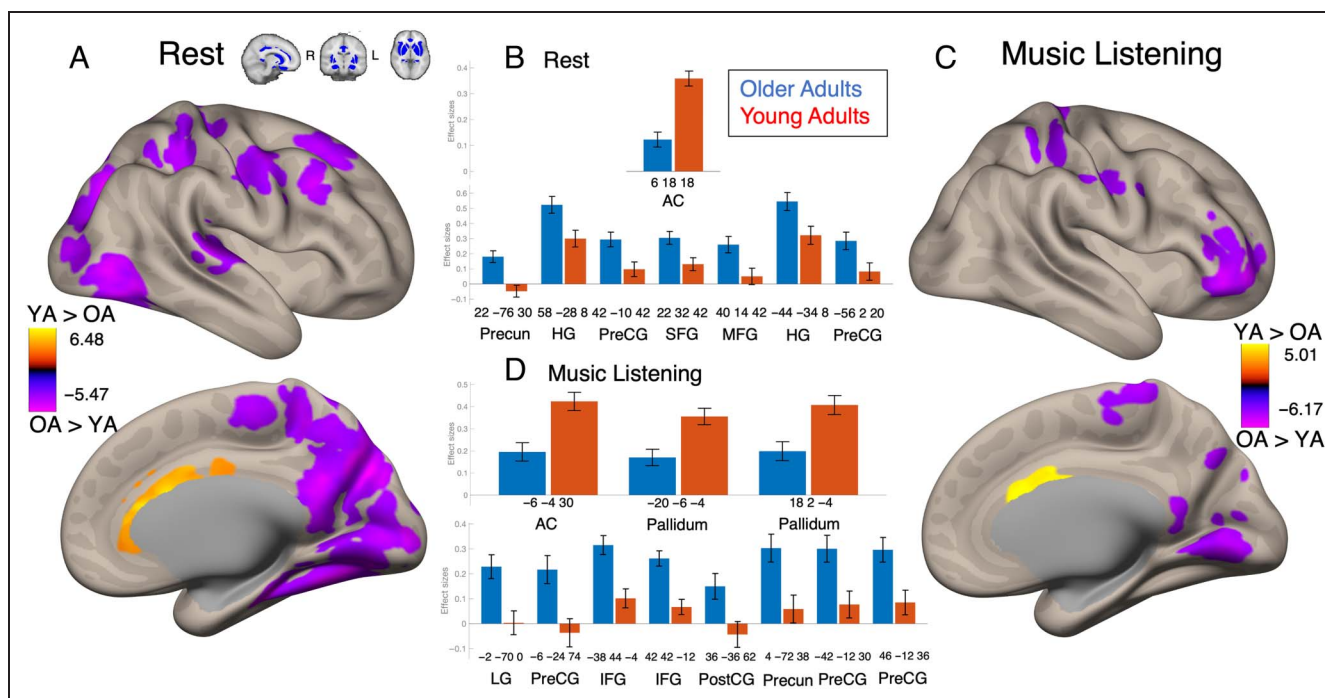
We seeded the auditory and reward networks separately and investigated the effects of age, task, musical liking ratings, selection, and BMRQ on functional connectivity from these seed networks. All seed-based analyses presented were performed at the  $p < .05$ , FDR-corrected level for both voxel height and cluster size. Significant clusters across all analyses are summarized in Table 3. Statistical maps of all significant results can be found at <https://neurovault.org/collections/QSMRNLRW/>.

#### Lower Network Differentiation in OAs

Contrasts between OAs and YAs (YA > OA) revealed significant effects of auditory and reward network-seeded connectivity during both music listening and rest. YAs



**Figure 3.** Age differences in auditory network seed-based connectivity: significant clusters for YA > OA contrast in auditory network seed, significant at the  $p < .05$ , FDR-corrected level for both voxel height and cluster size. (A) Visualization of significant clusters in the right hemisphere during resting-state scan, including clusters favoring YAs (warm tones) and clusters favoring OAs (cool tones). (B) Bar graphs depicting effect sizes for all significant clusters in resting-state contrast. Clusters with higher connectivity in YAs (red) are depicted in the top graph, and clusters with higher connectivity in OAs (blue) are depicted in the bottom graph. Cluster labels are MNI coordinates for center of mass of each significant cluster, as well as the most prevalent anatomical region included within each cluster. (C) Visualization of significant clusters in the right hemisphere during the music listening task, including clusters favoring YAs (warm tones) and clusters favoring OAs (cool tones). (D) Bar graphs depicting effect sizes for all significant clusters in music listening contrast. Clusters with higher connectivity in YAs (red) are depicted in the top graph, and clusters with higher connectivity in OAs (blue) are depicted in the bottom graph. (E) Line graph depicting ROI–ROI connectivity between auditory network regions and mPFC comparing across groups and liking ratings. Error bars depict  $\pm 2$  SEs, and marginal means are adjusted for covariates of gender, BMRQ, and within-group age.



**Figure 4.** Age differences in reward network seed-based connectivity: significant clusters for YA > OA contrast in reward network seed, significant at the  $p < .05$ , FDR-corrected level for both voxel height and cluster size. (A) Visualization of significant clusters in right hemisphere during resting-state scan, including clusters favoring YAs (warm tones) and clusters favoring OAs (cool tones). (B) Bar graphs depicting effect sizes for all significant clusters in resting-state contrast. Clusters with higher connectivity in YAs (red) are depicted in the top graph, and clusters with higher connectivity in OAs (blue) are depicted in the bottom graph. Cluster labels are MNI coordinates for center of mass of each significant cluster, as well as the most prevalent anatomical region included within each cluster. (C) Visualization of significant clusters in the right hemisphere during the music listening task, including clusters favoring YAs (warm tones) and clusters favoring OAs (cool tones). (D) Bar graphs depicting effect sizes for all significant clusters in music listening contrast. Clusters with higher connectivity in YAs (red) are depicted in the top graph, and clusters with higher connectivity in OAs (blue) are depicted in the bottom graph.

showed significantly higher auditory network-seeded connectivity to other regions in the auditory network, including bilateral STG and MTG, during rest (Figure 3A–B). During music listening, these effects were limited to the right hemisphere, and YAs additionally showed higher connectivity between auditory network and mPFC, hippocampus, and anterior cingulate compared with OAs (see Figure 3C–D). OAs showed higher connectivity to somatosensory, reward, and posterior default-mode processing regions compared with YAs, for which effects were similar during music listening as during rest. When including BMRQ as a covariate of no interest, significant effects were more constrained. During rest, regions of higher auditory network connectivity for the YA group were limited to the right hemisphere, and for the OA group, higher connectivity in the somatosensory and frontal clusters no longer reached significance. During music listening, only higher connectivity in the precuneus for the OA group remained significant, suggesting that the other effects are explained by individual differences in BMRQ.

At rest, YAs showed significantly higher reward-network seeded connectivity to anterior cingulate (AC) whereas OAs showed significantly higher connectivity to posterior DMN and somatosensory regions (Figure 4A–

B). During music listening, YAs once again showed connectivity to reward-associated regions, now including both AC and bilateral pallidum, whereas OAs now showed significant clusters of increased connectivity in bilateral IFG, in addition to effects observed at rest (Figure 4C–D). When including BMRQ as a covariate of no interest, only the AC cluster showing higher connectivity in the YA group at rest and the IFG cluster showing higher connectivity in the OA group during music listening remained significant.

Considering differences in age range across our two samples, all seed-based connectivity analyses were repeated using age, demeaned based on mean age for each sample, as a covariate of no interest. In all cases, there were no notable differences in the observed main effects of Group or Task. There were also no significant main effects of within-group age across all conditions.

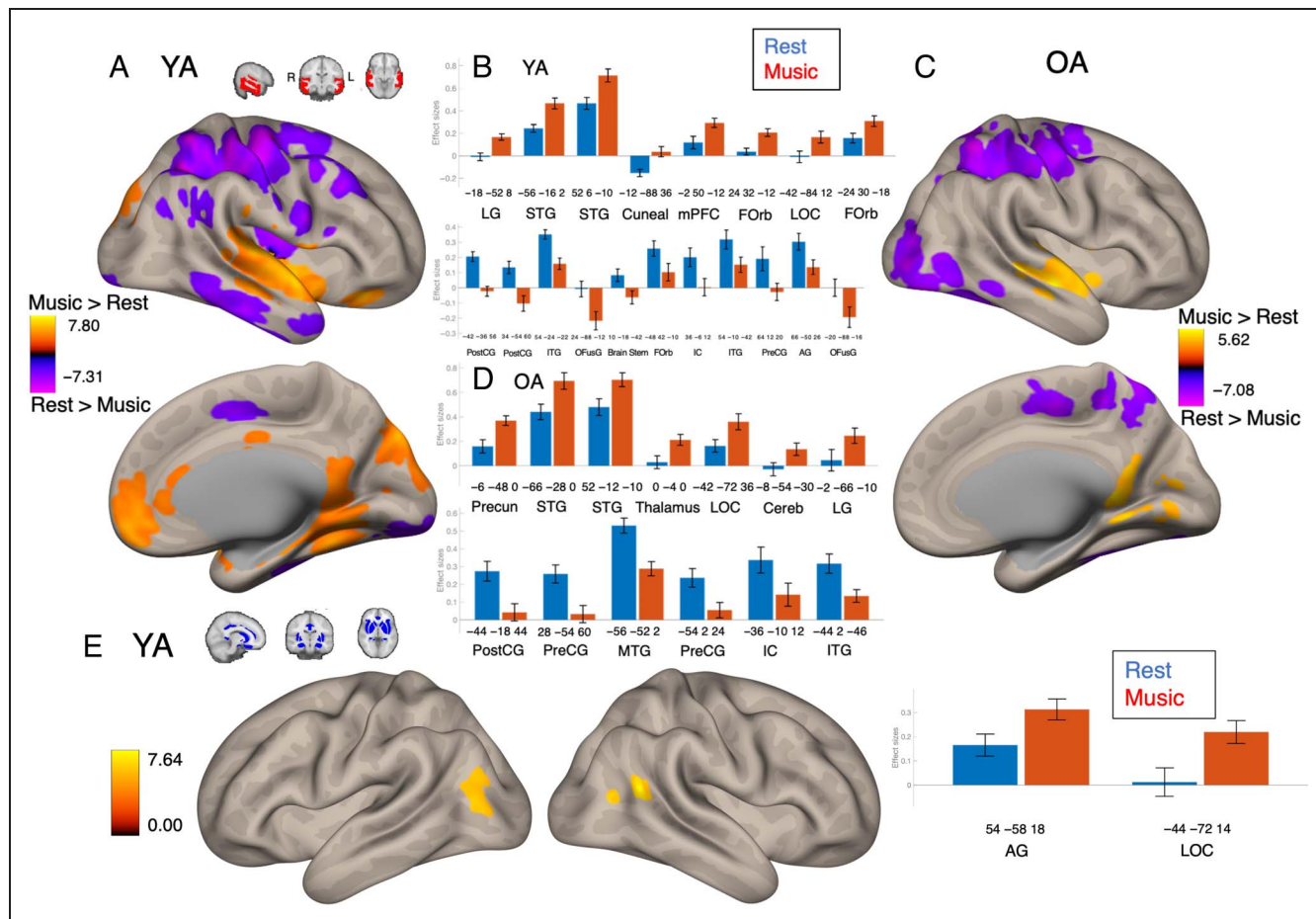
#### *Higher Auditory–mPFC Connectivity in YAs during Music Listening: Effects of Task*

Auditory network-seeded connectivity showed significant differences between task and rest within both of our age groups. In YAs, connectivity was higher during music

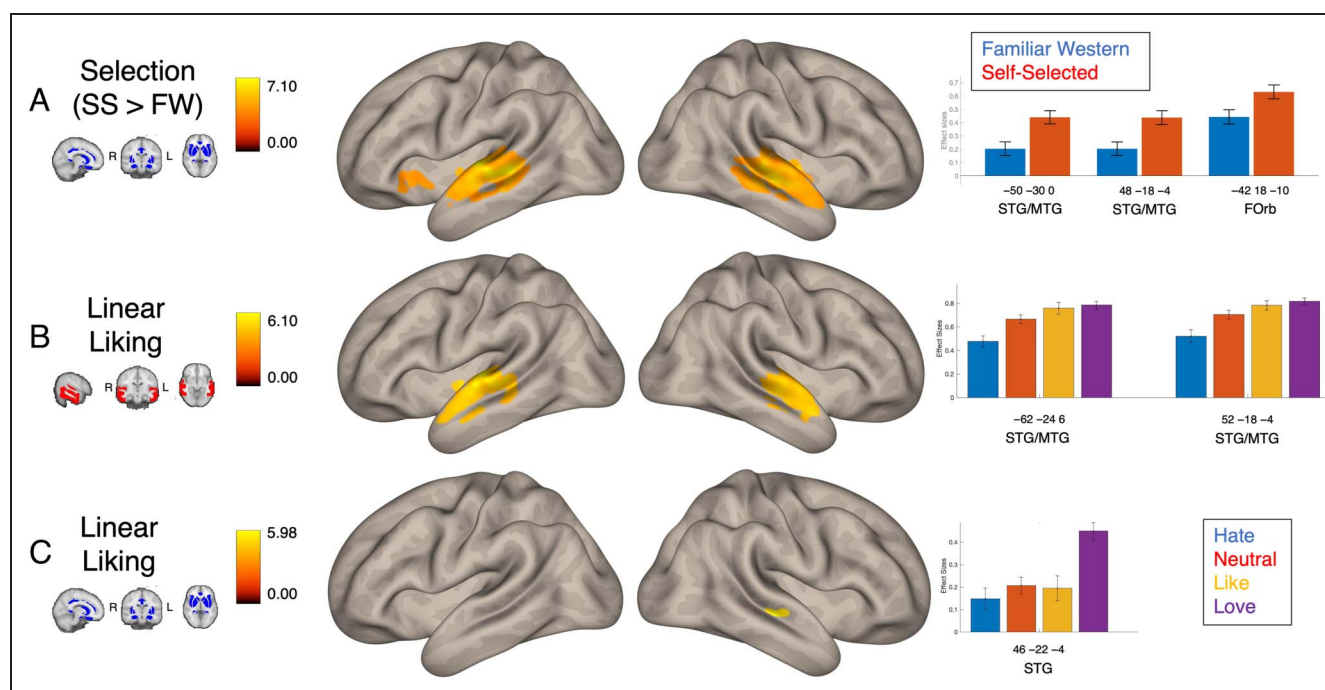
listening than rest in auditory cortex, reward, and default-mode regions, and at rest, connectivity was most notably higher than music listening in somatosensory regions and portions of the inferior temporal gyrus (Figure 5A–B). In OAs, many of the observed effects were similar, although positive effects of music listening were generally more limited, and there was no increased connectivity observed within the mPFC (see Figure 5C–D). Reward network-seeded main effects of Task were only observed in the YA group, including an increase in connectivity to bilateral LOC and angular gyrus (AG) during music listening (see Figure 5E). Inclusion of BMRQ as a covariate of no interest resulted in no significant clusters for this contrast. No Age  $\times$  Task interactions were observed.

### *Well-liked and Self-selected Music Increases Auditory–Reward Connectivity: Musical Stimulus Effects*

Effects contrasting different musical stimuli were also observed. There was significantly higher connectivity across all participants between reward network and bilateral auditory cortex in the participant-selected music condition as compared with researcher-selected familiar western music (see Figure 6A). There was also a significant linear effect of musical liking ratings across all participants in the auditory network seed. This took the form of increased connectivity to auditory regions, including bilateral STG and MTG (see Figure 6B). Inclusion of BMRQ as a covariate of no interest resulted in additional significant clusters for this effect in the amygdala and brainstem.



**Figure 5.** Task differences in seed-based connectivity: significant clusters for music > rest contrast, significant at the  $p < .05$ , FDR-corrected level for both voxel height and cluster size. (A) Visualization of significant clusters from auditory network seed in right hemisphere of YAs, including clusters favoring music listening (warm tones) and clusters favoring rest (cool tones). (B) Bar graphs depicting effect sizes for all significant clusters in young adult contrast. Clusters with higher connectivity during music listening (red) are depicted in the top graph, and clusters with higher connectivity during rest (blue) are depicted in the bottom graph. Cluster labels are MNI coordinates for the center of mass of each significant cluster, as well as the most prevalent anatomical region included within each cluster. (C) Visualization of significant clusters from the auditory network seed in the right hemisphere of OAs, including clusters favoring music listening (warm tones) and clusters favoring rest (cool tones). (D) Bar graphs depicting effect sizes for all significant clusters in OA contrast. Clusters with higher connectivity during music listening (red) are depicted in the top graph, and clusters with higher connectivity during rest (blue) are depicted in the bottom graph. (E) Visualization of significant clusters from the reward network seed in YAs, and bar graphs depicting effect sizes for all significant clusters. Cluster labels are MNI coordinates for the center of mass of each significant cluster, as well as the most prevalent anatomical region included within each cluster.



**Figure 6.** Differences of musical preference in seed-based connectivity: significant clusters for effects of musical selection (self-selected > familiar western) and linear effects of musical liking in auditory and reward network seed-based connectivity ( $[-3, -1, 1, 3]$ , two-tailed  $t$  test;  $p < .05$ , FDR-corrected for voxel height and cluster size). (A) Visualization of significant clusters from the reward network seed showing effects of selection, and bar graphs depicting effect sizes. Cluster labels are MNI coordinates for the center of mass of each significant cluster, as well as the most prevalent anatomical region included within each cluster. (B) Visualization of significant clusters from the auditory network seed showing linear effects of liking, and bar graphs depicting effect sizes. Cluster labels are MNI coordinates for the center of mass of each significant cluster, as well as the most prevalent anatomical region included within each cluster. (C) Visualization of significant clusters from the reward network seed showing linear effects of liking, and bar graphs depicting effect sizes. Cluster labels are MNI coordinates for the center of mass of each significant cluster, as well as the most prevalent anatomical region included within each cluster.

Reward network-seeded connectivity to auditory cortex also showed a significant linear effect of liking; however, this effect was limited to right lateral STG (see Figure 6C). There were no significant quadratic effects of liking observed, and no significant Stimulus  $\times$  Group interaction effects.

There were no significant main effects of BMRQ or Gender for either seed network in rest and music listening, and no significant BMRQ  $\times$  Task or Gender  $\times$  Task interaction effects.

#### *Linear and Quadratic Effects of Auditory, Reward, and DMN Network Connectivity for Liking and Age*

Follow-up MANCOVA of connectivity among and between auditory network ROIs, reward network ROIs, mPFC, and PCC indicated a significant main effect of group,  $F(1, 36) = 4.21, p = .003, \eta_p^2 = .522$ , characterized by higher connectivity in YA relative to OA. Also observed were quadratic, but not linear, interactions between liking and group in auditory–mPFC,  $F(1, 36) = 4.31, p = .046, \eta_p^2 = .116$  (Figure 3E) and auditory–PCC connectivity,  $F(1, 36) = 5.57, p = .024, \eta_p^2 = .144$ , as well between liking and BMRQ in auditory–auditory,  $F(1, 36) = 6.03,$

$p = .010, \eta_p^2 = .155$ ; auditory–mPFC,  $F(1, 36) = 7.357, p = .011, \eta_p^2 = .182$ ; and auditory–PCC connectivity,  $F(1, 36) = 4.27, p = .047, \eta_p^2 = .115$ . Linear interactions between liking and within-group age were also observed in auditory–auditory,  $F(1, 36) = 5.02, p = .032, \eta_p^2 = .132$ , and auditory–reward connectivity,  $F(1, 36) = 4.53, p = .041, \eta_p^2 = .121$ .

## DISCUSSION

Here, we characterize for the first time age-related differences in the neural substrates of musical reward. These data provide insight into the mechanisms underlying observed differences in musical reward in YAs and OAs (Cardona et al., 2022; Belfi et al., 2021; Mas-Herrero et al., 2013), relate the contributions of auditory and reward networks to music listening at varying levels of musical preference, and provide potential brain-based targets for the development of music-based interventions in OA populations.

Univariate analyses showed that both YAs and OAs activated multiple regions within the auditory network during music listening, as well as the mPFC during music listening that was rated as loved. The engagement of mPFC when



listening to preferred music is consistent with its observed role in musical reward processing (Salimpoor et al., 2013). Both groups showed specific activation of the hippocampus during preferred music listening. Although not classically considered part of the mesolimbic reward pathway, the hippocampus is an input into the ventral striatum (Lebreton, Jorge, Michel, Thirion, & Pessiglione, 2009) and is known to respond to reward and value, especially during reward learning (Wimmer, Li, Gorgolewski, & Poldrack, 2018; Davidow, Foerde, Galván, & Shohamy, 2016), memory formation, and emotion processing (Frühholz, Trost, & Grandjean, 2014; Bannerman et al., 2004). Here, the majority of main effects of music listening were similar between groups, suggesting that the overall activity patterns associated with music listening is preserved during aging. Nevertheless, univariate results, especially when listening to loved music, showed some clusters that were only significant in one group or another. Although a between-groups contrast was not statistically significant, main effects of music listening in each group pointed to differences when listening to loved music. OAs showed significant precuneus activity whereas YAs showed significant SMA activity. The precuneus is a highly metabolically active area in the brain; while being a hub of the DMN, it is also tied functionally to episodic memory retrieval as well as the experience of agency (Darby, Joutsa, Burke, & Fox, 2018; Cavanna & Trimble, 2006). In this study, the finding of larger clusters of activity in the precuneus that scale with liking in OAs may reflect higher metabolic demands in older adulthood for music listening; alternately, it may reflect default mode functions including but not limited to episodic memory processing and/or a greater sense of agency during music listening.

Only YAs showed SMA activity when listening to loved music. SMA is often activated in auditory imagery (Lima, Krishnan, & Scott, 2016), especially during beat perception in rhythmic music (Nombela, Hughes, Owen, & Grahn, 2013). Neurophysiological responses comparing YAs and OAs during music listening have shown that both groups are broadly sensitive to the beat in neural phase-locking measures, but subtle differences persist in topographical distributions of phase locking at different levels of the beat (Tichko, Page, Kim, Large, & Loui, 2022).

In ROI–ROI analyses, well-liked music resulted in higher connectivity among and between auditory and reward regions, as compared with music rated neutrally. The difference between YAs and OAs in functional connectivity was especially accentuated when listening to preferred music. We see that connectivity of auditory and reward regions during music listening is not a linear function in preference for the music, but rather determined by a u-shaped relationship with liking ratings. This stands in contrast to the effect of liking observed in our seed-based connectivity analysis, in which auditory network seed showed a significant linear effect, but not a quadratic effect, in connectivity to specific auditory regions. We

interpret these different effects as resulting from differences in the methodologies of seed-based connectivity and ROI–ROI analyses. Seed-based connectivity started with the auditory and reward networks taken as a whole, and thus, we observed that the strongest connections arising within these networks lie within regions that show a linear effect of liking. Meanwhile, our ROI–ROI approach granted equal weight to each region identified as contributing to the auditory and reward network. In this regard, vertices showing strong linear effects of liking were accompanied by vertices that showed stronger connectivity during hated music, resulting in the observed U-shaped curve.

We also observed higher overall connectivity among reward regions in YAs as compared with OAs. This is in keeping with observed decreases in overall hedonic response with age (Eppinger et al., 2012), and are consistent with previously observed losses of functional network connectivity in OAs, both generally (Sala-Llonch et al., 2015; Sheline et al., 2010) and specific to reward-sensitive systems (Geddes et al., 2018).

Seed-based connectivity results further support the finding that YAs have stronger within-network seed-based connectivity than OAs. This was seen in auditory–auditory and reward–reward connections during both rest and music listening. However, music listening and individual differences in musical reward did mediate these effects. Auditory–auditory group effects were limited to the right hemisphere during the music listening task, as well as when BMRQ was included as a covariate of no interest during rest. Research into hemispheric differences in auditory processing has long supported a right-hemispheric dominance in music processing as compared with speech (Zatorre, Evans, Meyer, & Gjedde, 1992). Musical training can also lead to a reduction in the rightward asymmetry of musical feature processing (Ono et al., 2011). As such, one possible explanation is that primary musical processing regions in the right hemisphere show a more robust effect of age, whereas left hemispheric differences can be accounted for by differences in task and individual differences in musical reward.

Alternatively, left auditory cortex is known to be more sensitive to rapid temporal information, whereas the right auditory cortex is more sensitive to spectral information (Albouy, Benjamin, Morillon, & Zatorre, 2020; Boemio, Fromm, Braun, & Poeppel, 2005; Zatorre & Belin, 2001). These differences are also reflected in the way people listen to music: Individuals who focus their listening toward spectral features show higher activity in the right HG, whereas those who focus on more holistic features show more left lateralization (Schneider et al., 2005). Therefore, another potential interpretation of these results, which may be tested in future studies, is that age-related differences affect spectral processing or spectral acuity more than holistic or temporal auditory processing, the latter being explained by differences in musical reward and recovered by active music listening. Furthermore, inclusion of BMRQ during the music listening task removed

all auditory–auditory and reward–reward effects favoring YAs. These results suggest that individual differences in musical reward account for some of the observed differences between age groups, and that music listening may remediate age-related deficits in auditory and reward network coherence.

Turning now to specific connectivity effects between our seed networks and other, out-of-network regions, one major finding is that music listening led to greater connectivity of mPFC from auditory network in YAs as compared with OAs. This can be observed in both the task > rest contrast, in which the effect was seen in YAs but not OAs, and YA > OA contrast, in which the effect was seen during music listening, but not rest. This, taken together with findings from whole-brain regression, suggests that whereas mPFC is activated during preferred music listening across age groups, the inclusion of mPFC in the auditory system during music listening in general is more readily observable in young adults specifically. This is also supported by the results of the follow-up MANCOVA comparing the average pairwise correlations between auditory regions and mPFC, which resulted in a significant Group  $\times$  Liking interaction. This is consistent with previous work demonstrating that functional connectivity of the default-mode network, and especially mPFC, decreases with age (Staffaroni et al., 2018; Sambataro et al., 2010), and continues to decline with age-related illnesses such as Alzheimer’s disease (Staffaroni et al., 2018; Schouten et al., 2016; Hafkemeijer et al., 2015).

Another region that showed a significant interaction between music listening and age was the LOC. Auditory-seeded connectivity to LOC was higher in music listening than rest in both groups; however, only the YA group showed increased connectivity between reward network and LOC. This result was not expected, considering LOC’s primarily observed role in object perception (Nagy, Greenlee, & Kovács, 2012; Malach, Levy, & Hasson, 2002). However, some work has shown preferential connectivity between precuneus and LOC in trained musicians (Tanaka & Kirino, 2016) and increased activity and structural connectivity of LOC during music reading as compared with word reading (Bouhali, Mongelli, de Schotten, & Cohen, 2020), suggesting a potential role of LOC in music processing that is not yet fully understood.

Meanwhile, OAs showed greater connectivity between auditory-seeded and reward-seeded networks and out-of-network regions, including middle frontal gyrus (MFG), precentral gyrus, and postcentral gyrus, consistent with the notion of age-related dedifferentiation. OAs also showed significantly higher connectivity to precuneus, lending further support to the effect observed within the global linear regression model. For the most part, effects favoring OAs took the form of moderately positive effect sizes in the OA group compared with moderately negative or near-zero effect sizes in the YA group. This suggests that whereas OAs show a decrease of network coherence,

there is simultaneously a gain of more distributed connectivity between functionally distinct brain regions.

However, some of the specific effects favoring OAs do warrant further discussion. For one, OAs showed higher connectivity between reward network and bilateral IFG as compared with YAs that was specific to the music listening task, and the right-lateral component of this effect was the only group effect within that contrast to survive correction for differences in BMRQ. IFG is known to play a role in musical syntax processing (Kunert, Willems, Casasanto, Patel, & Hagoort, 2015; Koelsch, 2005), and right IFG in particular is dominant over left IFG for the perception of pitch in song (Merrill et al., 2012) and for the integration of harmonic information into auditory and motor systems (Bianco et al., 2016). The fact that this result is only observed during music listening may suggest that the IFG is specifically responding to musical stimuli, and the effect favoring OAs may reflect compensatory changes in aging, and suggest that OAs may be more efficiently using IFG to incorporate musical information into multiple systems, including the reward network.

Another region that showed increased connectivity to auditory and reward networks in OAs is the lingual gyrus (LG). LG plays a critical role in the encoding and retrieval of visual memories (Machielsen, Rombouts, Barkhof, Scheltens, & Witter, 2000; Bogousslavsky, Miklossy, Deruaz, Assal, & Regli, 1987). It has also shown increased structural and functional connectivity related to creativity (Belden et al., 2020; Takeuchi et al., 2010), likely drawing on its role in memory retrieval for the generative and evaluative processes involved in creative behavior. OAs have also been shown to have higher relative activation than YAs in LG when comparing positive relative to negative visual stimuli (Kehoe, Toomey, Balsters, & Bokde, 2013).

Finally, there was a pronounced effect across all participants, in which listening to their own self-selected music led to increased connectivity between reward network and auditory regions as compared with other recognizable music within the larger western canon. Agency in music listening is known to be an important factor in health outcomes of music-based interventions (Howlin, Stapleton, & Rooney, 2022; Cassidy & Macdonald, 2009; Ruud, 1997). However, here for the first time, we present direct evidence that agency in song selection leads to increased connectivity of auditory and reward networks. This supports the use of these networks as neural targets for music-based interventions that center around the concept of agency, and helps to explain these previously observed behavioral effects. These results constitute a novel set of findings characterizing age-related differences in the musical reward response. These findings suggest that auditory and reward systems can be directly targeted by music-based interventions for OAs, and provide neurological evidence supporting the use of participant-selected music in such interventions.

Previous work has noted the importance of agency for music-based interventions for dementia (Baird &

Thompson, 2018). Specifically, the arguments for the sense of agency in music listening have focused on “embodied selfhood” (Kontos, 2014), in that the persistence of musical intention despite advanced Alzheimer’s disease is explained by “corporeality as a source of agency” (Kontos & Martin, 2013); that is, the predictive processes by which music engages the cognitive system confers cognitive benefit in dementia by restoring a sense of agency. The present study reconciles this idea with the notion of network dedifferentiation in neuroscientific studies of aging (Koen, Srokova, & Rugg, 2020). Specifically, these results showed that for OAs compared with YAs, music listening engages lower within-network connectivity, but greater out-of-network connectivity between auditory-seeded and reward-seeded networks and out-of-network regions. This suggests that persistent music listening in OAs, such as through receptive music-based interventions (Quinci et al., 2022), may confer an advantage by activating more disparate regions throughout different networks in the brain, especially during self-selected music listening. This is consistent with the de-emphasis of perceptual networks, and the relative upregulation of out-of-network processing, during music listening in older adulthood. Designs of music-based interventions may benefit from this finding by emphasizing strategies that are known to pull in out-of-network processes, such as episodic memory, self-referential processing, and/or “embodied” processing, that are uniquely engaged during music listening, especially self-selected music listening, in older adulthood.

Despite the strengths of the current study in reconciling theoretical and empirical findings across disciplines, some limitations should be addressed. Gender disparities do exist between our two samples: The young adult sample had more female participants than the OAs sample, which was relatively gender balanced. To account for these differences, we ran follow-up analyses to observe any main effects of gender. No significant effects were observed, suggesting that the gender differences were not confounding the patterns of results. The age span was also not consistent between our two samples. Our OA sample spanned 35 years of age, whereas our young adult sample only spanned 5 years of age. Follow-up analyses revealed no main effects of within-sample age, and including within-sample age as a covariate did not have a significant impact on the observed effects, thus increasing the confidence with which we claim that effects of age primarily arose from differences between the YA and OA samples.

Our data are also limited in the extent to which participants were asked to report on their feelings about a particular piece. We did not ask about the particular emotions evoked by each piece, nor did we ask participants about the autobiographical context behind their self-selected pieces. In future studies, a more granular approach to emotional classification of pieces may be warranted to better understand the relevant contributions to auditory–

reward connectivity. Furthermore, the young adult sample falls into an age range in which the brain is still developing (Sowell, Thompson, Tessner, & Toga, 2001; Giedd et al., 1999), and thus for future analyses, we would recommend expanding the sample to include a broader range of the life span, covering all age groups. Nevertheless, this novel set of findings demonstrates that different age groups do in fact vary in their auditory reward processing, further explaining observed differences in musical reward experience (Belfi et al., 2021), and adding to the depth of knowledge required for the understanding of musical reward processing.

### Acknowledgments

We acknowledge MIND Lab members Nicholas Kathios, Valerie Goutama, Dayang Gong, Jacob Ostapenko, Grace Neale, Catherine Zhou, Ritu Amarnani, Amira Toivoinen, Itamar Zik, Nicole Page, Jasper Olson, and Parker Tichko for assistance with fMRI data acquisition and analyses. We thank all our participants and staff of Northeastern University Biomedical Imaging Center (Fred Bidmead, Valur Olafsson, Susan Whitfield-Gabrieli) for help with MRI data acquisition and analysis.

Reprint requests should be sent to Psyche Loui, Northeastern University, ISEC 624, 360 Huntington Ave, Boston, MA 02115-5005, United States, or via e-mail: p.loui@northeastern.edu.

### Data Availability Statement

Preregistration can be found at <https://osf.io/zxd42>. Statistical maps of all significant results can be found at <https://neurovault.org/collections/QSMRNLRW/>.

### Author Contributions

Alexander Belden: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing—Original draft; Writing—Review & editing. Milena Aiello Quinci: Data curation; Formal analysis; Investigation; Methodology; Project administration; Writing—Original draft; Writing—Review & editing. Maiya Geddes: Writing—Original draft; Writing—Review & editing. Nancy J. Donovan: Investigation; Writing—Original draft; Writing—Review & editing. Suzanne B. Hanser: Conceptualization; Writing—Original draft; Writing—Review & editing. Psyche Loui: Conceptualization; Data curation; Funding acquisition; Investigation; Resources; Supervision; Visualization; Writing—Original draft; Writing—Review & editing.

### Funding Information

National Institutes of Health (<https://dx.doi.org/10.13039/100000002>), grant numbers: R01AG078376, R21AG075232, R43AG078012; National Science Foundation, grant numbers: NSF-BCS 2240330, and NSF-CAREER 1945436 to P. L.

## Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were  $M(\text{an})/M = .407$ ,  $W(\text{oman})/M = .32$ ,  $M/W = .115$ , and  $W/W = .159$ , the comparable proportions for the articles that these authorship teams cited were  $M/M = .549$ ,  $W/M = .257$ ,  $M/W = .109$ , and  $W/W = .085$  (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this article report its proportions of citations by gender category to be as follows:  $M/M = .438$ ;  $W/M = .302$ ;  $M/W = .104$ ;  $W/W = .156$ .

## REFERENCES

- Ai, M., Loui, P., Morris, T. P., Chaddock-Heyman, L., Hillman, C. H., McAuley, E., et al. (2022). Musical experience relates to insula-based functional connectivity in older adults. *Brain Sciences*, 12, 1577. <https://doi.org/10.3390/brainsci12111577>, PubMed: 36421901
- Alain, C., Zendel, B. R., Hutka, S., & Bidelman, G. M. (2014). Turning down the noise: The benefit of musical training on the aging auditory brain. *Hearing Research*, 308, 162–173. <https://doi.org/10.1016/j.heares.2013.06.008>, PubMed: 23831039
- Albouy, P., Benjamin, L., Morillon, B., & Zatorre, R. J. (2020). Distinct sensitivity to spectrotemporal modulation supports brain asymmetry for speech and melody. *Science*, 367, 1043–1047. <https://doi.org/10.1126/science.aaz3468>, PubMed: 32108113
- Alluri, V., Toivianen, P., Burunat, I., Kliuchko, M., Vuust, P., & Brattico, E. (2017). Connectivity patterns during music listening: Evidence for action-based processing in musicians. *Human Brain Mapping*, 38, 2955–2970. <https://doi.org/10.1002/hbm.23565>, PubMed: 28349620
- Aydogan, G., Flaig, N., Ravi, S. N., Large, E. W., McClure, S. M., & Margulis, E. H. (2018). Overcoming bias: Cognitive control reduces susceptibility to framing effects in evaluating musical performance. *Scientific Reports*, 8, 6229. <https://doi.org/10.1038/s41598-018-24528-3>, PubMed: 29670143
- Bäckman, L., Lindenberger, U., Li, S.-C., & Nyberg, L. (2010). Linking cognitive aging to alterations in dopamine neurotransmitter functioning: Recent data and future avenues. *Neuroscience & Biobehavioral Reviews*, 34, 670–677. <https://doi.org/10.1016/j.neubiorev.2009.12.008>, PubMed: 20026186
- Baird, A., & Thompson, W. F. (2018). The impact of music on the self in dementia. *Journal of Alzheimer's Disease*, 61, 827–841. <https://doi.org/10.3233/JAD-170737>, PubMed: 29332051
- Bannerman, D. M., Rawlins, J. N. P., McHugh, S. B., Deacon, R. M. J., Yee, B. K., Bast, T., et al. (2004). Regional dissociations within the hippocampus—Memory and anxiety. *Neuroscience & Biobehavioral Reviews*, 28, 273–283. <https://doi.org/10.1016/j.neubiorev.2004.03.004>, PubMed: 15225971
- Behzadi, Y., Restom, K., Liu, J., & Liu, T. T. (2007). A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. *Neuroimage*, 37, 90–101. <https://doi.org/10.1016/j.neuroimage.2007.04.042>, PubMed: 17560126
- Belden, A., Zeng, T., Przsinda, E., Anteraper, S. A., Whitfield-Gabrieli, S., & Loui, P. (2020). Improvising at rest: Differentiating jazz and classical music training with resting state functional connectivity. *Neuroimage*, 207, 116384. <https://doi.org/10.1016/j.neuroimage.2019.116384>, PubMed: 31760149
- Belfi, A. M., & Loui, P. (2020). Musical anhedonia and rewards of music listening: Current advances and a proposed model. *Annals of the New York Academy of Sciences*, 1464, 99–114. <https://doi.org/10.1111/nyas.14241>, PubMed: 31549425
- Belfi, A. M., Moreno, G. L., Gugliano, M., & Neill, C. (2021). Musical reward across the lifespan. *Aging & Mental Health*, 26, 932–939. <https://doi.org/10.1080/13607863.2021.1871881>, PubMed: 33442987
- Bianco, R., Novembre, G., Keller, P. E., Kim, S. G., Scharf, F., Friederici, A. D., et al. (2016). Neural networks for harmonic structure in music perception and action. *Neuroimage*, 142, 454–464. <https://doi.org/10.1016/j.neuroimage.2016.08.025>, PubMed: 27542722
- Boemio, A., Fromm, S., Braun, A., & Poeppel, D. (2005). Hierarchical and asymmetric temporal sensitivity in human auditory cortices. *Nature Neuroscience*, 8, 389–395. <https://doi.org/10.1038/nn1409>, PubMed: 15723061
- Bogousslavsky, J., Miklossy, J., Deruaz, J. P., Assal, G., & Regli, F. (1987). Lingual and fusiform gyri in visual processing: A clinico-pathologic study of superior altitudinal hemianopia. *Journal of Neurology, Neurosurgery & Psychiatry*, 50, 607–614. <https://doi.org/10.1136/jnnp.50.5.607>, PubMed: 3585386
- Bouhali, F., Mongelli, V., de Schotten, M. T., & Cohen, L. (2020). Reading music and words: The anatomical connectivity of musicians' visual cortex. *Neuroimage*, 212, 116666. <https://doi.org/10.1016/j.neuroimage.2020.116666>, PubMed: 32087374
- Brett, M., Anton, J.-L., Valabregue, R., & Poline, J.-B. (2002). Region of interest analysis using an SPM toolbox. In *8th International Conference on Functional Mapping of the Human Brain*. Sendai, Japan.
- Buckner, R. L., Snyder, A. Z., Shannon, B. J., LaRossa, G., Sachs, R., Fotenos, A. F., et al. (2005). Molecular, structural, and functional characterization of Alzheimer's disease: Evidence for a relationship between default activity, amyloid, and memory. *Journal of Neuroscience*, 25, 7709–7717. <https://doi.org/10.1523/JNEUROSCI.2177-05.2005>, PubMed: 16120771
- Cardona, G., Ferreri, L., Lorenzo-Seva, U., Russo, F. A., & Rodriguez-Fornells, A. (2022). The forgotten role of absorption in music reward. *Annals of the New York Academy of Sciences*, 1514, 142–154. <https://doi.org/10.1111/nyas.14790>, PubMed: 35589672
- Cassidy, G., & Macdonald, R. (2009). The effects of music choice on task performance: A study of the impact of self-selected and experimenter-selected music on driving game performance and experience. *Musicae Scientiae*, 13, 357–386. <https://doi.org/10.1177/102986490901300207>
- Cavanna, A. E., & Trimble, M. R. (2006). The precuneus: A review of its functional anatomy and behavioural correlates. *Brain*, 129, 564–583. <https://doi.org/10.1093/brain/awl004>, PubMed: 16399806
- Chowdhury, R., Guitart-Masip, M., Lambert, C., Dayan, P., Huys, Q., Duzel, E., et al. (2013). Dopamine restores reward prediction errors in old age. *Nature Neuroscience*, 16, 648–653. <https://doi.org/10.1038/nn.3364>, PubMed: 23525044
- Darby, R. R., Joutsa, J., Burke, M. J., & Fox, M. D. (2018). Lesion network localization of free will. *Proceedings of the National Academy of Sciences, U.S.A.*, 115, 10792–10797. <https://doi.org/10.1073/pnas.1814117115>, PubMed: 30275309

- Davidow, J. Y., Foerde, K., Galván, A., & Shohamy, D. (2016). An upside to reward sensitivity: The hippocampus supports enhanced reinforcement learning in adolescence. *Neuron*, *92*, 93–99. <https://doi.org/10.1016/j.neuron.2016.08.031>, PubMed: 27710793
- Ellis, R. J., Bruijn, B., Norton, A. C., Winner, E., & Schlaug, G. (2013). Training-mediated leftward asymmetries during music processing: A cross-sectional and longitudinal fMRI analysis. *Neuroimage*, *75*, 97–107. <https://doi.org/10.1016/j.neuroimage.2013.02.045>, PubMed: 23470982
- Eppinger, B., Nystrom, L. E., & Cohen, J. D. (2012). Reduced sensitivity to immediate reward during decision-making in older than younger adults. *PLoS One*, *7*, e36953. <https://doi.org/10.1371/journal.pone.0036953>, PubMed: 22655032
- Erixon-Lindroth, N., Farde, L., Robins Wahlin, T.-B., Sovago, J., Halldin, C., & Bäckman, L. (2005). The role of the striatal dopamine transporter in cognitive aging. *Psychiatry Research: Neuroimaging*, *138*, 1–12. <https://doi.org/10.1016/j.psychres.2004.09.005>, PubMed: 15708296
- Ferreri, L., Mas-Herrero, E., Zatorre, R. J., Ripollés, P., Gomez-Andres, A., Alicart, H., et al. (2019). Dopamine modulates the reward experiences elicited by music. *Proceedings of the National Academy of Sciences, U.S.A.*, *116*, 3793–3798. <https://doi.org/10.1073/pnas.1811878116>, PubMed: 30670642
- Fitzhugh, M. C., Hemesath, A., Schaefer, S. Y., Baxter, L. C., & Rogalsky, C. (2019). Functional connectivity of Heschl's gyrus associated with age-related hearing loss: A resting-state fMRI study. *Frontiers in Psychology*, *10*, 2485. <https://doi.org/10.3389/fpsyg.2019.02485>, PubMed: 31780994
- Frey, S., Campbell, J. S., Pike, G. B., & Petrides, M. (2008). Dissociating the human language pathways with high angular resolution diffusion fiber tractography. *Journal of Neuroscience*, *28*, 11435–11444. <https://doi.org/10.1523/jneurosci.2388-08.2008>, PubMed: 18987180
- Friston, K. J., Ashburner, J., Frith, C. D., Poline, J. B., Heather, J. D., & Frackowiak, R. S. (1995). Spatial registration and normalization of images. *Human Brain Mapping*, *3*, 165–189. <https://doi.org/10.1002/hbm.460030303>
- Frühholz, S., Trost, W., & Grandjean, D. (2014). The role of the medial temporal limbic system in processing emotions in voice and music. *Progress in Neurobiology*, *123*, 1–17. <https://doi.org/10.1016/j.pneurobio.2014.09.003>, PubMed: 25291405
- Geddes, M. R., Mattfeld, A. T., de los Angeles, C., Keshavan, A., & Gabrieli, J. D. (2018). Human aging reduces the neurobehavioral influence of motivation on episodic memory. *Neuroimage*, *171*, 296–310. <https://doi.org/10.1016/j.neuroimage.2017.12.053>, PubMed: 29274503
- Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., et al. (1999). Brain development during childhood and adolescence: A longitudinal MRI study. *Nature Neuroscience*, *2*, 861–863. <https://doi.org/10.1038/13158>, PubMed: 10491603
- Gold, B. P., Mas-Herrero, E., Zeighami, Y., Benovoy, M., Dagher, A., & Zatorre, R. J. (2019). Musical reward prediction errors engage the nucleus accumbens and motivate learning. *Proceedings of the National Academy of Sciences, U.S.A.*, *116*, 3310–3315. <https://doi.org/10.1073/pnas.1809855116>, PubMed: 30728301
- Grady, C., Sarraf, S., Saverino, C., & Campbell, K. (2016). Age differences in the functional interactions among the default, frontoparietal control, and dorsal attention networks. *Neurobiology of Aging*, *41*, 159–172. <https://doi.org/10.1016/j.neurobiolaging.2016.02.020>, PubMed: 27103529
- Hafkemeijer, A., Möller, C., Dopper, E. G., Jiskoot, L. C., Schouten, T. M., Van Swieten, J. C., et al. (2015). Resting state functional connectivity differences between behavioral variant frontotemporal dementia and Alzheimer's disease. *Frontiers in Human Neuroscience*, *9*, 474. <https://doi.org/10.3389/fnhum.2015.00474>, PubMed: 26441584
- Hafkemeijer, A., van der Grond, J., & Rombouts, S. A. (2012). Imaging the default mode network in aging and dementia. *Biochimica et Biophysica Acta (BBA)-Molecular Basis of Disease*, *1822*, 431–441. <https://doi.org/10.1016/j.bbadis.2011.07.008>, PubMed: 21807094
- Harrison, L. D., & Loui, P. (2014). Thrills, chills, frissons, and skin orgasms: Toward an integrative model of transcendent psychophysiological moments in music. *Frontiers in Psychology*, *5*, 970. <https://doi.org/10.3389/fpsyg.2014.00790>, PubMed: 25101043
- Howlin, C., Stapleton, A., & Rooney, B. (2022). Tune out pain: Agency and active engagement predict decreases in pain intensity after music listening. *PLoS One*, *17*, e0271329. <https://doi.org/10.1371/journal.pone.0271329>, PubMed: 35921262
- Hwang, J. H., Li, C. W., Wu, C. W., Chen, J. H., & Liu, T. C. (2007). Aging effects on the activation of the auditory cortex during binaural speech listening in white noise: An fMRI study. *Audiology and Neurotology*, *12*, 285–294. <https://doi.org/10.1159/000103209>, PubMed: 17536197
- Janata, P. (2009). The neural architecture of music-evoked autobiographical memories. *Cerebral Cortex*, *19*, 2579–2594. <https://doi.org/10.1093/cercor/bhp008>, PubMed: 19240137
- Kaas, J. H., & Hackett, T. A. (2000). Subdivisions of auditory cortex and processing streams in primates. *Proceedings of the National Academy of Sciences, U.S.A.*, *97*, 11793–11799. <https://doi.org/10.1073/pnas.97.22.11793>, PubMed: 11050211
- Karlsgodt, K. H., John, M., Ikuta, T., Rigoard, P., Peters, B. D., Derosse, P., et al. (2015). The accumbens tract: Diffusion tensor imaging characterization and developmental change from childhood to adulthood. *Human Brain Mapping*, *36*, 4954–4963. <https://doi.org/10.1002/hbm.22989>, PubMed: 26366528
- Kathios, N., Sachs, M. E., Zhang, E., Ou, Y., & Loui, P. (2023). Generating new musical preferences from multi-level mapping of predictions to reward. *bioRxiv*. <https://doi.org/10.1101/2022.06.17.496615>
- Kehoe, E. G., Toomey, J. M., Balsters, J. H., & Bokde, A. L. (2013). Healthy aging is associated with increased neural processing of positive valence but attenuated processing of emotional arousal: An fMRI study. *Neurobiology of Aging*, *34*, 809–821. <https://doi.org/10.1016/j.neurobiolaging.2012.07.006>, PubMed: 22892310
- Kessler, E.-M., & Staudinger, U. M. (2009). Affective experience in adulthood and old age: The role of affective arousal and perceived affect regulation. *Psychology and Aging*, *24*, 349–362. <https://doi.org/10.1037/a0015352>, PubMed: 19485653
- Klostermann, E. C., Braskie, M. N., Landau, S. M., O'Neil, J. P., & Jagust, W. J. (2012). Dopamine and frontostriatal networks in cognitive aging. *Neurobiology of Aging*, *33*, 623.e15–623.e24. <https://doi.org/10.1016/j.neurobiolaging.2011.03.002>, PubMed: 21511369
- Koelsch, S. (2005). Neural substrates of processing syntax and semantics in music. *Current Opinion in Neurobiology*, *15*, 207–212. <https://doi.org/10.1016/j.conb.2005.03.005>, PubMed: 15831404
- Koen, J. D., Srokova, S., & Rugg, M. D. (2020). Age-related neural dedifferentiation and cognition. *Current Opinion in Behavioral Sciences*, *32*, 7–14. <https://doi.org/10.1016/j.cobeha.2020.01.006>, PubMed: 32095492
- Kontos, P. C. (2014). Musical embodiment, selfhood, and dementia. In L. C. Hyden, J. Brockmeier, & H. Lindemann (Eds.), *Beyond loss: Dementia, identity, personhood* (pp. 107–119). New York: Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780199969265.003.0008>

- Kontos, P., & Martin, W. (2013). Embodiment and dementia: Exploring critical narratives of selfhood, surveillance, and dementia care. *Dementia*, *12*, 288–302. <https://doi.org/10.1177/1471301213479787>, PubMed: 24336852
- Kunert, R., Willems, R. M., Casasanto, D., Patel, A. D., & Hagoort, P. (2015). Music and language syntax interact in Broca's area: An fMRI study. *PLoS One*, *10*, e0141069. <https://doi.org/10.1371/journal.pone.0141069>, PubMed: 26536026
- Landau, S. M., Lal, R., O'Neil, J. P., Baker, S., & Jagust, W. J. (2009). Striatal dopamine and working memory. *Cerebral Cortex*, *19*, 445–454. <https://doi.org/10.1093/cercor/bhn095>, PubMed: 18550595
- Laukka, P. (2007). Uses of music and psychological well-being among the elderly. *Journal of Happiness Studies*, *8*, 215–241. <https://doi.org/10.1007/s10902-006-9024-3>
- Lebreton, M., Jorge, S., Michel, V., Thirion, B., & Pessiglione, M. (2009). An automatic valuation system in the human brain: Evidence from functional neuroimaging. *Neuron*, *64*, 431–439. <https://doi.org/10.1016/j.neuron.2009.09.040>, PubMed: 19914190
- Li, S.-C., & Rieckmann, A. (2014). Neuromodulation and aging: Implications of aging neuronal gain control on cognition. *Current Opinion in Neurobiology*, *29*, 148–158. <https://doi.org/10.1016/j.conb.2014.07.009>, PubMed: 25064177
- Lima, C. F., Krishnan, S., & Scott, S. K. (2016). Roles of supplementary motor areas in auditory processing and auditory imagery. *Trends in Neurosciences*, *39*, 527–542. <https://doi.org/10.1016/j.tins.2016.06.003>, PubMed: 27381836
- Loui, P., Alsop, D., & Schlaug, G. (2009). Tone deafness: A new disconnection syndrome? *Journal of Neuroscience*, *29*, 10215–10220. <https://doi.org/10.1523/jneurosci.1701-09.2009>, PubMed: 19692596
- Loui, P., Patterson, S., Sachs, M. E., Leung, Y., Zeng, T., & Przyrinda, E. (2017). White matter correlates of musical anhedonia: Implications for evolution of music. *Frontiers in Psychology*, *8*, 1664. <https://doi.org/10.3389/fpsyg.2017.01664>, PubMed: 28993748
- Loui, P., Zamm, A., & Schlaug, G. (2012). Enhanced functional networks in absolute pitch. *NeuroImage*, *63*, 632–640. <https://doi.org/10.1016/j.neuroimage.2012.07.030>, PubMed: 22836173
- Machielsen, W. C., Rombouts, S. A., Barkhof, F., Scheltens, P., & Witter, M. P. (2000). fMRI of visual encoding: Reproducibility of activation. *Human Brain Mapping*, *9*, 156–164. [https://doi.org/10.1002/\(sici\)1097-0193\(200003\)9:3<156::aid-hbm4>3.0.co;2-q](https://doi.org/10.1002/(sici)1097-0193(200003)9:3<156::aid-hbm4>3.0.co;2-q), PubMed: 10739366
- Malach, R., Levy, I., & Hasson, U. (2002). The topography of high-order human object areas. *Trends in Cognitive Sciences*, *6*, 176–184. [https://doi.org/10.1016/s1364-6613\(02\)01870-3](https://doi.org/10.1016/s1364-6613(02)01870-3), PubMed: 11912041
- Martínez-Molina, N., Mas-Herrero, E., Rodríguez-Fornells, A., Zatorre, R. J., & Marco-Pallarés, J. (2016). Neural correlates of specific musical anhedonia. *Proceedings of the National Academy of Sciences, U.S.A.*, *113*, E7337–E7345. <https://doi.org/10.1073/pnas.1611211113>, PubMed: 27799544
- Martínez-Molina, N., Mas-Herrero, E., Rodríguez-Fornells, A., Zatorre, R. J., & Marco-Pallarés, J. (2019). White matter microstructure reflects individual differences in music reward sensitivity. *Journal of Neuroscience*, *39*, 5018–5027. <https://doi.org/10.1523/JNEUROSCI.2020-18.2019>, PubMed: 31000588
- Mas-Herrero, E., Marco-Pallares, J., Lorenzo-Seva, U., Zatorre, R. J., & Rodríguez-Fornells, A. (2013). Individual differences in music reward experiences. *Music Perception*, *31*, 118–138. <https://doi.org/10.1525/mp.2013.31.2.118>
- Mather, M. (2016). The affective neuroscience of aging. *Annual Review of Psychology*, *67*, 213–238. <https://doi.org/10.1146/annurev-psych-122414-033540>, PubMed: 26436717
- Merrill, J., Sammler, D., Bangert, M., Goldhahn, D., Lohmann, G., Turner, R., et al. (2012). Perception of words and pitch patterns in song and speech. *Frontiers in Psychology*, *3*, 76. <https://doi.org/10.3389/fpsyg.2012.00076>, PubMed: 22457659
- Nagy, K., Greenlee, M. W., & Kovács, G. (2012). The lateral occipital cortex in the face perception network: An effective connectivity study. *Frontiers in Psychology*, *3*, 141. <https://doi.org/10.3389/fpsyg.2012.00141>, PubMed: 22593748
- Nombela, C., Hughes, L. E., Owen, A. M., & Grahn, J. A. (2013). Into the groove: Can rhythm influence Parkinson's disease? *Neuroscience & Biobehavioral Reviews*, *37*, 2564–2570. <https://doi.org/10.1016/j.neubiorev.2013.08.003>, PubMed: 24012774
- North, A. C., Hargreaves, D. J., & Hargreaves, J. J. (2004). Uses of music in everyday life. *Music Perception*, *22*, 41–77. <https://doi.org/10.1525/mp.2004.22.1.41>
- Ono, K., Nakamura, A., Yoshiyama, K., Kinkori, T., Bundo, M., Kato, T., et al. (2011). The effect of musical experience on hemispheric lateralization in musical feature processing. *Neuroscience Letters*, *496*, 141–145. <https://doi.org/10.1016/j.neulet.2011.04.002>, PubMed: 21513771
- Onoda, K., Ishihara, M., & Yamaguchi, S. (2012). Decreased functional connectivity by aging is associated with cognitive decline. *Journal of Cognitive Neuroscience*, *24*, 2186–2198. [https://doi.org/10.1162/jocn\\_a\\_00269](https://doi.org/10.1162/jocn_a_00269), PubMed: 22784277
- Penny, W. D., Friston, K. J., Ashburner, J. T., Kiebel, S. J., & Nichols, T. E. (2011). *Statistical parametric mapping: The analysis of functional brain images*. London: Elsevier.
- Pereira, C. S., Teixeira, J., Figueiredo, P., Xavier, J., Castro, S. L., & Brattico, E. (2011). Music and emotions in the brain: Familiarity matters. *PLoS One*, *6*, e27241. <https://doi.org/10.1371/journal.pone.0027241>, PubMed: 22110619
- Persson, J., Pudas, S., Nilsson, L.-G., & Nyberg, L. (2014). Longitudinal assessment of default-mode brain function in aging. *Neurobiology of Aging*, *35*, 2107–2117. <https://doi.org/10.1016/j.neurobiolaging.2014.03.012>, PubMed: 24767950
- Quinci, M. A., Belden, A., Goutama, V., Gong, D., Hanser, S., Donovan, N. J., et al. (2022). Longitudinal changes in auditory and reward systems following receptive music-based intervention in older adults. *Scientific Reports*, *12*, 11517. <https://doi.org/10.1038/s41598-022-15687-5>, PubMed: 35798784
- Rentfrow, P. J., Goldberg, L. R., & Levitin, D. J. (2011). The structure of musical preferences: A five-factor model. *Journal of Personality and Social Psychology*, *100*, 1139–1157. <https://doi.org/10.1037/a0022406>, PubMed: 21299309
- Ruud, E. (1997). Music and the quality of life. *Nordic Journal of Music Therapy*, *6*, 86–97. <https://doi.org/10.1080/08098139709477902>
- Sachs, M. E., Ellis, R. J., Schlaug, G., & Loui, P. (2016). Brain connectivity reflects human aesthetic responses to music. *Social, Cognitive, and Affective Neuroscience*, *11*, 884–891. <https://doi.org/10.1093/scan/nsw009>, PubMed: 26966157
- Sala-Llonch, R., Bartrés-Faz, D., & Junqué, C. (2015). Reorganization of brain networks in aging: A review of functional connectivity studies. *Frontiers in Psychology*, *6*, 663. <https://doi.org/10.3389/fpsyg.2015.00663>, PubMed: 26052298
- Salimpoor, V. N., Benovoy, M., Larcher, K., Dagher, A., & Zatorre, R. J. (2011). Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. *Nature Neuroscience*, *14*, 257–262. <https://doi.org/10.1038/nn.2726>, PubMed: 21217764
- Salimpoor, V. N., van den Bosch, I., Kovacevic, N., McIntosh, A. R., Dagher, A., & Zatorre, R. J. (2013). Interactions between the nucleus accumbens and auditory cortices predict music reward value. *Science*, *340*, 216–219. <https://doi.org/10.1126/science.1231059>, PubMed: 23580531

- Samanez-Larkin, G. R., Worthy, D. A., Mata, R., McClure, S. M., & Knutson, B. (2014). Adult age differences in frontostriatal representation of prediction error but not reward outcome. *Cognitive, Affective, & Behavioral Neuroscience, 14*, 672–682. <https://doi.org/10.3758/s13415-014-0297-4>, PubMed: 24853269
- Sambataro, F., Murty, V. P., Callicott, J. H., Tan, H.-Y., Das, S., Weinberger, D. R., et al. (2010). Age-related alterations in default mode network: Impact on working memory performance. *Neurobiology of Aging, 31*, 839–852. <https://doi.org/10.1016/j.neurobiolaging.2008.05.022>, PubMed: 18674847
- Scheibe, S., Sheppes, G., & Staudinger, U. M. (2015). Distract or reappraise? Age-related differences in emotion-regulation choice. *Emotion, 15*, 677–681. <https://doi.org/10.1037/a0039246>, PubMed: 25961143
- Schneider, P., Sluming, V., Roberts, N., Scherg, M., Goebel, R., Specht, H. J., et al. (2005). Structural and functional asymmetry of lateral Heschl's gyrus reflects pitch perception preference. *Nature Neuroscience, 8*, 1241–1247. <https://doi.org/10.1038/nn1530>, PubMed: 16116442
- Schouten, T. M., Koini, M., de Vos, F., Seiler, S., van der Grond, J., Lechner, A., et al. (2016). Combining anatomical, diffusion, and resting state functional magnetic resonance imaging for individual classification of mild and moderate Alzheimer's disease. *NeuroImage: Clinical, 11*, 46–51. <https://doi.org/10.1016/j.nicl.2016.01.002>, PubMed: 26909327
- Schultz, W., Dayan, P., & Montague, P. R. (1997). A neural substrate of prediction and reward. *Science, 275*, 1593–1599. <https://doi.org/10.1126/science.275.5306.1593>, PubMed: 9054347
- Sheline, Y. I., Raichle, M. E., Snyder, A. Z., Morris, J. C., Head, D., Wang, S., et al. (2010). Amyloid plaques disrupt resting state default mode network connectivity in cognitively normal elderly. *Biological Psychiatry, 67*, 584–587. <https://doi.org/10.1016/j.biopsych.2009.08.024>, PubMed: 19833321
- Spaniol, J., Bowen, H. J., Wegier, P., & Grady, C. (2015). Neural responses to monetary incentives in younger and older adults. *Brain Research, 1612*, 70–82. <https://doi.org/10.1016/j.brainres.2014.09.063>, PubMed: 25305570
- Sowell, E. R., Thompson, P. M., Tessner, K. D., & Toga, A. W. (2001). Mapping continued brain growth and gray matter density reduction in dorsal frontal cortex: Inverse relationships during postadolescent brain maturation. *Journal of Neuroscience, 21*, 8819–8829. <https://doi.org/10.1523/jneurosci.21-22-08819.2001>, PubMed: 11698594
- Staffaroni, A. M., Brown, J. A., Casaletto, K. B., Elahi, F. M., Deng, J., Neuhaus, J., et al. (2018). The longitudinal trajectory of default mode network connectivity in healthy older adults varies as a function of age and is associated with changes in episodic memory and processing speed. *Journal of Neuroscience, 38*, 2809–2817. <https://doi.org/10.1523/jneurosci.3067-17.2018>, PubMed: 29440553
- Sutcliffe, R., Du, K., & Ruffman, T. (2020). Music making and neuropsychological aging: A review. *Neuroscience and Biobehavioral Reviews, 113*, 479–491. <https://doi.org/10.1016/j.neubiorev.2020.03.026>, PubMed: 32302600
- Szucs, D., & Ioannidis, J. P. (2020). Sample size evolution in neuroimaging research: An evaluation of highly-cited studies (1990–2012) and of latest publications (2017–2018) in high-impact journals. *NeuroImage, 221*, 117164. <https://doi.org/10.1016/j.neuroimage.2020.117164>, PubMed: 32679253
- Takeuchi, H., Taki, Y., Sassa, Y., Hashizume, H., Sekiguchi, A., Fukushima, A., et al. (2010). White matter structures associated with creativity: Evidence from diffusion tensor imaging. *NeuroImage, 51*, 11–18. <https://doi.org/10.1016/j.neuroimage.2010.02.035>, PubMed: 20171286
- Tanaka, S., & Kirino, E. (2016). Functional connectivity of the precuneus in female university students with long-term musical training. *Frontiers in Human Neuroscience, 10*, 328. <https://doi.org/10.3389/fnhum.2016.00328>, PubMed: 27445765
- Tichko, P., Page, N., Kim, J. C., Large, E. W., & Loui, P. (2022). Neural entrainment to musical pulse in naturalistic music is preserved in aging: Implications for music-based interventions. *Brain Sciences, 12*, 1676. <https://doi.org/10.3390/brainsci12121676>, PubMed: 36552136
- Tomasi, D., & Volkow, N. D. (2012). Aging and functional brain networks. *Molecular Psychiatry, 17*, 549–558. <https://doi.org/10.1038/mp.2011.81>, PubMed: 21727896
- Vuust, P., Heggli, O. A., Friston, K. J., & Kringelbach, M. L. (2022). Music in the brain. *Nature Reviews Neuroscience, 23*, 287–305. <https://doi.org/10.1038/s41583-022-00578-5>, PubMed: 35352057
- Wang, D., Belden, A., Hanser, S. B., Geddes, M. R., & Loui, P. (2020). Resting-state connectivity of auditory and reward systems in Alzheimer's disease and mild cognitive impairment. *Frontiers in Human Neuroscience, 14*, 280. <https://doi.org/10.3389/fnhum.2020.00280>, PubMed: 32765244
- Wheeler, B. L. (Ed.). (2015). *Music therapy handbook* (Vol. 1). New York: The Guildford Press. <https://www.guilford.com/companion-site/Music-Therapy-Handbook/9781462529728>
- Whitfield-Gabrieli, S., & Nieto-Castanon, A. (2012). Conn: A functional connectivity toolbox for correlated and anticorrelated brain networks. *Brain Connectivity, 2*, 125–141. <https://doi.org/10.1089/brain.2012.0073>, PubMed: 22642651
- Wimmer, G. E., Li, J. K., Gorgolewski, K. J., & Poldrack, R. A. (2018). Reward learning over weeks versus minutes increases the neural representation of value in the human brain. *Journal of Neuroscience, 38*, 7649–7666. <https://doi.org/10.1523/JNEUROSCI.0075-18.2018>, PubMed: 30061189
- Yee, D. M., Adams, S., Beck, A., & Braver, T. S. (2019). Age-related differences in motivational integration and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience, 19*, 692–714. <https://doi.org/10.3758/s13415-019-00713-3>, PubMed: 30980339
- Yeterian, E. H., & Pandya, D. N. (1998). Corticostriatal connections of the superior temporal region in rhesus monkeys. *Journal of Comparative Neurology, 399*, 384–402. [https://doi.org/10.1002/\(SICI\)1096-9861\(19980928\)399:3<384::AID-CNE7>3.0.CO;2-X](https://doi.org/10.1002/(SICI)1096-9861(19980928)399:3<384::AID-CNE7>3.0.CO;2-X), PubMed: 9733085
- Zatorre, R. J. (2015). Musical pleasure and reward: Mechanisms and dysfunction. *Annals of the New York Academy of Sciences, 1337*, 202–211. <https://doi.org/10.1111/nyas.12677>, PubMed: 25773636
- Zatorre, R. J., & Belin, P. (2001). Spectral and temporal processing in human auditory cortex. *Cerebral Cortex, 11*, 946–953. <https://doi.org/10.1093/cercor/11.10.946>, PubMed: 11549617
- Zatorre, R. J., Evans, A. C., Meyer, E., & Gjedde, A. (1992). Lateralization of phonetic and pitch discrimination in speech processing. *Science, 256*, 846–849. <https://doi.org/10.1126/science.1589767>, PubMed: 1589767
- Zendel, B. R., & Alain, C. (2013). The influence of lifelong musicianship on neurophysiological measures of concurrent sound segregation. *Journal of Cognitive Neuroscience, 25*, 503–516. [https://doi.org/10.1162/jocn\\_a\\_00329](https://doi.org/10.1162/jocn_a_00329), PubMed: 23163409