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Music-Evoked Nostalgia Activates Default Mode and Reward Networks Across the Lifespan

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ABSTRACT

Nostalgia is a mixed emotion that is often evoked by music. Nostalgic music may induce temporary improvements in autobiographical memory in individuals with cognitive decline. However, the neural mechanism underlying music-evoked nostalgia and its associated memory improvements is unclear. With the ultimate goal of understanding how nostalgia-evoking music may help retrieve autobiographical memories in individuals with cognitive impairment, we first sought to understand the neural underpinnings of these processes in healthy younger and older adults. Methodological constraints, including the lack of personally tailored and experimentally controlled stimuli, have impeded our understanding of this mechanism. Here, we utilized an innovative machine-learning-based method to construct three categories of songs, all matched for musical features: (1) personalized nostalgic, (2) familiar non-nostalgic, and (3) unfamiliar non-nostalgic. In 57 participants (29 aged 18–35; 28 aged 60 and older), we investigated the functional neural correlates of music-evoked nostalgia using fMRI. Four main findings emerged: (1) Listening to nostalgic music, more than familiar non-nostalgic or unfamiliar music, was associated with bilateral activity in the default mode network, salience network, reward network, medial temporal lobe, and supplementary motor regions, (2) Psychophysiological interaction (PPI) models indicated that listening to nostalgic music involved increased functional connectivity of self-referential (posteromedial cortex) and affect-related regions (insula), (3) Older adults had stronger BOLD signals than younger adults in nostalgia-related regions during nostalgic listening, (4) While the BOLD response to nostalgic music in younger adults was associated with trait-level factors of nostalgia proneness and cognitive ability, the response in older adults was related to affective responses to the music. Overall, our findings serve as a foundation for understanding the neural basis of music-evoked nostalgia and its potential use in future clinical interventions.

1 | Introduction

Nostalgia, "a wistful or excessively sentimental yearning for a return to or of some past period or irrecoverable condition" (Merriam-Webster 2024). It is a complex, self-relevant, and pancultural emotion (Hanson et al. 2022; Hepper et al. 2024; Saarikallio et al. 2020) associated with fond memories (Hepper et al. 2012, 2024), and serves psychological functions to maintain sense of self, promote social connectedness, and promote emotion regulation (Abeyta et al. 2020; Hepper et al. 2024; Juhl et al. 2010; Sedikides, Wildschut, Gaertner, et al. 2008; Wildschut et al. 2006). Nostalgia's affective profile is comprised primarily of positive (Hepper et al. 2012; Leunissen et al. 2021; Sedikides et al. 2015a; Sedikides et al. 2015b; Wildschut et al. 2006) with

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Summary

- Listening to self-selected nostalgic music, more than musically-matched familiar non-nostalgic or unfamiliar music, was associated with bilateral activity in the default mode network, salience network, reward network, medial temporal lobe, and supplementary motor regions.
- Nostalgic music involved increased functional connectivity of self-referential (posteromedial cortex) and affect-related (insula) regions.
- Older adults had stronger BOLD signals than younger adults in several nostalgia-related regions during nostalgic listening.

peripheral negative components (Hepper et al. 2012; Holak and Havlena 1998; Turner and Stanley 2021), making it an unevenly mixed emotion. Nostalgia is intertwined with autobiographical memory (Wildschut et al. 2006), and associated primarily with self- and socially relevant memories from one's past (Ismail et al. 2022; Madoglou et al. 2017; Wildschut et al. 2006). It can be evoked by visual stimuli (Kikuchi and Noriuchi 2017; Oba et al. 2015), olfactory triggers (Matsunaga et al. 2011; Reid et al. 2015), and music (Barrett et al. 2010; Cheung et al. 2013). When listening to music, nostalgia is a top-reported emotion (Jakubowski and Ghosh 2019), making music an ideal stimulus from which to study this emotion. While a vast literature has documented the psychological underpinnings of nostalgia and, to a lesser degree, music-evoked nostalgia, we lack a basic understanding of how nostalgia is processed in the brain.

1.1 | Music-Evoked Autobiographical Memory and Familiarity in the Brain

While few studies have investigated the neural correlates of music-evoked nostalgia, there is a growing body of adjacent research outlining the neural basis of musical-evoked autobiographical memories (MEAMS; Janata et al. 2007). In a recent theoretical proposal, Ren and Brown (2023) suggest that musical memory is segmented into two broad levels: (1) *musical syntactical structure* memory, comprised of musical syntax and rules related to melody, rhythm, and structure, and (2) *contextual associates memory*, comprised of elements of music that contribute to episodic memory traces, emotion, and reward. While *musical syntactical structure* memory is mainly reliant on the primary auditory cortex and inferior frontal gyrus, *contextual associates memory* is proposed to rely on these regions in addition to areas that support affect and reward (i.e., amygdala, striatum) and autobiographical processing (i.e., hippocampus, default mode network). The default mode network, including the medial prefrontal cortex (MPFC), posteromedial cortex (PMC), angular gyrus, and medial temporal lobe (MTL), is implicated in self-referential processing and autobiographical memory (Buckner et al. 2008; Davey et al. 2016; Qin and Northoff 2011), making it an ideal candidate for the processing of music-evoked autobiographical memories. Indeed, these regions have been reported in numerous investigations of the neural correlates of music-evoked autobiographical memories.

In two meta-analyses of healthy younger adults, familiar music was associated with activity in the superior frontal gyrus (SFG) (Freitas et al. 2018; Vuong et al. 2023), supplementary motor area (SMA)/pre-SMA (Freitas et al. 2018; Vuong et al. 2023), inferior frontal gyrus (IFG) (Vuong et al. 2023) superior temporal gyrus (STG) (Vuong et al. 2023), middle temporal gyrus (MTG) (Vuong et al. 2023), thalamus (Freitas et al. 2018) and precentral gyrus (Vuong et al. 2023). Beyond familiarity, memory for popular songs appears to engage broadly the MPFC (Ford et al. 2011; Janata 2009; Kubit and Janata 2018), ventrolateral prefrontal cortex (Janata 2009) posterior cingulate cortex (PCC) (Ford et al. 2011; Janata 2009), and MTL (Ford et al. 2011). Specifically for music that was rated as familiar, autobiographically salient, and pleasing, Janata (2009) revealed activity in primarily left-lateralized MPFC, ventrolateral prefrontal cortex (VLPFC), and PCC. These areas additionally tracked the time-varying tonal structure of the music played during the scan. In a later investigation, Kubit and Janata (2018) observed that attending to memories evoked by music involves the co-activation of the default mode network (DMN), hippocampus, and sensory and motor regions.

These findings have additionally been observed across the age spectrum in studies investigating familiar, liked, and loved music selected as a proxy for memory-evoking music. In healthy older and younger adults, familiarity with popular songs was associated with increased dorsomedial prefrontal cortex (DMPFC), ventral prefrontal cortex (VMPFC), lateral parietal lobe, and MTL activity (Ford et al. 2016).

Between age groups, familiarity was associated with greater activity in medial limbic regions for younger adults and in lateral parietal, temporal, and superior midline regions in older adults (i.e., anterior cingulate (ACC) and PCC) (Ford et al. 2016). Healthy older adults listening to well-liked familiar music exhibited activation in auditory (STG, MTG) and default mode regions (MPFC, PCC, inferior parietal lobule [IPL]), with self-selected music also activating parahippocampal regions (Quinci et al. 2022). Both younger and older adults showed engagement of MPFC, PCC, precuneus, orbital frontal cortex (OFC), paracingulate, and lateral occipital cortex when listening to *loved* music (Belden et al. 2023). Younger adults showed greater activation during loved music in SFG, parahippocampal gyrus, brainstem, and SMA, whereas older adults showed greater activity in the ventral striatum, brainstem, and cerebellum (Belden et al. 2023). These findings highlight the importance of auditory, default mode, and memory-related regions in the processing of familiar, liked, and loved music across the age spectrum and suggest preliminary evidence for age-related differences in reward and motor regions.

In investigations of functional connectivity during liked and loved music in younger and older adults, individuals across the age spectrum show greater connectivity between auditory and reward regions associated with song liking (Belden et al. 2023) and temporal mesolimbic connectivity involved in self-selected music listening (Faber et al. 2023). Between age groups, younger adults additionally demonstrated stronger functional connectivity within networks (auditory to auditory and reward to reward) and between networks (reward to auditory) during listening than older adults. In contrast, older adults showed more functional connectivity between reward and auditory regions to out-of-network regions (i.e., sensorimotor regions, IFG, occipital). Similarly, Faber et al. (2023) observed that older adults show patterns consistent with age-related dedifferentiation, in which network-level distinctions between music listening conditions (i.e., self-selected vs. experimenter-selected) were less pronounced than those of younger adults. After an 8-week music listening intervention with the same healthy older adult participants, functional connectivity increased between auditory and reward regions (MPFC) and, for most-liked songs, within the default mode network (Quinci et al. 2022).

In sum, while no study has investigated music-evoked autobiographical memory specifically in older adults, findings from investigations of familiarity and preference indicate that familiar, well-liked music engages the auditory cortex, the default mode network (MPFC, PCC, IPL), and reward regions, and coactivates auditory and reward regions across the age spectrum. Older adults additionally demonstrate greater out-of-network functional connectivity compared to younger adults. However, differences between age groups in task-related activation show heterogeneity across studies and require further investigation. In summary, although no study has specifically explored music-evoked autobiographical memory in older adults, findings suggest that familiar and well-liked music activates the auditory cortex, the default mode network, and reward regions across all ages. Older adults show increased out-of-network functional connectivity compared to younger adults. Yet, variations in task-related activation between age groups are inconsistent and warrant further study.

1.2 | Nostalgia in the Brain

While the aforementioned studies provide critical information on the neural regions involved in listening to preferred, familiar, or memory-evoking music, few studies have examined the neural correlates of specifically *nostalgic* music that is both affect-laden and memory-evoking. Yang and colleagues (Yang et al. 2022, 2023) proposed a model of nostalgic processing in the brain, not specific to music, involving overlapping hubs related to autobiographical memory (MPFC, precuneus, VMPFC, hippocampus), emotion regulation (ACC, VMPFC), self (MPFC, VMPFC, PCC, precuneus) and reward (substantia nigra, ventral tegmental area, striatum).

To our knowledge, only five studies have explicitly explored the neural correlates of nostalgia (Barrett and Janata 2016; Matsunaga et al. 2013; Oba et al. 2015; Trost et al. 2012; Zhang et al. 2022). Of these, only two have investigated nostalgia as evoked by music (Barrett and Janata 2016; Trost et al. 2012). Studies using pictures to elicit nostalgia detected activation in memory and reward regions, including the hippocampus, ventral tegmental area (Oba et al. 2015), and ventral striatum (Oba et al. 2015), as well as the supramarginal gyrus (SMG), OFC, and lateral occipital cortex (Zhang et al. 2022). In a small PET study of odor-evoked nostalgia, Matsunaga et al. (2013) observed activity in the precuneus and medial OFC.

Using musical stimuli, Trost et al. (2012) conducted one of the first large-scale investigations of music-evoked emotions, demonstrating that positive, low-arousal emotions such as nostalgia and tenderness were associated with activity in the VMPFC, hippocampus, right striatum, and OFC. However, this study used experimenter-chosen classical music that was not well known to participants, and they observed that nostalgic music did not show activation greater than or different from related emotions (i.e., tenderness, transcendence) (Trost et al. 2012). Barrett and Janata (2016) conducted the first and only investigation focusing on music-evoked nostalgia using familiar music. In their study, 12 young adult participants listened to experimenter-selected music that varied in its ability to elicit nostalgia. The authors reported no voxels associated with nostalgia ratings across individuals. However, regions involved in emotion processing and reward, including the insula and substantia nigra, tracked the tonal structure of nostalgia-evoking music. Additionally, when examining the interaction of nostalgia rating and personality, they observed that participants with lower trait nostalgia and higher trait sadness had increased activity in reward regions during highly nostalgic songs.

1.3 | Limitations in the Present Literature

These studies provide a strong scientific premise for music's ability, both self- and experimenter-selected, to engage neural networks involved in memory, self-referential processing, reward, and sensorimotor activities. However, several questions are left unanswered. First, while several studies investigate music-evoked emotions, musical familiarity, and music-evoked memories, there is still little research on music-evoked *nostalgia* specifically. Given nostalgia's highly affective nature, it is likely that music-evoked nostalgia recruits different or greater neural regions than musical familiarity or music-evoked autobiographical memory alone. For example, Quinci et al. (2022) observed that self-selected, familiar, and well-liked music was most effective at driving activity in auditory and reward areas in healthy older adults, suggesting that using nostalgic music as a stimulus may yield more robust findings. The one study that did investigate this concept specifically (Barrett and Janata 2016), however, found minimal activity for their general nostalgia regressor, which may have been due to their small sample size ($N = 12$) or stimulus selection method.

Relatedly, a second key unanswered question is whether self-selected nostalgic music, as compared to experimenter-selected music, may be accompanied by different or stronger neural activation. Many studies utilize participant-general stimuli, taking songs from the Billboard Top 100 from participants' adolescence (Barrett and Janata 2016; Ford et al. 2016; Janata 2009). However, as online platforms increase accessibility to less popular music and radios become obsolete, nostalgia will likely be evoked by music outside a given year's most popular songs. Additionally, this stimulus selection method ignores the broad and heterogeneous range of human musical experiences that may be influenced by culture, age, personality, and life experiences, fundamentally limiting the scope of research. By 2040, nearly half of older adults in the United States are expected to come from diverse racial/ethnic and socioeconomic backgrounds (Vincent 2010). Therefore, selecting music that aligns with cultural preferences for therapeutic purposes is an important consideration.

A more informative method of capturing the experience of music-induced nostalgia would be through personalized stimuli, where each participant rates musical pieces for their ability to evoke nostalgia. While some studies have utilized participant-selected music (Belden et al. 2023; Quinci et al. 2022; Thaut et al. 2020), pieces are typically chosen based on their enjoyment-producing characteristics, not nostalgia or memory-evoking qualities. Therefore, the observed effects compared to experimenter-selected music may be due to a preferred set of musical features and not to the fact that the music evoked a highly affective memory. For example, behaviorally, Irish et al. (2006) reported reduced anxiety associated with non-memory-evoking music as compared to silence, and El Haj et al. (2012) found that memories recalled after music listening contained more emotionally positive words, suggesting that effects may have been due to a positive mental state induced by pleasurable music. It may be that any pleasant or emotionally potent musical stimulus is enough to elicit vivid memories and that nostalgia-evoking music (i.e., music that is autobiographically salient *and* elicits a state of mixed affect) does not produce additional neural activation.

Another limitation of current research utilizing participant-selected music is the need for systematically chosen non-nostalgic control music to serve as comparison stimuli within each individual. To accurately assess the effects of personalized nostalgia-evoking music, experimenters must present participants with another selection of familiar music that shares the same musical features, such as mode or tempo, as the nostalgia-inducing stimuli, yet does not elicit nostalgia. Several studies have worked to address this by playing musically matched composed music (Fischer et al. 2021; Thaut et al. 2020). These methods may capture, to a degree, some of the variance attributable to musical features but do not control for familiarity.

Finally, no study to our knowledge has examined the neural correlates of music-evoked nostalgia in younger *and* older adults. Behavioral evidence points to the preservation of music-evoked autobiographical memories in older adults with Alzheimer's Disease (AD) (Baird et al. 2018; Cuddy et al. 2015) and the positive impact of personalized music listening for AD psychological symptom relief (Lineweaver et al. 2021; McCreedy et al. 2022). Preliminary neuroimaging evidence suggests that familiar and preferred music may activate many of the same neural regions in patients with Alzheimer's Disease as those observed in healthy younger and older adults and highlights the particular importance of the medial prefrontal cortex in music-evoked autobiographical memories (Belfi, Karlan, et al. 2018). However, these studies are limited by many of the same factors present in healthy adult literature. Thus, understanding the mechanism underlying music-evoked nostalgia across the lifespan is the first step toward understanding these mechanisms in older adults with AD. Given AD's clinical and neural diversity, it is reasonable to first examine these processes in healthy adults.

1.4 | Present Study

In the present study, we addressed the limitations in the literature by (1) Assessing the neural mechanisms underlying the experience of music-evoked nostalgia, (2) Allowing participants to *self-select* all of their nostalgic pieces of music, (3) Including nostalgic, non-nostalgic familiar, and non-nostalgic unfamiliar music to examine whether nostalgia-evoking music is distinguished from familiar music in the brain, (4) Tailoring non-nostalgic stimuli for each individual using a machine-learning algorithm, such that control stimuli are manipulated for familiarity and matched based on musical and acoustic features (Hennessy et al. 2024), and (5) Including both healthy younger and older adults to examine how the neural correlates of music-evoked nostalgia may or may not differ across the lifespan. Given the impact of individual differences demonstrated in Barrett and Janata (2016), we also included several trait-level measures that may influence activation associated with music-evoked nostalgia (i.e., trait nostalgia).

With these methods, we aimed to assess the neural basis of how music evokes nostalgia across the lifespan and how the neural signature of nostalgic music is different from that of musically matched familiar and unfamiliar music. Secondarily, we assessed how individual differences, such as cognitive ability, trait nostalgia, and tendency to feel positive or negative during nostalgic listening, impacted the neural activation associated with nostalgia. We hypothesized that (1) BOLD activity, as measured with fMRI, in the DMN, MTL, and reward networks would be greater when listening to self-selected nostalgia-evoking music compared to familiar non-nostalgic music and unfamiliar music, (2) Functional connectivity between DMN, auditory cortices, and reward would be greater when listening to self-selected nostalgia-evoking versus familiar non-nostalgic control music, and (3) Older and younger adults would demonstrate similar patterns of neural activity. We expected that age-related differences might emerge but considered the description of any such differences (i.e., what neural regions would show differences) as exploratory, given the mixed findings in previous work. Hypotheses related to individual differences were exploratory. However, we predicted that cognitive ability would not influence neural activation during nostalgic listening and that individuals higher in trait nostalgia would experience less activation in hypothesized regions during nostalgic listening, as observed in Barrett and Janata (2016).

2 | Materials and Methods

All procedures were approved by the Institutional Review Board of the University of Southern California (IRBUP: UP-22-00569). This study and its hypotheses were not pre-registered. All materials, including musical stimuli, datasheets, and analysis code, are available online on our OSF page: https://osf.io/jw4bz/. All z-maps referenced in Results are available at Neurovault at https://neurovault.org/collections/FEHSKFWF/.

2.1 | Participants

We recruited 60 right-handed English-speaking participants from the Los Angeles area, consisting of 30 young adults (ages 18–35) and 30 older adults (ages 60+). Inclusion criteria were as follows: (1) fluent in English, as determined by self-report and the ability to complete the pre-screening questionnaire without difficulty; (2) had no contraindication to participate in an MRI study (i.e., no irremovable metal implants, pacemakers, etc.); (3) right-handed, to reduce fMRI data variability due to differences in handedness or lateralization of brain function; (4) not currently experiencing psychiatric symptoms by self-report; (5) no history of neurologic disorders; and (6) a score of 26 or above on the Montreal Cognitive Assessment (MoCA; Nasreddine et al. 2005) to ensure that participants did not have evidence of Mild Cognitive Impairment.

Participants were recruited from online research platforms, Facebook advertisements, and the USC Undergraduate Subject Pool from November 2022 to March 2023. In total, 258 participants were screened for eligibility. After applying exclusion criteria (see Supplemental Methods), 60 participants were deemed eligible to participate in the study and underwent MRI scanning. Three participants were excluded from the final analysis: one due to incidental findings unrelated to the study protocol and two due to incomplete data, resulting in a final sample size of 29 younger adults and 28 older adults. See Table S1 for demographic characteristics.

2.1.1 | Power Analysis

A sample size of 60 was chosen based on a power analysis using existing fMRI literature (Barbara Jennings and Vance 2002; Belfi, Kasdan et al. 2018; Kaufman et al. 2007; Younes et al. 2019). Region-of-interest analyses of contrasts similar to those in the current project yielded effect sizes ranging from 0.78 to 2.4. To capture a minimum effect size of $d = 0.78$, at an alpha level of 0.05, with a power of 0.80 to detect a difference in percent signal change, ~25 participants per group were needed. We included an additional five participants per group to account for a ~20% dropout or missing/incomplete data.

2.2 | Procedure

General procedures for this study involved an online screening, a one-hour online Zoom screening, an online stimulus selection survey, a 2-h visit comprised of an fMRI scan and follow-up autobiographical memory task, and a 20-min follow-up Zoom visit comprised of an autobiographical memory task and song appraisals. After completing the study, participants were thanked for their time and compensated USD 60. Each portion of the procedure, including the materials used, is described below.

2.2.1 | Screening

Participants completed screening Informed Consent and then were screened for eligibility using REDCap (Harris et al. 2009, 2019). REDCap (Research Electronic Data Capture) is a secure, web-based software platform designed to support data capture for research studies, providing (1) an intuitive interface for validated data capture; (2) audit trails for tracking data manipulation and export procedures; (3) automated export procedures for seamless data downloads to common statistical packages; and (4) procedures for data integration and interoperability with external sources. In the screening survey, participants were asked to report their age, gender, history of neurologic, psychiatric, and vascular disorders, history of traumatic brain injury, English fluency, handedness, and primary contact information. If initially eligible, participants were contacted to complete an MRI safety screening form, which included questions related to MRI contraindications (i.e., metal implants, presence of pacemaker).

If no MRI contraindications were noted, participants were invited to participate in a one-hour screening visit via Zoom (Zoom.us). Informed Consent was obtained through a secure electronic form during the Zoom meeting. Participants then completed the Montreal Cognitive Assessment (MoCA; Nasreddine et al. 2005) online with a MoCA-certified experimenter to assess the presence of Mild Cognitive Impairment. This task includes measures of memory, language, attention, visuospatial skills, mental calculation, and orientation. The full version of MoCA was used, with amendments made for several components due to the videoconferencing platform. Specifically, during the Alternating Trail Making task, we amended the task by asking participants to use their mouse or finger to draw on a shared screen using Zoom's "Annotate" function. Secondly, during the Cube and Clock drawing tasks, participants were asked to complete their drawings on a piece of physical paper and then to hold their drawings to the camera so that the researcher could take a screenshot of the drawing. Third, during the Attention task, in which the experimenter read a list of letters and asked the participant to clap on the letter "A," participants were asked to hold their hands to the camera to be visible as they clapped. Due to the approximate one-second delay of the Zoom call, experimenters were trained to watch and listen for the participant's hand clap during the letter directly following the letter "A," corresponding to one second after the prompt. We chose to use these methods on the full version of the MoCA rather than using the telephone version (T-MoCA) to enable the completion of all portions of the cognitive assessment (T-MoCA excludes all drawing sections). These methods were piloted in a small group of older adults for feasibility and were found to be easy to complete for this age cohort. If a participant scored below 26/30, they were notified that they were ineligible for the remainder of the study. They were encouraged to seek additional testing and referred to resources at USC (adrc.usc.edu) and the Alzheimer's Association (alz.org). Participants who were ineligible at this stage received $20 for their participation in the Zoom visit. If participants scored 26 or higher on the MoCA, they were notified that they were eligible for the remainder of the study. They were then asked to complete an online stimulus selection survey via Qualtrics (Qualtrics 2022).

2.2.2 | Online Music Personalization Survey

Eligible participants were asked to complete an online stimulus selection survey via Qualtrics (Qualtrics 2022). This survey aimed to identify six songs selected by the participant that were known to evoke nostalgia and to identify non-nostalgic "Familiar Control" and "Unfamiliar Control" songs. Familiar Control songs were intended to be musically matched, familiar, non-nostalgic, and Unfamiliar Control songs were intended to be musically matched, unfamiliar songs. This was accomplished by using a control song selection tool (described below) embedded via Javascript into the backend of the Qualtrics survey to allow interactivity.

This survey took ~40 min to complete. Participants were instructed to complete the survey in a quiet space with headphones or speakers. Audio quality was tested at the beginning of the survey. During the survey, they were asked to do the following:

1. List six nostalgia-inducing songs.
2. Listen to each of the self-reported Nostalgia songs and up to 10 candidate Control songs as identified by the control song selection model (see below) for 30 s.
3. Appraise songs based on familiarity, valence, and arousal for each song and a free-response prompt regarding why such songs are nostalgic.
4. Complete psychological and personality measures.
5. Report demographic information (i.e., music training).

Participants were given definitions of nostalgia (“sentimental longing for the past”) and of a nostalgia-evoking song (“a song that brings you back to a pleasant moment or era of your life and evokes a strong memory”). Then, they were asked to complete a comprehension check, in which they were asked to choose the definition of “nostalgia” and of a “nostalgia-evoking song,” “as this study defines it,” from a list of five options. The survey would not let participants continue until they had chosen the correct response. The options for both prompts are listed in the Supplemental Methods. Then, participants were asked to enter six nostalgia-inducing songs into a form that fed into our control song selection model (see below). Setting these six songs as seeds, we then used Spotify's API to find recommendations for songs released within 5 years of each seed song, with valence and energy ratings within 0.15 points (out of 1) of the seed song and popularity of at least 80. If Spotify could not generate recommendations for an input song, a respondent was prompted to enter another nostalgic song.

After inputting three nostalgia-inducing songs, participants were then presented a 30-s clip from a maximum of 66 songs in random order: the six songs that they input as nostalgic and up to 10 songs that were recommendations for each nostalgic song presented in a set, which we will call “candidate Control songs.” Specifications for the model used to generate these candidates are reported below (Control Song Selection Model). The 30-s clip was chosen by Spotify's automatic preview by a privileged music segmentation algorithm. After each song, participants rated their familiarity with the song (“Not at all familiar,” “Somewhat familiar,” “Very familiar”). If songs were rated as “Somewhat familiar” or “Very familiar,” participants rated how nostalgic the song made them feel on a scale from 1 (“Not nostalgic at all”) to 9 (“Extremely nostalgic”). If a subject labeled a candidate Control song as sufficiently familiar (“Somewhat” or “Very”) and sufficiently not nostalgic (< 5 on the nostalgia rating scale), the song would be selected for the experimental paradigm, and the other candidate Control songs from the set would not be presented to that subject. If a song was either too nostalgic or unfamiliar, participants would continue to listen to the next Control song candidate (see Figure S1). Unfamiliar Control songs were selected for each seed song from the list of songs participants had indicated as “Not at all familiar.” If a suitable Familiar Control or Unfamiliar Control song was not found for one or more of the Nostalgic songs after 10 tries, participants were presented with additional Control Song candidates at the beginning of their in-person visit, before the fMRI scan until all Familiar Control and Unfamiliar Control songs were identified.

More than 10 candidate Control songs were required for 1–2 songs in 25 participants, 3–4 songs in 20 participants, and 5–6 songs in 1 participant. For 11 participants, 1–2 Nostalgic songs could not be matched to appropriate Familiar Control or Unfamiliar Control songs, even after presenting additional candidates, due to unfamiliarity with or feeling too nostalgic in response to candidates. In these cases, the unmatched stimulus set was dropped from the analysis for that participant, such that the participant had a fewer Nostalgic, Familiar Control, and Unfamiliar Control songs in the final analysis. By the end of the control song selection process, participants with complete sets had six Nostalgic songs, six non-nostalgic Familiar Control songs, and six Unfamiliar Control songs.

Control song selection model. To identify control songs that were musically matched to participant-selected Nostalgia songs, we developed a music-matching tool using Spotify's web API (Lamere n.d.). Spotify's API is a free tool for Music Information Retrieval (MIR) that indexes any song from Spotify's library for various musical features, including key, tempo, loudness, danceability, valence, energy, popularity, mode, acousticness, liveness, and instrumentalness. The control song selection tool took in a user-inputted nostalgia-evoking song and recommended a set of “candidate Control songs,” all of which were matched based on the similarity of three key Spotify API features: valence, energy, and release date. Valence, defined as a musical piece's positiveness, was measured on a scale from 0.0 to 1.0, where 1 is highly positive. This measure's origin is privileged information from Spotify (originally developed by EchoNest), but likely relies on a combination of musical and acoustic features (e.g., tempo, key). For example, previous music information retrieval (MIR) work has shown that valence is influenced by features including, but not limited to, acoustic brightness (Lartillot et al. 2008), melodic contour (Schubert 2004), mode (Eerola 2011), and pulse clarity (Eerola 2011). Energy, defined as a song's intensity or activity, was measured from 0.0 to 1.0 and aligns with the psychological concept of arousal. Arousal, in previous work, has been found to be related to loudness (Schubert 2004), tempo (Schubert 2004), spectral flux (Lartillot et al. 2008), acoustic brightness (Lartillot et al. 2008), pulse clarity (Eerola 2011), and inharmonicity (Eerola 2011). These lower-level features that make up the overall expressed valence and energy profile of a song may influence a listeners felt experience (Evans and Schubert 2008). While nostalgic songs across a given sample likely vary in terms of their valence and arousal dimensions, we controlled for these factors *between* Nostalgia and Control songs to isolate the felt experience of nostalgia.

The release date was additionally manipulated to ensure that Nostalgia and Control song pairs would evoke familiarity from the same period of a participant's life and to Control for era-dependent musical style variations. We set a minimum threshold for popularity, a Spotify metric ranging from 0 to 100, to enhance the likelihood that a song would be rated as “familiar” to a given participant. Our previous work indicated that manipulating these key features was sufficient to provide songs that were matched for all other available Spotify API features (Greer et al. under review; Hennessy et al. 2024).

We used Spotify's *Recommendations* call to compile a list of four candidate Control songs for every Nostalgia song, in which the minimum popularity was 0.80, the valence and energy were matched to the Nostalgia song within 0.15 points, and the release date was within 5 years of that of the Nostalgia song. The script for this music matching tool is available at https://github.com/hennessysarah/SoundsLikeThis-Qualtrics-backend and a personalizable web-based version, *SoundsLikeThis* (soundslikethis.us), is available freely for public research and entertainment use.

Subjective appraisals of valence and arousal. While each song pair was controlled for Spotify-derived measures of valence and arousal, we expected subjective listening experiences to differ among participants. Thus, we additionally measured participants' feelings during listening. After each nostalgia and control song, participants rated the musical clip for felt valence using a two-part Likert question ("Rate how positive the emotion was that you FELT while listening to the song" and "Rate how negative the emotion was that you FELT while listening to the song") and arousal using a two-part Likert question ("How activated was the emotion that you FELT while listening to the song. An example of a highly activated emotion is excitement or fear" and "How deactivated was the emotion that you FELT while listening to the song. An example of a highly deactivated emotion is sadness or calm"). "Activation" was used to describe arousal to capture embodied feeling states; this language has been successfully used in other investigations involving self-reporting of emotional arousal (e.g., Presti et al. 2022). Both sets of questions were on a scale of 0 to 10. To reduce exposure to Unfamiliar Control songs before the scan, the same set of valence and arousal questions were probed after listening for each Unfamiliar Control song after the conclusion of the scan during their follow-up Zoom visit.

Trait-level measures. At the end of the online stimulus selection survey, participants were asked to complete the seven-item version of the Southampton Nostalgia Scale (SNS; Sedikides et al. 2015a), to assess trait-level nostalgia (Barrett et al. 2010; Routledge et al. 2008). In this task, participants rated, on a seven-point scale ranging from 1 ("Not at all") to 7 ("Very much"), their experience of nostalgia in daily life. Items include questions related to nostalgia's importance ("How significant is it for you to feel nostalgia?") and proneness ("How often do you feel nostalgia?"). Scores across all items are averaged (with one backward-scored item) to create one Trait Nostalgia score for each participant.

Participants additionally completed the Music Training Questions from the Goldsmith Music Sophistication Index (Müllensiefen et al. 2014). These scores were summed to create a "music training" aggregate score, and individual elements were kept in their raw form for descriptive purposes (i.e., "Do you play an instrument?"), and are reported in Table S1.

2.2.3 | fMRI Task

After completing the music personalization survey, participants were invited for an in-person visit to the University of Southern California's Dana and David Dornsife Neuroimaging Center to complete their fMRI scan. The fMRI task was a music-listening task presented using MATLAB version 9.13.0 (The MathWorks Inc. 2022) to play music from each participant's personalized stimulus folder. A single-song block design was used (see Figure 1), consisting of Nostalgia, Familiar Control, and Unfamiliar Control blocks. The order of these blocks was counterbalanced across participants. Participants completed two functional runs containing nine blocks each, with one song played per block. The start of each run contained a 5-s buffer. Each run contained three Nostalgia, three Familiar Control, and three Unfamiliar Control songs, with feature-matched triplets present within each run (i.e., Nostalgia Song 1, Familiar Control Song 1, Unfamiliar Control Song 1), for a total of 18 songs across runs. Participants listened to the first 40 s of a nostalgia-evoking, Familiar Control, or Unfamiliar Control song during each block, as determined by the stimulus selection procedure. Between each block, there was a 15-s rest period. Participants were told to keep their eyes closed and remain still in the scanner for the entirety of each run to help participants focus on imagery, memories, or feelings evoked by the music. Participants were asked between each run if they had remained awake for the entirety of the run. This happened for one participant during the beginning of one run. The run was stopped early and repeated. Music was played through fMRI-safe active noise-canceling headphones that actively attenuated the noise of the functional scan sequence (OptoAcoustics OptoActive) to allow participants to hear the music over the sound of the scanner. Volume was set for each participant so that it was audible above the scanner yet not too loud to be uncomfortable. This was set using a segment of a standard test song prior to the start of the experimental runs, while asking participants to provide feedback on volume comfortability. Volume was kept consistent across all stimuli within each participant.

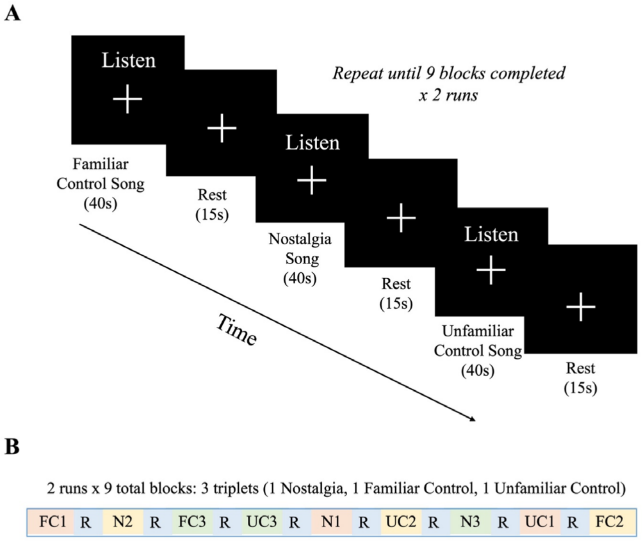

FIGURE 1 | fMRI task design (A) and example shuffling of song triplets within one run (B). In panel B, FC = Familiar Control song block, UC = Unfamiliar Control song block, N = Nostalgia song block, R = rest period. Numbers indicate placement within triplet (i.e., FC1 is the Familiar Control song that is musically matched to Nostalgia song 1 (N1) and Unfamiliar Control song 1 (UC1)).

2.2.4 | Autobiographical Memory Task

After the fMRI scan, participants were asked to complete an autobiographical memory task modeled after Belfi et al. (2016) and Levine et al. (2002). A randomly selected pair of one Nostalgia song and its matched Familiar Control song was used as a free-recall autobiographical memory task. Participants listened to the first 40 s of either the Nostalgia or Familiar Control song, with order counterbalanced across participants. After the song, participants were asked to "verbally describe, in detail, a memory of your past." After an initial response, participants were prompted to think of more details to add to their description ("Do you have any additional details you'd like to provide?"). Participants were given a maximum of 5 min for the initial response and 20 min for the follow-up response. After the follow-up, participants were asked if the memory was related to the song that had been played. The audio responses were recorded. One week after the scan, participants were invited to a follow-up Zoom visit, during which they repeated the task for the other song in the pair. Results involving this memory recall task will be reported in a future manuscript.

2.3 | Neuroimaging Parameters

A 3T Siemens MAGNETOM Prisma System with a 32-channel head coil, located at the Dana and David Dornsife Neuroimaging Institute at the University of Southern California, was used for this study. We obtained high-resolution T1-weighted structural MRI images (1 mm × 1 mm × 1 mm resolution, over a 256 mm × 256 mm × 256 mm FOV, TR = 2300 ms, TE = 2.05 ms; flip angle = 8°) using a 3D magnetization-prepared rapid acquisition gradient (MPRAGE) sequence. Diffusion-weighted images were also obtained during the scan session and will be reported in a future manuscript.

Functional images were obtained using a gradient-echo, echo-planar T2*-weighted multiband pulse sequence with a multiband factor of M = 8 (TR = 1000 ms, TE = 35 ms, flip angle = 52°, 68 × 68 mm in-plane resolution). 48 slices were obtained with 3 mm × 3 mm voxel resolution, with no interslice gap, acquired parallel to the anterior commissure –posterior commissure line. For the nostalgic music listening task, 512 functional volumes were obtained. The gradient-echo field map was obtained to correct for field inhomogeneity in analysis (TR = 1000 ms, TE1 = 5.19 ms, TE2 = 7.65 ms, flip angle = 60°, 68 × 68 mm in-plane resolution).

2.4 | Data Analysis

2.4.1 | Music Stimuli Analysis

To assess whether our stimulus selection was successful in identifying musically matched non-nostalgic control songs for each participant's nostalgic songs, we compared music stimuli across conditions along the following Spotify-derived features: acousticness, key, mode, danceability, energy, instrumentalness, liveness, loudness, popularity, release year, speechiness, tempo, and valence. Due to the clustered structure of the data, in which each participant had six songs for each condition, multi-level models were used using R version 4.3.2 (R Core Team 2023) with R Studio and the *lme4* (Bates et al. 2015) package. A separate model was fitted for each continuous feature (all, excluding key and mode), with Condition predicting the feature, including random intercept for participant. If an effect of Condition was observed, effects were further probed using Tukey's Honestly Significant Difference with *emmeans* (Lenth 2023). Effect sizes for fixed effects were calculated as Cohen's f^2 (Cohen 1992) with the *MuMin* package (Bartoń 2023). Bonferroni-comparison was used for Spotify feature analyses (number of comparisons = 11). Musical key and mode were assessed with a chi-squared test of association, to determine whether musical key or mode categories differed by condition. Lastly, to estimate approximately when during a participant's life they may have listened to their self-reported nostalgic songs, song-specific age (SSA) was calculated by subtracting a participant's birth year from a song's release year. These results were plotted as descriptive statistics only, as the release date was already included in the above models.

2.4.2 | Behavioral Analysis

To assess differences in the subjective feeling while listening, ratings of nostalgia were assessed between Nostalgia and Familiar Control conditions and age groups using multi-level models, with a random slope of condition on the participant. Participant-rated felt positive valence, negative valence, high arousal, and low arousal were assessed in separate models, again with condition (Nostalgia, Familiar Control, Unfamiliar Control) and age group as fixed effects and a random slope of condition on the participant. Significant effects were further assessed with Tukey's HSD, and Cohen's f^2 was calculated. Bonferroni comparison was used (number of comparisons = 5).

To assess differences between age groups in trait-level measures, scores from the MoCA and SNS were compared between age groups using a one-way analysis of variance using the *lm* and *anova* functions from the base package of R (R Core Team 2021). Cohen's f^2 was calculated. Across analyses, *ggplot* (Wickham 2016) was used for plotting and visualizations.

2.4.3 | fMRI Preprocessing

Pre-processing and analyses of functional images were performed using FSL version 6.0 (Jenkinson et al. 2012). Skull stripping was performed using FSL's BET brain extraction tool. The gradient-echo field map was used to correct inhomogeneity in the magnetic field using FSL's FUGUE unwarping tool (anterior–posterior, 10% signal loss threshold). Motion correction was performed using FSL's MCFLIRT, and additional motion scrubbing was conducted for each functional run using root-mean-squares intensity differences (dvars) to identify slices that should be regressed out during analyses (Power et al. 2012). Specifically, slices with dvars values outside of the 75th percentile and 1.5*interquartile range were regressed out of the GLM analyses in a confound matrix. Slice timing correction was performed with Fourier-space time series phase shifting and spatial smoothing was performed (5.0 mm FWHM Gaussian kernel). High-pass temporal filtering with a Gaussian weighted least-squares line (sigma = 100 s) was performed. Functional images were initially registered to their T1 image using FSL's FLIRT and then further nonlinearly registered to standard space (MNI 152 space) with a 12° of freedom affine transformation using FSL's FNIRT. Motion artifacts were then further removed using ICA-AROMA (Pruim et al. 2015).

2.4.4 | Whole Brain

To assess what regions were active during nostalgic listening versus Familiar Control and Unfamiliar Control listening, we performed a whole-brain general linear model (GLM) analysis. After pre-processing, the music task was modeled with a regressor for each music condition (Nostalgia, Familiar Control, Unfamiliar Control), using a boxcar convolved with a double-gamma hemodynamic response function. BOLD signal between conditions was contrasted using a GLM. A fixed effects analysis was then used to combine the two functional runs of the music task for each participant. Participant-level models were combined into a mixed-effects analysis using FSL's FLAME 1 to assess group-level contrasts of each condition. Independent sample t-tests were used to determine differences in brain activation between age groups in each contrast, as well as activation differences across groups between conditions (Nostalgia > Familiar Control, Nostalgia > Unfamiliar Control). We thresholded Z statistical images using FSL's cluster thresholding (which aims to control Family-wise error rate), with a cutoff of $Z > 3.1$, and a corrected cluster-size probability of $p = 0.05$. For contrasts that included double subtractions (i.e., Nostalgia > Familiar Control, Older > Younger), the directionality of the effect was investigated using FSL's Featquery by extracting beta values for each main effect at the group level. Whole brain results were visualized with MRIcroGL (https://www.mccauslandcenter.sc.edu/mricrogl/) and on a 3D surface using FreeSurfer's FreeView.

2.4.5 | Region of Interest

To further test our hypotheses regarding regions that would be more active during nostalgic listening vs. non-nostalgic listening, we conducted a region-of-interest (ROI) analysis. We obtained percent signal change values in regions selected a priori due to their known involvement in reward, autobiographical memory, and self-referential processing (medial prefrontal cortex, posteromedial cortex, medial temporal lobe, and ventral tegmental area). We created 8-voxel diameter spheres with center coordinates located at peak clusters observed in published meta-analyses on autobiographical memory (Kim 2012), reward (Diekhof et al. 2012), and auditory processing (Chan and Han 2022) (see Table S2). Due to overlapping spheres on cortical midline structures (VTA, MPFC, PMC), adjusted center coordinates were used such that the absolute value of the x coordinate had a minimum absolute value of 8. Percent signal change was calculated from beta values using FSL's Featquery at each subject's second-level contrasts (one contrast across two runs for each participant). A repeated measures ANOVA was conducted for each ROI using *anova_test* from *rstatix* (Kassambara 2023), with condition (Nostalgia, Familiar Control, or Unfamiliar Control) and hemisphere (Left or Right) as within-subjects factors and age group (younger or older) as the between-subjects factor, with an alpha level of 0.05. For significant main and interaction effects, pairwise comparisons were computed using Tukey's HSD. Effect sizes were computed using Cohen's f^2.

2.4.6 | Individual Differences

To investigate our exploratory hypotheses related to the role of individual differences in the neural response to Nostalgia and Familiar Control music, we added regressors of interest at the group level in three separate models: (1) Cognitive Ability (as measured by MoCA; Nasreddine et al. 2005), (2) Trait Nostalgia (as measured by SNS; Sedikides et al. 2015a; Sedikides et al. 2015b), and (3) Nostalgia Valence (felt positive and negative valence averaged within the Nostalgia condition). Each set of regressors was applied to the Nostalgia > Familiar Control and Nostalgia > Rest contrasts. The Cognitive Ability and Trait Nostalgia models were also assessed in the Familiar Control > Rest contrast. For all models, behavioral ratings were mean-centered across participants. Regions of activation in each contrast predicted by the regressor of interest were assessed across and between age groups. For contrasts that included double subtractions (i.e., Nostalgia > Familiar Control, Older > Younger), the directionality of the effect was investigated using FSL's Featquery by extracting beta values for each participant at the second level (averaged across runs) and regressed behavioral ratings. Whole brain results were visualized with MRIcroGL and on a 3D surface using FreeSurfer's FreeView. For the Cognitive Ability model, mean-centered age was included as a regressor of non-interest. For Valence, positive valence was assessed while controlling for negative valence (as a regressor of non-interest) and vice versa. Averaged positive or negative valence across all nostalgic songs comprised the valence score for each participant for the Nostalgia > Rest contrast and the Nostalgia > Familiar Control contrast. These measures were intended to capture the typical response pattern of an individual listening to a nostalgic piece of music and do not reflect song-level changes in felt or expressed valence. Due to the focus on typical nostalgic listening, the Familiar Control > Rest contrast was excluded from the valence analysis.

2.4.7 | Functional Connectivity

To test our hypotheses regarding networks of interacting regions that would support the experience of music-evoked nostalgia, we conducted a functional connectivity analysis. We constructed psychophysiological interaction (PPI) models to test for differences in whole brain and seed connectivity between the Nostalgia > Familiar Control contrast across and between age groups. Seeds were chosen for their known involvement in auditory (Heschl's Gyrus; HG) and self-related (PMC) processing. Seeds were 8-mm voxel spheres with center coordinates at peak clusters observed in meta-analyses (see Table S2). At the subject level, after pre-processing (described above), we extracted the time series of each run's cerebrospinal fluid (CSF) and white matter using FSL's FMRIB's Automated Segmentation Tool (FAST; Zhang et al. 2001), and the time series of the masked seed region of interest. De-noised data was then input into a lower-level PPI GLM. In this model, we included (1) one regressor reflecting task condition (psychological variable), (2) one regressor representing the timeseries for the region of interest (physiological variable), and (3) one regressor representing the interaction between the condition and region of interest (PPI). Timeseries of CSF and white matter were included as regressors of non-interest for each run, and then runs were combined for each participant in a higher-level analysis. Subject-specific motion parameters were included as nuisance regressors. Then, at the group level, we combined data across participants, using a cluster threshold of $Z > 3.1$, with a corrected cluster significance threshold of $p = 0.05$ (Worsley 2001). Results were visualized with MRIcroGL.

3 | Results

3.1 | Music Stimuli Features

The complete list of musical stimuli used in this study and their Spotify URLs are uploaded on OSF. Word clouds of musical artists of participants' self-selected nostalgic songs are displayed in Figure S2. Nostalgia song-specific age was younger for younger adults (median = 12.23 years, IQR = 11.5 years) than for older adults (median = 18.73, IQR = 16) (see Figure 2). SSA did not differ across music conditions ($ps > 0.05$).

Means and standard deviations of computer-derived Spotify-MIR features are reported in Table S3. Spotify MIR features of valence, energy, release year, danceability, loudness, speechiness, tempo, instrumentalness, acousticness, and liveness did not differ between conditions (Figure 2). There was a main effect of song condition on popularity (Nostalgia $\beta = 18.00$, $t(913.78) = 11.48$, $p_{adjusted} < 0.001$, $f^2 = 0.12$), where Nostalgia songs had greater popularity than Familiar Control and Unfamiliar Control songs, and Familiar Control songs had greater popularity than Unfamiliar Control songs (Figure 2). Multilevel model results for Spotify MIR features are reported in Table S6.

3.2 | Behavioral Results

3.2.1 | Subjective Song Ratings

Means and standard deviations of ratings of felt nostalgia, valence, and arousal are presented in Table S4 and Figure 3. The intra-class correlation coefficient (ICC) for nostalgia rating was ~0, indicating that nearly none of the variance for nostalgia ratings was at the individual participant level before including additional variables into the model. Nostalgic songs were rated as significantly more nostalgic than Familiar Control songs ($\beta = 5.75$, $t(553.78) = 36.514$, $p_{adjusted} < 0.001$, $f^2 = 7.71$) (see Table S5 for full multi-level model results). No differences between age groups were observed.

For felt valence and arousal, ICCs indicated that 13%, 20%, 20%, and 17% of the variance for positivity, negativity, high arousal, and low arousal, respectively, were at the individual participant level before including additional variables into the model. Nostalgia songs were rated as significantly more positively valenced than Unfamiliar Control songs ($\beta = 4.61$, $t(52.46) = 13.87$, $p_{adjusted} < 0.001$, $f^2 = 0.79$) and Familiar Control songs ($p_{adjusted} < 0.001$). Older adults had higher positivity ratings across conditions than younger adults ($\beta = 1.32$, $t(55.27) = 2.73$, $p_{adjusted} < 0.05$, $f^2 = -0.79$). Familiar Control songs were rated as significantly less negative than Unfamiliar Control songs ($\beta = -0.68$, $t(52.62) = -3.00$, $p_{adjusted} < 0.05$, $f^2 = 0.02$). Nostalgia songs were rated as higher in arousal than Unfamiliar Control songs ($\beta = 3.14$, $t(55.10) = 8.75$, $p_{adjusted} < 0.001$, $f^2 = 0.41$), and Familiar Control songs ($p_{adjusted} < 0.001$). An interaction between age group and condition was additionally observed ($\beta = -1.16$, $t(51.46) = -2.82$, $p_{adjusted} < 0.05$, $f^2 = -0.81$), such that Unfamiliar Control songs were rated as higher arousal than Familiar Control songs in the older adult group only. No additional condition, age group, or interaction effects were observed for felt valence or arousal.

3.2.2 | Cognitive Ability

Cognitive ability, as measured with MoCA, did not differ between older (M = 27.68, SD = 1.36) and younger (M = 28.14, SD = 1.38) adults ($p > 0.05$) (Table S1; Figure S3).

3.3 | Trait Nostalgia

Trait Nostalgia, as measured with SNS, did not significantly differ between age groups ($p = 0.051$), but older adults trended toward lower scores than younger adults (Figure S3).

3.4 | Whole Brain Results

Whole brain results for the Nostalgia–Familiar Control contrast are presented in Figure 4, and coordinates of peak activation clusters are listed in Table 1. Significant activation was observed in the Default Mode Network (bilateral PCC, bilateral precuneus, bilateral angular gyrus, bilateral ACC, bilateral dorsomedial and ventromedial prefrontal cortices), motor regions (bilateral supplementary motor area, bilateral precentral gyrus), occipital regions (bilateral superior lateral occipital cortex, left occipital pole, left intracalcarine), frontal regions (left DLPFC, left VLPFC, bilateral IFG (pars opercularis), bilateral OFC, R SFG), left MTG (temporooccipital region), bilateral SMG, and bilateral anterior insula. Activity was also observed subcortically in the bilateral ventral tegmental area (VTA), superior colliculus, bilateral caudate, bilateral thalamus, and bilateral posterior parahippocampal gyrus. Lastly, cerebellar activity was observed in bilateral crus I, lobules VI, I–IV, and vermis VIIIa.

Between-group contrasts within the Nostalgia > Familiar Control contrast revealed significant activation in the Older > Younger age contrast (see Figure 5A). For coordinates of peak clusters, see Table 2. Specifically, activation for this contrast was observed in the bilateral STG, right parietal operculum, bilateral planum polare, right temporal pole, bilateral MTG, right postcentral gyrus, and left angular gyrus. Further investigation of this effect was conducted using FSL's Featquery to extract percent signal change from rest in each condition for each age group. This indicated that, in the Familiar Control condition, younger adults had greater activation in these regions than older adults, but in the Nostalgia condition, older adults had greater activation than younger adults (See Figure 5B). For replicability and transparency, we additionally have uploaded z-maps for the

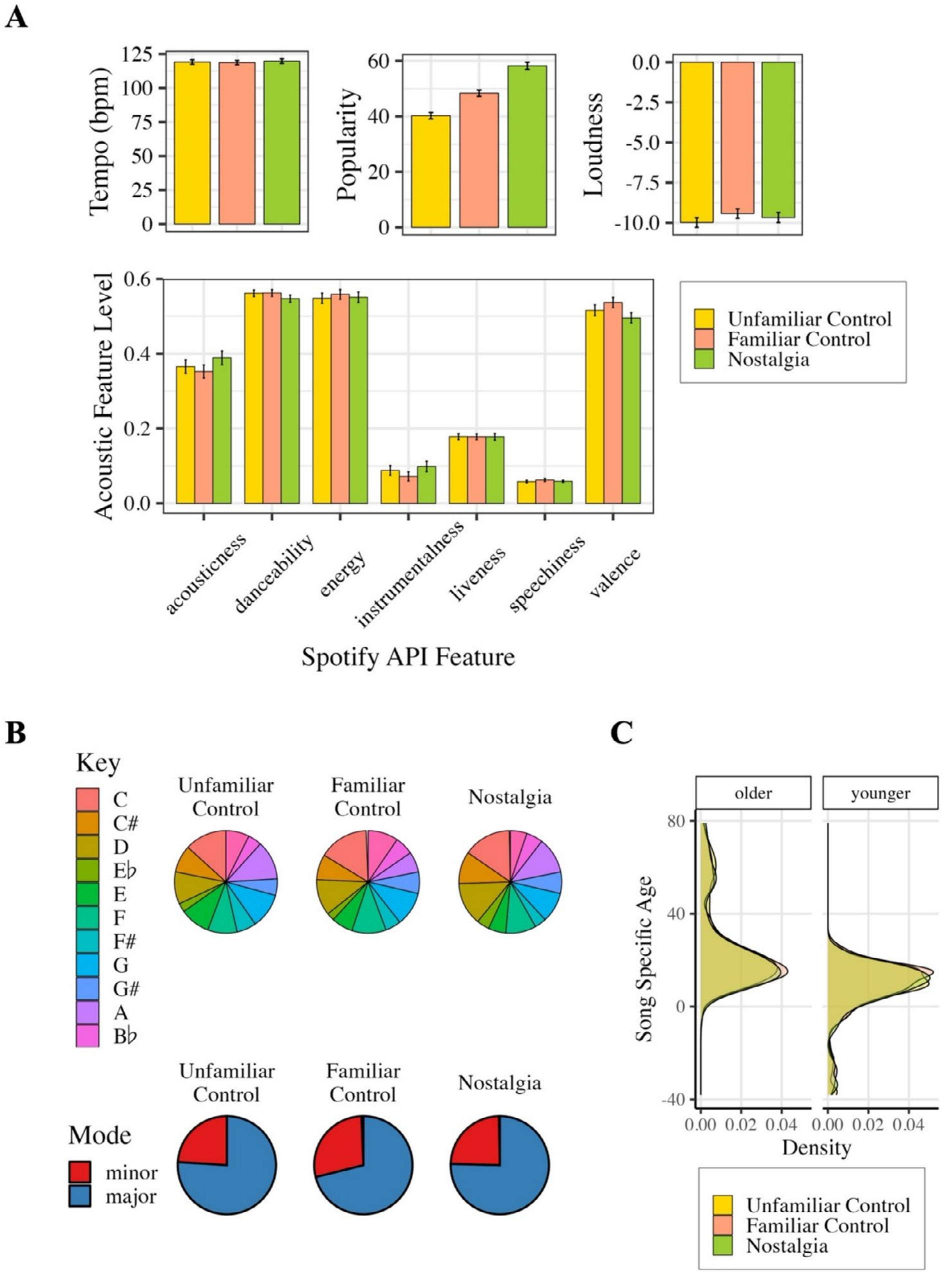

FIGURE 2 | Spotify features between conditions. Panel A: Spotify API feature levels of tempo, popularity, loudness, acousticness, danceability, energy, instrumentalness, liveness, speechiness, and valence compared across Nostalgia, Familiar Control, and Unfamiliar Control conditions. Panel B: Key and mode compared across Nostalgia, Familiar Control, and Unfamiliar Control conditions. For key, both major and minor keys are used. Panel C: Song-specific age (SSA) of Nostalgia, Familiar Control, and Unfamiliar Control songs in younger and older adults.

Nostalgia > Familiar Control contrast for each age group separately at https://neurovault.org/collections/FEHSKFWF/.

In the Nostalgia > Unfamiliar Control contrast, significant activation was observed in regions overlapping those observed in the Nostalgia > Familiar Control contrast (see Supplemental Results).

3.5 | ROI Analysis

In region-of-interest analyses of percent signal change from rest (see Figure 6), we observed a significant interaction effect of Condition by Hemisphere on percent signal change from rest in MPFC (F(2, 110) = 8.68, $p < 0.01$, $f^2 = 0.003$). Specifically, percent signal change in the Nostalgia condition was greater than each of the control conditions, and this was most pronounced in Left MPFC. In PMC, we observed an interaction effect of Condition by Hemisphere (F(1.75, 96.02) = 12.25, $p < 0.001$, $f^2 = 0.003$). Again, percent signal change in the Nostalgia condition was greater than the Unfamiliar and Familiar Control conditions, and this was strongest in Left PMC. In VTA, an interaction effect of Age Group by Condition by Hemisphere was observed (F(1.76, 96.75) = 4.12, $p < 0.05$, $f^2 = 0.004$). This indicated that the effect of Condition was much stronger in older adults in comparison to younger adults

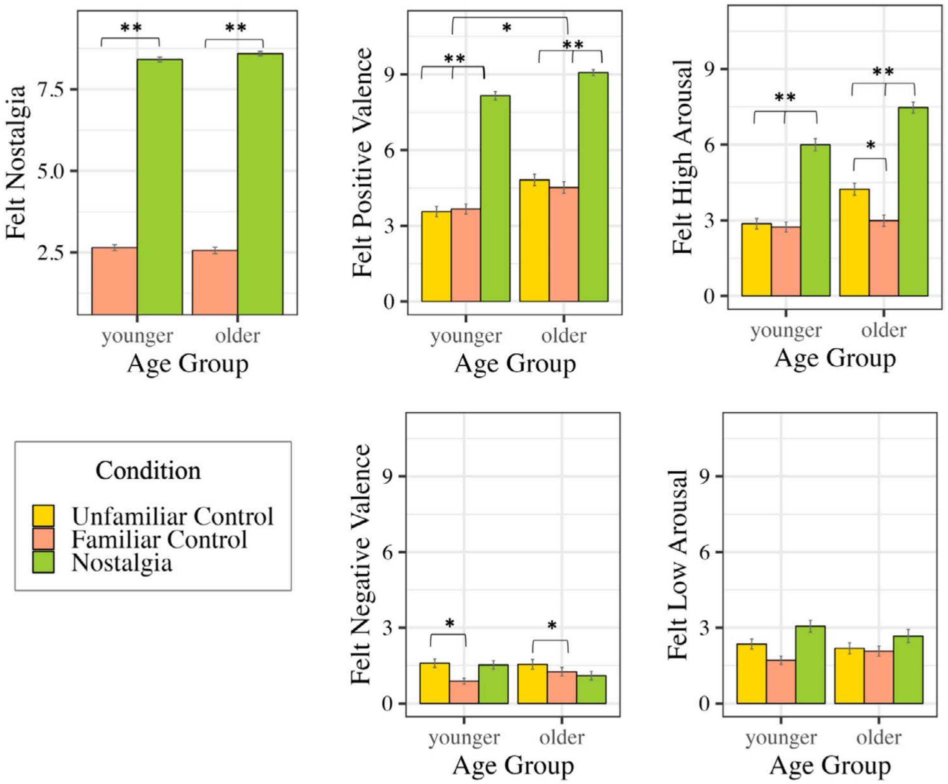

FIGURE 3 | Felt nostalgia, valence, and arousal during Nostalgia, Familiar Control, and Unfamiliar Control songs. Error bars represent standard errors. Stars indicate statistical significance (*$p < 0.05$, **$p < 0.001$, ***$p < 0.001$). Younger $N = 29$, Older $N = 28$.

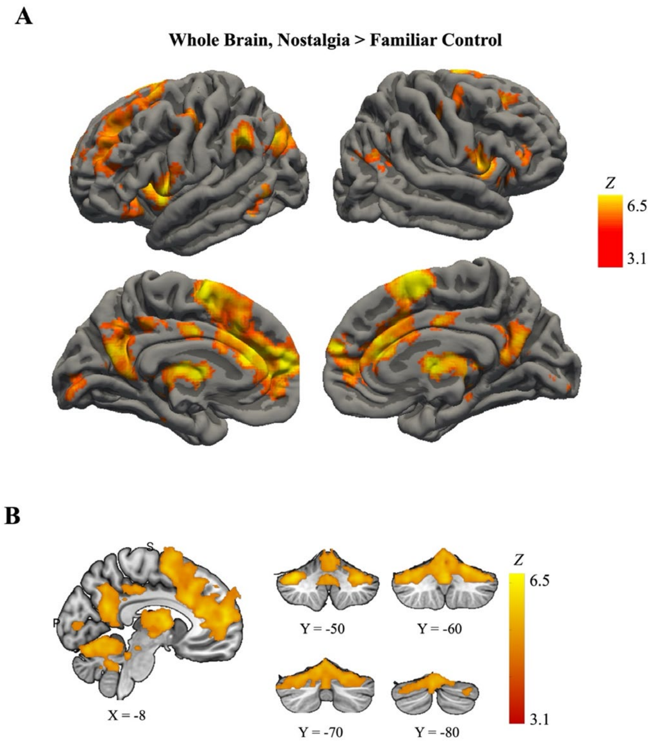

FIGURE 4 | Whole brain results for Nostalgia > Familiar Control contrast, across all participants. Color bar represents Z statistic. Total $N = 57$. Panel A: Whole brain results displayed on a cortical surface. Panel B: Whole brain results display subcortical and cerebellar activity.

and that, in older adults specifically, the Nostalgia condition had its greatest effect in Left VTA. In MTL, we observed a significant effect of Condition, in which percent signal change was greater in the Nostalgia condition than in the Familiar Control Condition.

3.6 | Individual Differences

3.6.1 | Cognitive Ability

For the Nostalgia > Familiar Control contrast, MoCA did not predict activation across participants. However, for the Nostalgia > Familiar Control, Younger > Older contrast, the MoCA score was associated with activation in the right lingual gyrus, right SFG, right frontal pole, bilateral postcentral gyrus, right precentral gyrus, bilateral superior parietal lobule, right parietal operculum, and right ACC (Table 3; Figure S6A). In younger adults, cognitive ability predicted activation, such that higher cognitive ability was associated with greater activation in the Nostalgia condition, whereas, in older adults, the relationship between cognitive ability and activation was uncorrelated in either condition (Figure S6B).

3.6.2 | Trait Nostalgia

Trait Nostalgia did not predict activation in the Nostalgia > Familiar Control or Nostalgia > Rest contrasts. In the Familiar

TABLE 1 | Coordinates of peak clusters by region for the Nostalgia > Familiar Control contrast, across participants.

	Area	Z-value	x	y	z
Frontal	L ACC	5.52	−6	30	16
	L anterior insula	5.96	−37	12	6
	L DLPFC	4.66	−32	47	26
	L DMPFC	4.79	−5	25	42
	L IFG (pars opercularis)	6.09	−48	8	4
	L OFC	4.03	−41	25	−12
	L precentral gyrus	4.63	−46	−9	46
	L SMA	5.49	−4	−1	62
	L VLPFC	4.86	−24	46	15
	L VMPFC	5.66	−5	57	11
	R ACC	5.24	4	32	14
	R anterior insula	5.97	36	11	6
	R DMPFC	4.79	1	17	50
	R OFC	3.66	40	24	−14
	R precentral gyrus	4.04	47	−8	41
	R SFG	6.04	6	12	62
	R SMA	5.76	5	6	58
	R VMPFC	4.68	1	53	2
Temporal	L MTG (temporooccipital regions)	4.6	−61	−54	1
	L posterior PHG	3.85	−22	−26	−26
	R posterior PHG	4.36	14	−27	−14
Parietal	L angular gyrus	4.03	−44	−51	36
	L PCC	5.21	−6	−59	23
	L precuneus	5	−10	−60	38
	L SMG	4.86	−58	−42	34
	R angular gyrus	3.82	46	−48	21
	R PCC	4.24	3	−50	14
	R precuneus	4.1	3	−61	27
	R SMG	3.56	49	−38	34
Occipital	L intracalcarine	4.15	−2	−87	4
	L occipital pole	4.32	0	−91	3
	L superior lateral occipital cortex	4.78	−43	−67	34
	R superior lateral occipital cortex	4.32	52	−72	32
Subcortical	L caudate	4.68	−18	15	11
	L thalamus	5.29	−6	0	6
	L VTA	4.27	−4	−30	−17
	R caudate	4.47	18	23	6
	R thalamus	5.35	4	−2	8
	R VTA	3.53	3	−30	−12
	Superior colliculus	3.39	0	−20	−2

(Continues)

TABLE 1 | (Continued)

	Area	Z-value	x	y	z
Cerebellar	L crus I	5.02	−38	−59	−32
	L I-IV	4.23	−6	−50	−15
	L VI	5.05	−25	−60	−23
	R crus I	4.3	39	−64	−29
	R I-IV	4.32	4	−53	−5
	R VI	5.35	35	−50	−28
	Vermis VIIIa	4.3	0	−61	−34

Note: Coordinates are in MNI space.
Abbreviations: ACC = anterior cingulate cortex, DLPFC = dorsolateral prefrontal cortex, DMPFC = dorsomedial prefrontal cortex, IFG = inferior frontal gyrus, MTG = middle temporal gyrus, OFC = orbitofrontal cortex, PCC = posterior cingulate cortex, SFG = superior frontal gyrus, SMA = supplementary motor area, VLPFC = ventrolateral prefrontal cortex, VTA = ventral tegmental area.

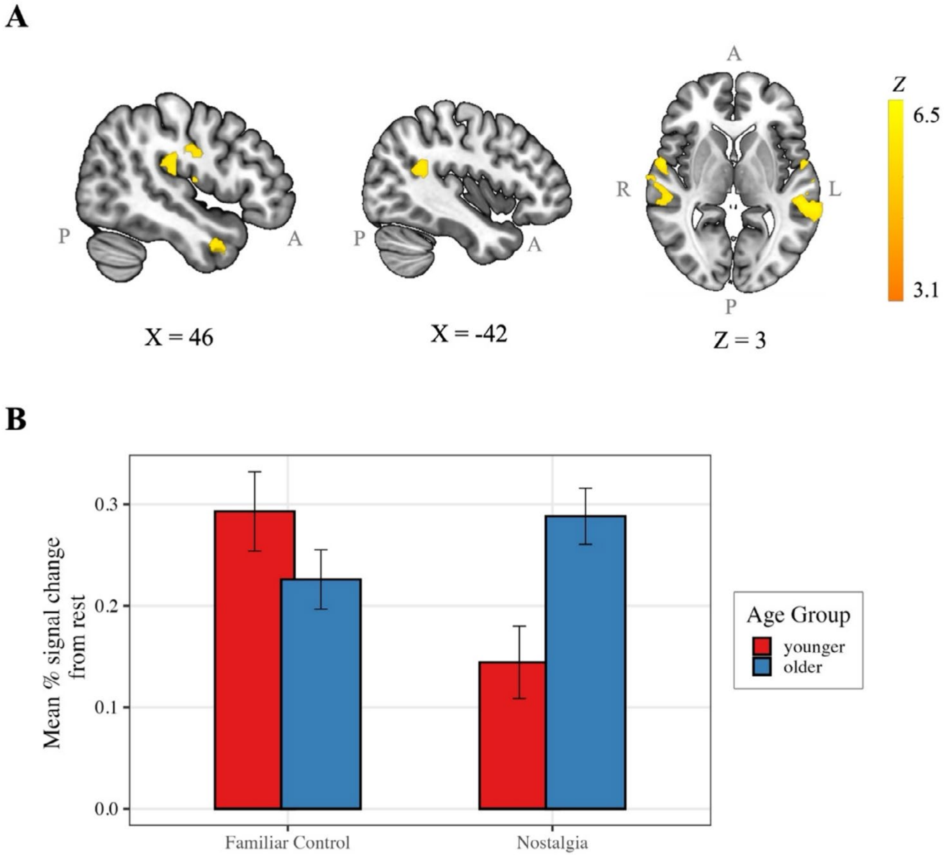

FIGURE 5 | Whole brain results for Nostalgia > Familiar Control contrast, Older > Younger adults (A) and bar plots of younger and older adults percent signal change from rest in the Nostalgia and Familiar Control condition, within clusters significant in Nostalgia > Familiar Control, Older > Younger contrast (B). Color bar (top) represents Z statistic. Orientation markers are displayed (A = Anterior, L = Left, P = Posterior, R = Right). Younger *N* = 29, Older *N* = 28.

Control > Rest, Older > Younger contrast, Trait Nostalgia was associated with activation in the bilateral precuneus (see Figure S7A). Coordinates of peak clusters are presented in Table S9. In younger adults, higher Trait Nostalgia was associated with decreased activation in the precuneus during Familiar Control music listening. This relationship was much flatter in older adults but trended positively, with higher Trait Nostalgia predicting greater activation (Figure S7B). This result should be taken with caution, however, as the only significant cluster appeared in a condition versus rest, and therefore likely do not appropriately reflect responses to nostalgia.

3.6.3 | Valence

In the Nostalgia > Familiar Control contrast across participants, positive felt valence across nostalgic songs was associated with small clusters of activity in bilateral

TABLE 2 | Coordinates of peak clusters by region for the Nostalgia > Familiar Control contrast, Older > Younger.

	Area	Z-value	x	y	z
Frontal	L STG	4.36	−58	−35	5
	R STG	3.88	58	−22	2
Parietal	L angular	3.96	−40	−50	23
	R parietal operculum	4.02	44	−25	16
	R postcentral gyrus	3.55	56	−9	29
Temporal	L MTG	4.2	−64	−8	−14
	L planum polare	3.99	−59	0	0
	R MTG	4.2	63	−4	−10
	R planum polare	4.29	58	0	2
	R temporal pole	4.06	33	5	−37

Note: Coordinates are in MNI space.
Abbreviations: MTG = middle temporal gyrus, STG = superior temporal gyrus.

precuneus, right PCC, and right caudate (see Figure S8). In the Nostalgia > Familiar Control, Older > Younger contrast, positive valence ratings were additionally associated with activity in the bilateral cerebellum (vermis VIIIa, bilateral VI, bilateral crus I, bilateral crus II), right PCC, and right precuneus (Figure S9). Coordinates of peak clusters are presented in Table 4. Investigation of the directionality of this effect revealed that, in the Nostalgia condition, older adults who felt more positively while listening to nostalgic songs had greater activation than those who felt more neutral. This pattern was not observed in the younger adult group.

For the negative valence model in the Nostalgia > Familiar Control contrast, negative nostalgic song valence ratings were associated with small clusters of activity across participants in the right PCC, bilateral precuneus, right caudate, right precentral gyrus, and right SMG (see Figure S8). In the Nostalgia > Familiar Control, Older > Younger contrast, negative valence ratings were additionally associated with activity in the right posterior MTG, right anterior STG, right thalamus, bilateral PCC, bilateral precuneus, and left cerebellum (crus II) (see Figure S9). Coordinates of peak clusters are presented in Table 4. Investigation of the directionality of this effect revealed that, in the Nostalgia condition, older adults who felt more negatively while listening to nostalgic songs had greater activation than those who felt more neutral. This pattern was not observed in the younger adult group.

3.7 | Functional Connectivity

3.7.1 | Posteromedial Cortex Seed

PPI results for the PMC seed are presented in Figure 7. In the Nostalgia > Familiar Control contrast, the right PMC co-activated with the right anterior insula. Coordinates of the peak cluster are presented in Table 5. No significant clusters were observed for the left PMC. No age differences were observed.

3.7.2 | Heschl's Gyrus Seed

No clusters of significant co-activation were observed for the Nostalgia > Familiar Control contrast in either left or right Heschl's Gyrus. No age differences were observed.

4 | Discussion

This study investigated the neural correlates of music-evoked nostalgia across the lifespan. Healthy participants (29 younger adults and 28 older adults) listened to self-selected nostalgia-evoking pieces of music while undergoing functional MRI. Participants also listened to familiar and unfamiliar non-nostalgic control songs, matched for musical and acoustic features to each of the self-selected nostalgic songs. We observed two main findings across age groups: (1) Listening to nostalgic music, more than familiar non-nostalgic or unfamiliar music, was associated with bilateral activity in the default mode network, reward network, supplementary motor regions, medial temporal lobe, and cerebellum; (2) Listening to nostalgic music involved increased functional connectivity of self-referential (posteromedial cortex) and affect-related regions (insula). We observed two findings between age groups: (1) Older adults demonstrated stronger recruitment of nostalgia-related regions; (2) While the neural response to nostalgic music in younger adults was associated with trait-level factors of dispositional nostalgia and cognitive ability, the response in older adults was related to emotional response tendency (i.e., felt valence). We discuss each of these findings, their relation to existing literature, and implications for future work below.

4.1 | Self-Selected Music Successfully Evokes Nostalgia

We demonstrated that our method of asking participants to identify their own nostalgic music was effective at evoking potent feelings of nostalgia in both age groups. Nostalgic songs were rated as 8.4 and 8.6 out of 9 for younger and older adults, respectively. This supports previous work from our group that self-selection is a highly effective method for identifying nostalgic stimuli while accounting for the heterogeneous nature of music habits, preferences, and experiences (i.e., Hennessy et al. 2024; Greer et al. under review). Similarly, our method of identifying both familiar and unfamiliar non-nostalgic songs to create musically matched stimuli triplets was also successful. These songs were adequately matched on acoustic and musical features that may otherwise contribute to neural activation patterns and allowed us to systematically separate the effect of nostalgia from the effect of musical style preference or familiarity. We invite researchers to take advantage of this method for future work on music-evoked emotion and autobiographical memories, utilizing our freely available online matching tool (soundslikethis.us).

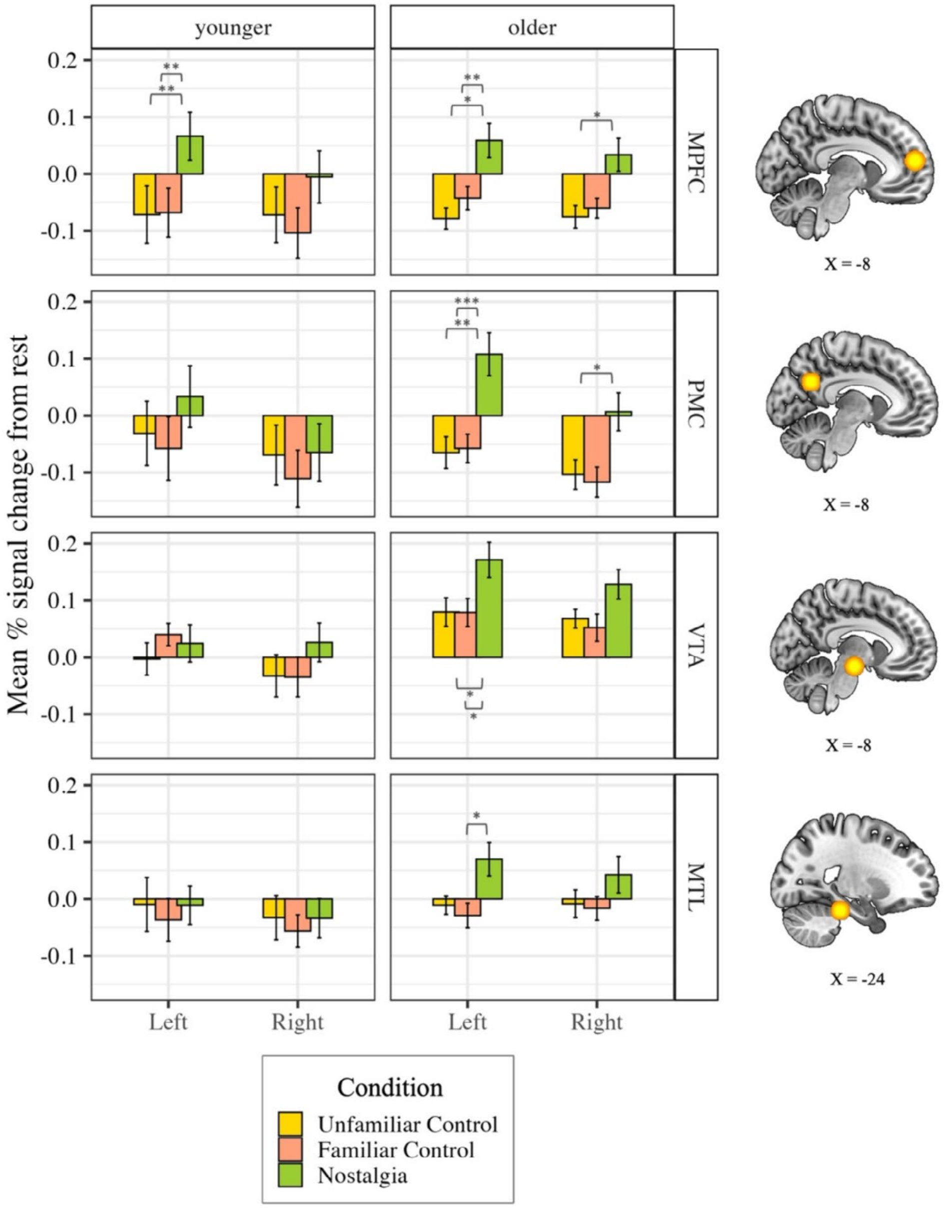

FIGURE 6 | Mean percent signal change from rest between conditions and age groups in a priori-selected regions of interest. MPFC = medial prefrontal cortex, MTL = medial temporal lobe, PMC = posteromedial cortex, VTA = ventral striatum. Error bars represent standard error. Stars indicate statistical significance (*$p < 0.05$, **$p < 0.001$, ***$p < 0.001$). Younger $N = 29$, Older $N = 28$. See Table S2 for full coordinates of ROIs.

4.2 | Music-Evoked Nostalgia Activates DMN, MTL, and Reward Regions

In support of our hypothesis, we observed that nostalgic music, compared to musically matched, familiar, but non-nostalgic music, was associated with activation in the default mode network, medial temporal lobe, and reward regions. We saw additional activation in the salience network (ACC, insula), regions implicated in emotion regulation (ACC, DLPFC), feature processing regions (SMG; Celsis et al. 1999; Oberhuber et al. 2016; Schaal et al. 2015, 2017), motor regions, visual areas, and cerebellum. In comparison to musically matched unfamiliar music, nostalgic music listening was associated with similar and larger regions of activation, with additional activation in areas implicated in musical familiarity (i.e., MTG and pars triangularis; Vuong et al. 2023). In a priori-selected regions of interest, percent signal change from rest was significantly greater in the nostalgia condition than in non-nostalgic conditions. This was true in the MPFC across age groups and, among older adults, in the PMC, MTL, and VTA.

These findings are in line with previous work examining picture- and music-evoked nostalgia, in which activity was observed in reward regions (ventral tegmental area) (Oba et al. 2016; Trost et al. 2012), SMA (Oba et al. 2016), cerebellum (Oba et al. 2016), thalamus (Oba et al. 2016), SMG (Zhang et al. 2022), OFC (Trost et al. 2012; Zhang et al. 2022), and lateral occipital cortex (Zhang et al. 2022). Our large cluster of activity encompassing the dorsomedial and ventromedial prefrontal cortex is additionally consistent with work examining odor-evoked nostalgia (Matsunaga et al. 2013), music-evoked nostalgia (Trost et al. 2012) and music-evoked autobiographical memory (Ford et al. 2011; Janata 2009;

TABLE 3 | Coordinates of peak clusters by region for the MoCA regressor, Nostalgia > Familiar Control contrast, Younger > Older.

	Area	Z-value	x	y	z
Frontal	R ACC	3.66	7	−5	42
	R frontal pole	4.62	31	62	15
	R precentral	0.7	32	−8	52
	R SFG	4.24	17	32	55
Parietal	L postcentral	3.8	−30	−39	62
	L SPL	3.6	−31	−46	49
	R parietal operculum	4	42	−32	22
	R postcentral	4.36	32	−36	65
	R SPL	3.7	36	−44	51
Occipital	R lingual	4	17	−42	−6

Note: Coordinates are in MNI space.
Abbreviations: ACC = anterior cingulate cortex, SPL = superior parietal lobule.

TABLE 4 | Coordinates of peak clusters by region for the valence regressors, Nostalgia > Familiar Control contrast, Older > Younger.

Positive valence

	Area	Z-value	x	y	z
Parietal	R PCC	3.9	2	−50	17
	R precuneus	4.9	14	−50	22
Cerebellar	L crus I	3.8	−24	−82	−25
	L crus II	3.8	−12	−76	−35
	L VI	3.7	−7	−7	−26
	R crus I	4.5	44	−68	−32
	R crus II	3.4	8	−79	−30
	R VI	3.5	16	−62	−21
	Vermis VIIIa	3.56	−2	−62	−32

Negative valence

	Area	Z-value	x	y	z
Temporal	R posterior MTG	3.8	59	−12	−10
	R anterior STG	4.14	49	−12	−3
Parietal	L PCC	4.33	−2	−28	34
	R PCC	4.8	4	−26	34
	L precuneus	4.23	−11	−56	32
	R precuneus	4.27	2	−62	28
Subcortical	R thalamus	4.8	2	−14	5
Cerebellar	L crus II	4.19	−18	89	−32

Note: Coordinates are in MNI space.
Abbreviations: MTG = middle temporal gyrus, PCC = posterior cingulate cortex, STG = superior temporal gyrus.

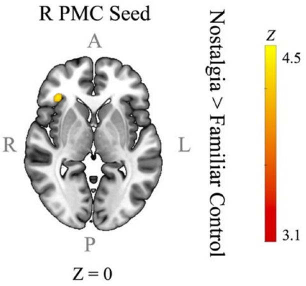

FIGURE 7 | PPI results: Right posteromedial cortex (PMC) seed, Nostalgia > Familiar Control contrast. Color bar represents Z statistic. Total $N = 57$. A = anterior; P = posterior; R = right; L = left.

Trost et al. 2012). Additionally, our observed finding in the insula and reward regions (VTA and substantia nigra) is consistent with Barrett and Janata's (2016) finding that these regions tracked the tonal structure of nostalgic music. Moreover, the fact that these regions were observed in the nostalgic versus non-nostalgic *familiar* music contrast suggests that music-evoked nostalgia is associated with neural activation above and beyond what can be accounted for by familiarity.

With these results, we provide evidence for a true nostalgia-related brain network that mirrors the psychological and social functions of the emotion (Yang et al. 2022, 2023). First, observed activation in self-referential regions of the brain (precuneus, PCC, MPFC) connects to nostalgia's inherent nature as a self-salient and self-reflective emotion (Sedikides et al. 2016; Sedikides, Wildschut, Gaertner, et al. 2008). Second, observed activation in regions implicated in autobiographical processing (parahippocampal gyrus, temporal pole, PCC, MPFC, angular gyrus) reflect nostalgia's role in narrative autobiographical thought and ties to past events (Sedikides et al. 2015b; Wildschut et al. 2006). Third, we observed activity in regions implicated in emotion regulation (ACC, DLPFC), accordant with the regulatory role of nostalgia to ameliorate negative emotion (Wildschut and Sedikides 2023). Finally, we observed activity in a network of reward-related regions (VTA/SN, MPFC), aligning with nostalgia's place as a mostly pleasurable emotion (Leunissen et al. 2021; Sedikides et al. 2015a; Sedikides et al. 2015b; Wildschut et al. 2006) that facilitates approach motivation (Stephan et al. 2014). Overall, the present findings support a neural model of nostalgia that implicates circuitry for self-referential processing and autobiographical memory (both of which encompass the majority of the default mode network), emotion regulation, and reward.

In addition to these hypothesized regions, we observed activation in regions of the brain previously observed in general music-evoked emotion, including sensory and motor regions (Koelsch 2020). The observed activation in occipital regions (lateral occipital cortex, intracalcarine cortex) additionally aligns with past work on music-evoked emotions (Belden et al. 2023; Sachs et al. 2020; Trost et al. 2012) and autobiographical memory retrieval (Ferris et al. 2024; Spreng et al. 2009; Summerfield et al. 2009). Additionally, this is consistent with Janata (2009)'s finding that tonality tracking activation of visual regions biased toward autobiographical music. Participants were asked to keep their eyes closed during the entirety of the fMRI scan and,

TABLE 5 | Coordinates of peak clusters by region for the PPI analyses.

Seed	Contrast	Area	Z-value	x	y	z
R PMC	Nostalgia > Familiar Control	R anterior insula	4.3	36	30	40

Note: Coordinates are in MNI space.
Abbreviation: PMC = posteromedial cortex.

although we did not monitor adherence to this instruction with eye tracking software, we believe it is unlikely that participants systematically kept their eyes open more for the nostalgic listening than for other listening conditions. Instead, we interpret this finding as reflecting involvement of mental imagery during nostalgic listening.

In the medial temporal lobe ROI, obtained from Kim (2012)'s meta-analysis on autobiographical memory, we observed an attenuated effect compared to our initial hypotheses. We observed greater percent-signal change in the nostalgic versus familiar control in older adults only. We did, however, observe small clusters of activity in nearby regions of the medial temporal lobe, specifically the bilateral posterior parahippocampal gyrus, during our whole-brain analysis, which was located dorsal to our MTL seed. In his study on music-evoked autobiographical memory, Janata (2009) observed that medial temporal lobe activity did not correlate with autobiographical salience. This was interpreted as the result of differences between passive listening (as done in Janata (2009)) and effortful retrieval (as done in previous autobiographical memory imaging work, e.g. Ford et al. 2011). This interpretation was supported by a later study in which the authors observed that the MTL was involved in music-evoked autobiographical memory processing only when participants were explicitly instructed to attend to the memories listening (Kubit and Janata 2018). In the current study, participants engaged in passive listening only. Thus, the engagement of even small clusters of the hippocampal regions is notable. This finding suggests that nostalgic music's affective quality may help participants transition into a more memory-attentive neural state.

4.3 | DMN and Insula Integration During Nostalgic Listening

Functional connectivity findings indicated that listening to nostalgic music, more than control music, involved co-activation of the right PMC and the right anterior insula. The nostalgic quality of a musical piece, therefore, appears to drive the integration of information between key self-related (PMC) and affect-related (anterior insula) regions.

Contrary to our hypothesis, we did not see changes in co-activation with reward regions from either of our PPI seeds from the Familiar Control to the Nostalgia condition. Previous work has observed greater auditory-to-reward connectivity during well-liked familiar music listening (Belden et al. 2023), and auditory-to-reward connectivity scaling positively with esthetic pleasure from music (Salimpoor et al. 2013). Functional connectivity measures vary widely, however, and differences between the present result and previous work could be a product of our choice of a more conservative method of functional connectivity analysis (seed-based whole-brain PPI), as compared to the methods utilized in Belden et al. (2023). In their analysis, multiple regions were combined across each network before averaging timeseries across the network of interest, and analyses were constrained between the individual networks of interest, rather than searching across the entire brain. These methodological differences may account for the lack of auditory-reward findings in the present study, but future work is needed to investigate this phenomenon further.

4.4 | Age-Related Findings

4.4.1 | Older Adults Have Stronger Activation in Nostalgia-Related Regions During Listening

We observed several age-related findings when examining the neural correlates of music-evoked nostalgia. First, across all music conditions, older adults showed greater VTA activation than younger adults. This is broadly consistent with the age-related "positivity effect" (Mather and Carstensen 2005) in which older adults have a bias toward attending to positive stimuli and away from negative stimuli (Reed et al. 2014). This bias manifests in many ways, including a greater prevalence of positive emotion and greater memory for positive versus negative events (Sakaki et al. 2019), and is thought to reflect the shifting goals and motivations associated with aging (Kennedy et al. 2004; Mather and Carstensen 2005). In the present study, we report evidence of this effect in behavioral valence ratings, in which older adults reported feeling more positive than younger adults, regardless of song condition. This positivity bias may thus be reflected in overall increased VTA activity, as VTA is implicated in reward (Lammel et al. 2012), musical pleasure (Blood and Zatorre 2001; Menon and Levitin 2005; Salimpoor and Zatorre 2013), and savoring positive memories (Speer et al. 2014).

Secondly, differences between nostalgia and control conditions in our region-of-interest analyses were largely driven by older adults and were stronger in the left hemisphere. While both younger and older adults demonstrated greater percent signal change in nostalgic listening compared to control music listening in the MPFC, these effects were only observed in older adults in the PMC, VTA, and MTL. These effects showed a left-hemispheric bias, aligning with previous work showing stronger activation of MPFC and PMC in the left hemisphere in response to loved music (Belden et al. 2023) and familiar, pleasing, and autobiographically salient music (Janata 2009). This lateralization is observed in autobiographical memory processing (D'Argembeau et al. 2014; Ralph et al. 2017) and narrative production (AbdulSabur et al. 2014), in which the left hemisphere is implicated in semantic cognition and connecting memories and cues to personal meaning.

Additionally, when listening to nostalgic music in comparison to familiar non-nostalgic music, older adults had greater activation than younger adults in several regions involved in nostalgic listening: temporal regions (STG, planum polare, MTG, temporal pole), somatosensory regions (right postcentral gyrus, right parietal operculum), and the left angular gyrus. While not explicitly hypothesized in this investigation, the parietal operculum has been suggested to relate to the generation of subjective feeling states (Koelsch et al. 2015) as evoked by music (Koelsch et al. 2021). In comparison to unfamiliar music, older adults also showed greater activity in nostalgia-related regions, including the precuneus and angular gyrus, and less deactivation in the superior parietal lobule. This finding is consistent with evidence that older adults over-activate task-relevant neural regions during emotion (Kehoe et al. 2013) and memory tasks (Cabeza et al. 2002; Galdo-Alvarez et al. 2009) and fail to fully de-activate task-irrelevant regions (Gordon et al. 2014; Lustig et al. 2003; Persson et al. 2007). Here, the superior parietal lobule, a region involved in top-down processing of information (Shomstein 2012) and reciprocally deactivated with DMN (Nakano et al. 2013), is considered task-irrelevant.

These age-related findings can be interpreted in one of two ways. First, older adults may over-recruit and fail to fully de-activate from irrelevant networks as a way of compensating for declining efficiency in other neural regions involved in nostalgic listening. This explanation is in line with the Compensation Related Utilization of Neural Circuits Hypothesis (CRUNCH; Reuter-Lorenz and Lustig 2005), suggesting that age-related structural decline and processing inefficiencies force older adults to compensate by over-recruiting less-affected regions, showing larger responses in task-related regions. Alternatively, over-recruitment, particularly involving default mode regions, may reflect healthy age-related shifts in self-referential thought and autobiographical memory retrieval priorities that ultimately promote emotional well-being and social connectedness (Andrews-Hanna et al. 2019; Grilli and Sheldon 2022). These shifts might lead to consistently increased neural recruitment during tasks that involve self-referential and autobiographical memory, like nostalgic music listening. Future work could probe these explanations by examining qualitative differences in music-evoked memories (i.e., episodic details, gist-level details, autobiographical integration, or references to the self) between age groups and relating these findings to neural activation in response to nostalgic music. If neural responses are predicted more by differences in self-referential or high-level narrative elements, rather than by a reduction in episodic details, the second interpretation may be supported.

4.4.2 | Age-Related Stabilization of Trait-Level Measures on Neural Activation of Nostalgia

In our investigation of the role of individual differences on nostalgia-related neural activity, we observed that trait-level measures of cognitive ability and dispositional nostalgia predicted neural activity for younger adults but not older adults. Specifically, less nostalgic younger adults appeared to have more activity in a key nostalgia-related region (precuneus) while listening to non-nostalgic songs. Barrett and Janata (2016) observed that younger adults who had lower trait nostalgia had greater activity associated with nostalgia ratings during music listening in SFG, temporal pole, and reward regions. Here, however, we see activity in a key node of self-referential processing implicated in nostalgia across analyses, active during *non-nostalgic* music. This suggests that younger adults who routinely experience nostalgia may have a greater differentiation between nostalgic and non-nostalgic brain states during music listening than those who experience nostalgia less frequently. In contrast, older adults' neural responses to music do not appear to be impacted by trait-level nostalgia. Previous behavioral evidence points to an age-related decline in the relationship between episodic memory and the personality dimension of neuroticism (Steenhaut et al. 2018), which is linked to trait nostalgia (Barrett et al. 2010; Hennessy et al. 2024). Our results similarly suggest that older adults' neural response to autobiographically salient music is robust to individual differences in personality. However, this effect warrants further exploration.

Similarly, while older adults' nostalgia-related neural activity was not impacted by cognitive ability, younger adults with higher cognitive ability had greater activation during nostalgic listening in several sensory and motor regions implicated in nostalgia processing. Overall, this finding suggests that cognitive ability's influence on neural response to nostalgic music stabilizes with age. While this may be promising due to its implications for the preservation of music-evoked emotions and memories in individuals with cognitive decline, these findings are taken with caution. Participants in this study were intentionally screened to keep the sample in the healthy range of cognitive scores, and thus, the range of scores present is extremely limited (26–30 out of 30). Future research is needed with a larger range of cognitive scores to appropriately assess whether the neural correlates of music-evoked nostalgia are robust to cognitive decline.

4.4.3 | Positive and Negative Felt Valence Predict Neural Activity in Older Adults

We observed that, across age groups, average positive and negative felt valence were both associated with activity in self-related (precuneus, PCC) and reward regions (caudate) during nostalgic music listening. Negative valence was associated with additional activity in motor (precentral gyrus) and feature processing regions (SMG; Celsis et al. 1999; Oberhuber et al. 2016; Schaal et al. 2015, 2017). Previous findings have shown similar regions implicated in valence experienced from music (Koelsch et al. 2006; Trost et al. 2012) valence of self-directed thoughts during music listening (Koelsch et al. 2022), and valence associated with autobiographical memories (Speer et al. 2014). However, it is important to note that our finding does not imply that activity in these regions correlates with the valence of an individual stimulus. We retrieved an average valence response across nostalgic songs for each participant, creating a measure that reflects an individual's *tendency* to feel more positive or negative when listening to nostalgic music (i.e., “positive feelers” and “negative feelers”).

Unlike other trait measures, younger and older adults differed in how valence impacted their neural response to nostalgic music. Specifically, neural activation associated with positive valence appeared to be driven by the older adult group. In the older adult group, individuals who tended to feel more positively when listening to nostalgic music had greater activation than those who felt more neutral in self-related regions (PCC and precuneus) as well as the cerebellum. Similarly, the effect of negative valence was driven by the older adult group, such that older adults who felt more negatively had greater activation than those who felt more neutral during nostalgic songs in auditory (MTG, STG), self-referential (precuneus, PCC), thalamus, and cerebellum.

While the increased activation in positive feelers may be explained by age-related positivity effects, overlapping and additional activation for negative feelers complicates this interpretation. Additionally, many studies observe that aging is associated with increased reliance on prefrontal regions during emotion processing (reviewed in Nashiro et al. 2011), as opposed to posterior and temporal regions observed here. It is conceivable that the processing of music-evoked emotions undergoes distinct age-related shifts in neural activation compared to responses to other stimuli. Unlike images and words often used in emotion regulation studies, music is a dynamic stimulus whose emotion-inducing properties unfold over time. Thus, music—particularly nostalgic music—may be more potent in maintaining attention toward an emotion because the nature of the experience does not allow for attentional redirection. In the face of this immersive stimulus, it may be that older adults are more willing to engage with both positive and negative feelings without actively regulating them (as might be reflected in increased prefrontal activity; Golkar et al. 2012). This finding is consistent with our overall observation that older adults tended to over-recruit task-relevant regions in our general whole-brain analyses.

4.4.4 | No Age-Related Differences in Functional Connectivity

We did not observe age-related differences in functional connectivity between nostalgic and control listening. Again, this contrasts with Belden et al. (2023), who observed more diffuse connectivity patterns in older compared to younger adults during music listening. Our results could suggest that functional connectivity patterns supporting the experience of nostalgia stay consistent across the lifespan. However, given the presence of age-related findings in the general activation patterns for each condition, we are hesitant to make this claim. Instead, divergence from Belden et al.'s (2023) findings may simply be due to methodological differences, as noted in the previous discussion of functional connectivity.

4.5 | Limitations and Future Directions

We note several limitations of this study. First, this cross-sectional investigation cannot draw temporal inferences about music-evoked nostalgia in aging. It could be that age-related effects observed in this study result from generational differences in how individuals respond to music or experience nostalgia. Longitudinal research is required to systematically investigate the effect of age on the neural representation of nostalgia as evoked by music.

Second, we acknowledge that, while studying a dynamic stimulus such as music, choosing which segment of the piece to play may greatly impact findings. In this study, we used the first 40 s of each song for consistency. However, for some pieces of music, it is likely that the first 40 s may not have included the chorus, which may have been the most recognizable or potentially most nostalgic part of the piece. However, behavioral research has demonstrated that individuals can determine familiarity and liking for a song within the first 750 ms (Belfi, Kasdan et al. 2018), suggesting that the emotional qualities of a piece of music may be evoked early on in a piece of music. Additionally, given that we did observe highly significant clusters of activation for our contrasts of interest using the beginning portion of each song, we contend that this was an adequate choice. Future behavioral work could examine the relative nostalgic quality of different structural elements of nostalgic music (i.e., verse, chorus, bridge). Future neuroimaging work could show how neural activity relates to dynamic aspects of full-length nostalgic songs using naturalistic methods and analyses like intersubject correlation (i.e., Sachs et al. 2020) and hidden Markov modeling (i.e., Williams et al. 2022).

Finally, our study differs from previous research in that we did not obtain ratings of pleasantness or enjoyment from participants for each piece of music. Previous investigations have used preference ratings as a primary regressor in their analyses, which were not done here. While it is reasonable to assume that nostalgic music might have been rated as preferred to non-nostalgic music, we do not see this as a necessary limitation. From valence ratings, we observed that participants felt more positive while listening to nostalgic music compared to familiar and unfamiliar non-nostalgic music, which is in line with the affective experience of nostalgia. To assess the emotional construct of nostalgia, we expected that these ratings would differ between conditions, and we see this as a separate construct from enjoyment. Given the stimulus matching procedure, we feel confident that enjoyment (specifically, enjoyment due to musical style) was matched across song conditions. Preferences for specific acoustic and musical features predict enjoyment of music (Barone et al. 2017; Rentfrow et al. 2011); thus, our steps to match these features should control for this enjoyment aspect. We see this matching as a considerable strength of our experimental design. Yet, it is possible that nostalgic songs, due to their personal relevance, are more enjoyed by listeners than their musically matched counterparts. Relatedly, it is possible that an overall tendency to feel pleasure from music may predict stronger responses to nostalgic music. Future research may probe these questions by including enjoyment ratings and collecting trait-level music reward information (i.e., the Barcelona Music Reward Questionnaire; Mas-Herrero et al. 2013) in their nostalgia-focused experiments.

4.5.1 | Constraints on Generality

Several factors in this study constrain our ability to generalize findings. Most notably, our sample is not representative of the population of adults in the United States. Most of our younger adult sample was recruited from the University of Southern California's undergraduate population, which is skewed to be wealthier (Opportunity Insights 2018) and more educated than the general U.S. population. The older adult sample was recruited from the greater Los Angeles area, whose demographics mirror more closely those of the U.S. (U.S. Census Bureau 2020). However, we did not collect race or ethnicity information from our participants and, therefore, cannot claim that our sample was racially or ethnically representative. Future research should employ a statistically representative sample of both younger and older adults. This is particularly important given this work's implications for Alzheimer's Disease and Related Dementias, as ADRD disproportionately affects people of color (Lennon et al. 2022). Yet, people of color are historically underrepresented in aging and dementia research.

5 | Conclusion

This is the first study to explore how self-selected nostalgic music affects neural activity in younger and older adults. We demonstrate that music-evoked nostalgia is supported by neural activation and functional connectivity patterns that differ from musical familiarity and are not attributable to acoustic features or musical style. These patterns involve brain regions implicated in self-referential processing, autobiographical memory, reward, and emotion regulation. We demonstrate that these patterns are consistent in location across the lifespan, but older adults show stronger recruitment of several nostalgia-related regions. Lastly, we show that neural correlates of nostalgic music listening stabilize across the lifespan regarding person-level characteristics of nostalgia-proneness and cognitive ability and become more variable with differences in affective tendencies. This study underscores the use of personalized stimuli in investigating music-evoked emotions and highlights the preservation of neural resources during nostalgic music listening in aging. This work may serve as a healthy baseline for future studies examining the neural correlates of music-evoked nostalgia in individuals with Alzheimer's Disease and Related Dementias.

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Ethics Statement

All procedures were approved by the Institutional Review Board of the University of Southern California (IRBUP: UP-22-00569).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Neurovault at https://neurovault.org/collections/FEHSKFWF/, reference number https://identifiers.org/neurovault.collection:17097.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.