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Attention, working memory, and inhibitory control in aging: Comparing amateur singers, instrumentalists, and active controls

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Abstract

Despite the ubiquity of musical activities, little is known about the specificity of their association with executive functions. In this cross-sectional study, we examined this relationship as a function of age. Our main hypotheses were that executive functions would decline in older age, that this relationship would be reduced in singers and instrumentalists compared to nonmusician active controls, and that the amount of musical experience would be more strongly associated with executive functions compared to the specific type of activity. A sample of 122 cognitively healthy adults aged 20–88 years was recruited, consisting of 39 amateur singers, 43 amateur instrumentalists, and 40 nonmusician controls. Tests of auditory processing speed, auditory selective attention, auditory and visual inhibitory control, and auditory working memory were administered. The results confirm a negative relationship between age and executive functions. While musicians' advantages were found in selective attention, inhibitory control, and auditory working memory, these advantages were specific rather than global. Furthermore, most of these advantages were independent of age and experience. Finally, there were only limited differences between instrumentalists and singers, suggesting that the relationship between music-making activities and executive functions may be, at least in part, general as opposed to activity-specific.

KEYWORDS
aging, cognitive aging, executive functions, instrumentalists, singers

INTRODUCTION

There is a broad consensus among scientists that healthy aging is characterized by a decline in cognition, including executive functions. Executive functions can be broadly defined as control processes responsible for planning, assembling, coordinating, sequencing, and monitoring other cognitive operations.[1] Executive functions play a central role in maintaining daily functioning in older adults, even in the face of cognitive decline, being central to multiple daily activities such as driving, cooking, dialing on the phone, and for communication and social interactions. Executive decline can compromise the planning and execution of cognitive tasks and the monitoring of one's performance and can thus affect all aspects of life. The relationship between attentional and functional status has been demonstrated empirically.[2] While executive functions decline with age, they remain plastic, and as such could, at least in theory, be improved with training, including in the elderly.[3] It is, therefore, crucial to investigate strategies to maintain executive functions.

There is accumulating evidence suggesting that certain lifestyle factors, including the practice of musical activities, can have a positive impact on cognition in aging, especially on executive functions.[4–6] The *mental exercise hypothesis* proposes the general notion that lifestyle factors can affect cognitive functioning and reduce cognitive decline in aging.[7] One set of hypotheses, developed by Salthouse, provides a theoretical framework for the study of the relationship between mental activities and cognition.[8,9] The first hypothesis—*the differential preservation hypothesis*—stipulates that highly active and less cognitively active young adults do not differ. However, with age, only highly active adults maintain a youth-like cognitive performance. This hypothesis predicts that group differences should increase with age, with highly active adults maintaining or improving performance over time, while the performance of less active adults should become lower over time. This is expressed statistically as a Group by Age interaction. The second hypothesis—*the preserved differentiation hypothesis*[8,9]—stipulates that the difference in performance between active and less active people is stable over the lifespan (i.e., independent of age), with highly active individuals exhibiting an advantage throughout their lifespan. This is expressed statistically as a main effect of Group. For Salthouse, however, only results coherent with the differential preservation hypothesis support the mental exercise hypothesis, because it is expected that age-related cognitive decline occurs with less use (i.e., less cognitive exercise) and, therefore, the most meaningful outcome in aging research should be the rate of change over time in the variables of interest. Alongside the mental exercise hypothesis, this framework can be used to study the association between all kinds of activities—including musical activities—and cognitive aging.[10]

Music-making activities are complex and cognitively demanding activities. Studies conducted in individuals of all ages have found that playing a musical instrument was associated (mostly in a noncausal manner) with better performance on tests of executive function, including tests of attention,[11,12] working memory (WM),[12–15] inhibitory control, and cognitive flexibility.[11,12,16–18] Likewise, a few studies found that singing in a formal setting such as a choir was associated with better executive functions[19–21] and auditory cognition (speech perception in noise) under certain conditions of practice (e.g., ≥3 h of singing per week[22]). Yet, the association between musical activities and executive functions is not straightforward. Several training studies, including musical instrument[23–26] and singing training,[27,28] have failed to report a greater cognitive improvement in those who learned music compared to a control group. Moreover, among the longitudinal and cross-sectional studies that have found positive relationships between musical activities and cognition, benefits are often specific rather than being general, for example, Refs. 16, 18, 19, 20, 21, 29–34. A recent cross-sectional study reported that older adults who were singing at least once a week in a choir were better than nonsingers at phonemic fluency but did not perform better in semantic fluency, digit span, Simon task, and Trail Making tests.[21] Bugos and Wang[35] randomly assigned 115 older adults to a group of piano training (increased difficulty), a computer cognitive training group, and a control group. Compared to controls and to the cognitive training group, those in piano training demonstrated enhanced WM, complex processing speed, and verbal fluency. Adults in the cognitive training group showed increased WM and complex processing speed compared to controls. Thus, although musical activities may be positively associated with cognition, multiple key questions remain.

An unresolved question is whether the association between musical activities and executive functions is activity-dependent (e.g., singing-specific) or general. Given the differences in brain structures that have been found between people engaged in different types of musical activities,[36] one might predict that the associations with cognitive-executive performance may as well differ depending on the type of musical activity. For example, the memorization of lyrics is specific to singing, while the ability to read music is essential in an orchestra but is not required in many (if not most) amateur choirs. One could, therefore, predict that singing would be more strongly associated with verbal cognition than instrument playing, and that instrument playing would be more strongly associated with visual processing. However, as WM, inhibitory control, and selective attention are required for both activities, one could also expect similar performances between instrumentalists and singers on tests that do not specifically assess verbal or visual modalities. In line with these expectations, in a cross-sectional study comparing groups of percussionists, vocalists, and nonmusicians, only a marginal difference between percussionists and vocalists was found in speech-in-noise perception (differences were not significant when the control group was included in the analysis) but not in auditory WM.[37] In other studies, the effects of instrument playing and singing differed little, regardless of task modality. Comparing instrument players and singers, Mansens et al.[14] found only limited group differences in terms of processing speed, WM, verbal fluency, and memory. Only the group difference in processing speed reached statistical significance. More recently, Vetere et al. found an association between verbal reasoning and both musical activities (playing a musical instrument and singing). WM was also associated with playing an instrument, but not with singing.[38] In both Mansens' and Vetere's studies, there was no indication that the groups were comparable in terms of age, sex, or musical experience, making it difficult to interpret the results. Overall, the number of studies that have compared executive functioning in instrumentalists and singers is insufficient to draw any solid conclusion. Yet, this information is crucial, given that the choice of activity is influenced not just by preferences and skills but also by the benefits one may seek. Furthermore, in most studies, musicians are compared to a passive group of nonmusicians, making it difficult to determine whether group differences are related specifically to *musical* activities, or to some other difference between the groups.

Another important unresolved set of issues concerns the relationship between the kind and amount of musical experience as well as the neuroplasticity and cognitive/behavioral advantages. As reviewed in Merrett et al.,[36] while evidence for an association between music training and brain plasticity is extensive, numerous factors can shape how and where neuroplasticity occurs, and, in turn, cognitive-executive outcomes. These factors include the age of onset of musical training, as well as training and practice parameters such as the amount, duration, and intensity of practice, the complexity of training, and the amount of learning. For instance, Gray and Gow found a positive association between years of musical experience and WM abilities assessed using the digit span test in older instrumentalists.[11] Relatedly, Hanna-Pladdy and MacKay found that only older adults with a high level of musical experience (i.e., with >10 years of experience and formal musical training) outperformed nonmusicians on a few cognitive tasks, including part B of the Trail Making Test,[29] which involves visual attention and cognitive flexibility.

The specific objective of the current study was to explore differences in nonmusical executive functions as a function of age and musical activity experience in amateur musicians, via a noncausal cross-sectional study. From a rehabilitation perspective, only amateur musical activities represent a realistic model, as achieving a professional level is not universally accessible. Indeed, while music is ubiquitous in all human societies, music aptitudes vary greatly across individuals and have been associated with genetic predispositions.[39,40] Yet, the practice of leisure musical activities such as community choir singing is very inclusive, with the level of musical aptitude varying widely within and between choirs. To achieve our main objective, we examined a subset of executive functions—processing speed, auditory selective attention, auditory and visual inhibitory control, and auditory WM—in healthy young and older adult singers and instrumentalists and, importantly, to compare performance in these groups with performance in an age-matched group of people involved with nonmusical cognitive-motor activities. This control group provides a more adequate test for the association between musical activity and cognition-executive function than the usual comparison of musicians against a passive group. These executive functions were selected because they are likely more strongly associated with musical activities than higher-order executive functions such as reasoning, problem-solving, and planning, and each has been investigated in previous work on the relationship between musical activities and cognition. Our first hypothesis was that executive capabilities would be lower in older adults. Our second hypothesis was that those involved in musical activities would have overall better executive functions than the active control group, consistent with the differential preservation hypothesis.[9] Our third hypothesis was that the amount of experience, rather than the type of activity, would be the driving factor for the association between executive capabilities and musical activities.

MATERIALS AND METHODS

The study was approved by the Comité d'éthique de la recherche sectoriel en neurosciences et santé mentale, Institut Universitaire en Santé Mentale de Québec (# 2023-2718). All participants provided informed consent. The resulting dataset is referred to as the PICCOLO Project (from the French "Projet de recherche sur les effets de la Pratique d'un Instrument ou du Chant sur la COgnition, le Langage et l'Organisation cérébrale"). The R syntax and aggregated data that support the findings of this study will be available upon publication on Borealis, the Canadian Dataverse Repository (https://doi.org/10.5683/SP3/HM3ZBU). This work was not preregistered.

Participants

A total of 125 healthy adults were recruited through emails, posters, and flyers distributed in the general community at Université Laval, and through emails and Facebook posts targeting choirs and music harmonies in the Quebec City area. Recruitment started in 2019 and ended in 2023.

The general inclusion criteria were to be right-handed, according to the Edinburgh Handedness Inventory[41]; fluent speakers of French; to have normal or corrected-to-normal vision; no self-reported speech, voice, swallowing, or respiratory disorder; no active diagnosed language, hearing, or psychological disorder; no neurological or neurodegenerative disorder; and normal general cognitive functioning, as assessed using the French version of the Montreal Cognitive Assessment (MoCA).[42] Because the larger project involved a magnetic resonance imaging (MRI) session, participants also had to be MRI-compatible. Figure 1 illustrates the recruitment process and highlights its challenges (1155 contacts were necessary to achieve a sample size of 122 participants).

Participants belonged to one of the following three groups: amateur singers, amateur instrumentalists, or active nonmusicians. All participants had to practice their musical or nonmusical activities for at least 5 years at the amateur level. Professionals, defined as those having a career as a musical performer, were excluded. Singers and instrumentalists could not practice other cognitive-motor or musical activities (e.g., instrument playing [for singers], singing [for instrumentalists], dancing, figure skating, artistic gymnastics) for more than half of the time spent singing (for singers) or playing a musical instrument (for instrumentalists) each week. Participants from the control group could not be involved in any musical activities for more than half of the time spent practicing their cognitive-motor activity each week. Participants in all groups could not be involved in any physical activities for more than half of the time spent practicing their main activity. Three participants were excluded from the study after recruitment: two had a MoCA score below the normal range based on the most recent local norms[43] and one had a hearing impairment.

The final sample (n = 122) included 39 amateur singers (mean age 61.8 ± 16.4; 23–88 years, 62% females), 43 amateur instrumentalists (mean age 52.1 ± 18.2; 20–88 years, 36% females), and 40 nonmusician active controls (mean age 55.6 ± 19; 20–87 years, 50% females). Fifteen singers and 39 instrumentalists had received some form of musical training. The active control group included people who practiced at least one nonmusical activity that is demanding on the motor and cognitive levels, such as golf (n = 12), knitting (n = 10), billiards (n = 8), curling (n = 5), yoga (n = 4), strategy and precision video games (n = 4), petanque (boules) (n = 2), bowling (n = 1), and tai chi (n

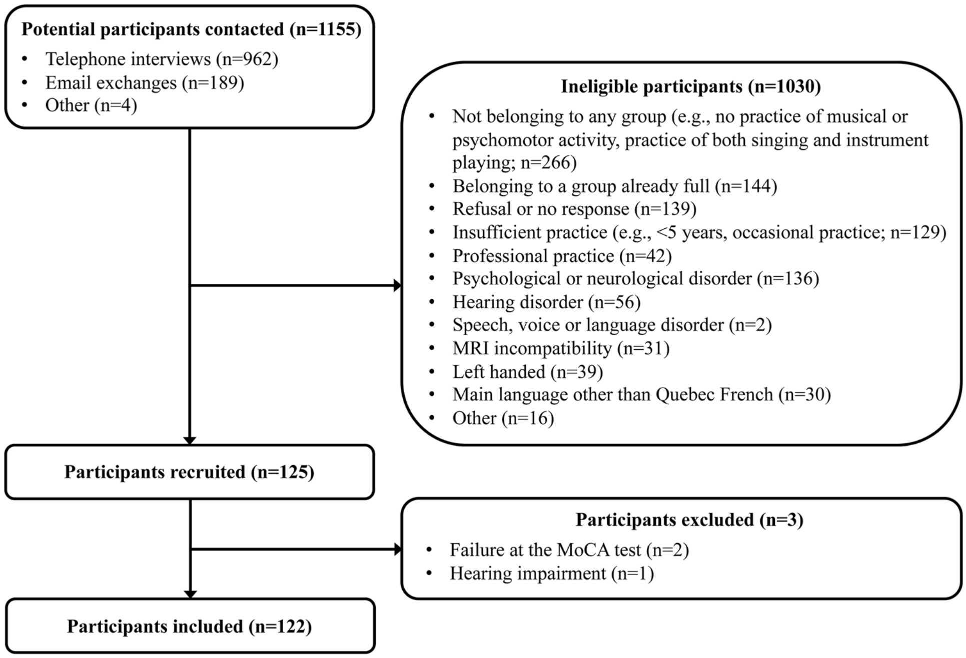

FIGURE 1 Recruitment flowchart.

= 1). None of those activities was aerobic or musical in nature. Table 1 provides a summary of participants' characteristics.

We performed a post hoc power analyses based on one dependent variable (conflict resolution) using this sample and the full statistical model, for the predictors Group and Age using the *simr* package with 1000 permutations[44] at a significance level of 0.05. The results yielded a power estimate of 99.80% (95% CI = [99.28, 99.98]) for detecting a statistical Group difference and 97.40% (95% CI = [96.21, 98.29]) to detect an Age effect.

To ensure that the groups were comparable, we tested for group differences in education, engagement in social activities, linguistic background, self-perceived health, depression symptoms using the 15-item version of the Geriatric Depression Scale (GDS)[45] (no participant exhibited signs of major depression), dementia risk factor (see Supplementary Material 2), and pure-tone hearing. Statistical comparison of the groups, presented in Table 1, revealed that the three groups were matched for biological sex, age, education, number of spoken languages, MoCA, GDS, engagement in social activities, self-reported physical health, hearing, and risk of dementia.

We also compared the number of participants in each group who regularly engaged in sports (aerobic activities), social activities, cognitive activities, cognitive-motor activities, singing, and playing a musical instrument, using χ^2 tests or Fisher tests when the number of observations in at least one cell was less than 5. The results revealed that the groups were matched in terms of their engagement in sports ($\chi^2 = 1.446$, df = 2, $p = 0.485$), cognitive activities ($\chi^2 = 2.975$, df = 2, $p = 0.226$), and social activities ($\chi^2 = 2.226$, df = 2, $p = 0.329$). As was expected, the singers were engaged in singing more so than the other groups (Fisher's exact test, $p \leq 0.001$), the instrument players were more engaged than any other group in playing a musical instrument (Fisher's exact test, $p \leq 0.001$), and the active controls were more engaged in cognitive-motor activities (Fisher's exact test, $p \leq 0.001$).

Finally, we also examined whether the groups differed in their experience with their main activity (singing, instrument playing, or cognitive-motor activity). We documented: (1) the number of years of active practice of their activity; (2) the years of experience relative to their age (experience ratio; ER); (3) the intensity of their practice over the past 5 years (calculated as the mean number of hours spent singing, playing a musical instrument, or practicing a cognitive-motor activity each week); (4) the age of onset (AO); and (5) overall experience, a score that combines AO and the ER. It consists of the multiplicative inverse of the subtraction between the age of onset and the product of the age of onset and the ER, which is expressed as the formula $1/(\text{AO}-(\text{AO} \times \text{ER}))$. A higher score indicates that a person started practicing early and has practiced for a large proportion of his/her life. One-way ANOVAs revealed that the groups did not differ in terms of years of practice and practice intensity, but they differed in terms of AO, with instrumentalists starting earlier in life, and ER, with instrumentalists having a higher ER. Because the groups also differed on the global experience score—which takes both AO and ER into account—we decided to include this variable in all statistical analyses.

The characteristics of individual participants and a comparison of the singers and instrumentalists in terms of their musical characteristics are provided in Supplementary Material 1.

Procedures

The visit had a duration of approximately 3 h, including a hearing assessment and a cognitive assessment that included a test of WM

TABLE 1 Participant's characteristics.

	Active controls n = 40 (50% ♀)				Singers n = 39 (62% ♀)				Instrumentalists n = 43 (35% ♀)				ANOVA/Chi^2	
Characteristics	M	SD	min	max	M	SD	min	max	M	SD	min	max	F/X^2	*p*
General characteristics														
Age	55.6	18.98	20	87	61.18	16.41	23	88	52.05	18.15	20	88	2.689	0.07
Education (years)[a]	14.8	2.21	11	18	15.05	2.66	10	23	15.3	2.31	11	21	0.455	0.64
Nb lng.[b]	2.17	0.55	1	4	2.33	0.62	1	3	2.4	0.62	1	4	1.473	0.23
MoCA[c] (/30)	27.42	1.6	25	30	27.95	1.7	24	30	28	1.75	22	30	1.446	0.24
GDS[d] (/15)	0.95	1.57	0	7	0.92	1.53	0	7	0.79	1.01	0	3	0.159	0.85
Health[e]	5.21	0.85	3	7	5.21	1.11	3	7	5.18	1	3	7	0.014	0.99
Dementia risk[f]	9.56	6.55	0	28.39	9.07	7.34	0	29.82	8.21	4.71	0	16.2	0.498	0.61
Right ear PTA[g]	19.04	15.05	−4.17	59.17	19.23	13.03	−0.83	54.17	16.57	9.92	−2.5	33.33	0.564	0.57
Left ear PTA[g]	19.46	15.37	−3.33	70.83	19.96	13.87	0	53.33	17.52	12.33	−0.83	51.67	0.358	0.70
Better ear PTA[h]	16.71	13.28	−4.17	50	17.39	12.71	−0.83	53.33	14.67	10.06	−2.5	33.33	0.573	0.57
Inter-aural difference	−0.42	8.3	−24.17	34.17	−0.73	6.17	−22.5	10	−0.95	5.85	−18.33	9.17	0.063	0.94
Practice of phy. act.[i]	0.64	0.49	0	1	0.74	0.44	0	1	0.63	0.49	0	1	1.446[t]	0.48
Intensity of phy. act.[j]	2.65	3.66	0	18.75	3.48	4.82	0	21.5	3.5	5.02	0	22	0.451	0.64
Practice of cogn. act.[k]	0.64	0.49	0	1	0.72	0.46	0	1	0.53	0.50	0	1	2.975[t]	0.23
Intensity of cogn. act.[l]	2.41	2.95	0	14	4.24	4.74	0	15.25	2.27	3.34	0	14	3.392	**0.04**
Practice of social act.[m]	0.95	0.22	0	1	0.97	0.16	0	1	1	0	1	1	2.226[t]	0.33
Intensity of social act.[n]	5.38	4.65	0	18.25	5.11	3.20	0.5	13.62	7.07	5.55	0.75	29	2.199	0.12
Practice-related characteristics														
Years of experience[o]	26.04	17.05	8	80	27.89	15.82	5.08	72	31.73	17.99	5.5	65	1.214	0.30
Experience ratio[p]	0.48	0.24	0.11	0.92	0.46	0.21	0.08	0.83	0.6	0.23	0.08	0.91	4.88	**0.01**
Intensity of practice[q]	9.96	8.19	2.5	40	9.92	8.15	1.38	45.6	7.95	7.78	1.8	50.8	0.857	0.43
Age of onset[r]	25.38	18.78	5	62	26	18.56	3	69	14.12	11.32	5	62.5	6.893	**0.00**
Global experience score[s]	0.28	0.44	0.02	2.49	0.17	0.18	0.02	0.71	0.41	0.43	0.02	2.32	4.312	**0.02**

(Continues)

TABLE 1 (Continued)

Abbreviations: M, mean; *n*, number of participants per group; SD, standard deviation of the mean; ♀, female participants. Bold values denote statistically significant group differences.

[a]Number of years of education, standardized. Elementary = 6; High school = 11; CEGEP (general) = 13; CEGEP (technique) = 14; Undergraduate = 16; Master = 18 (includes medical doctors); PhD = 21; Medical doctors with specialization = 23.

[b]Nb. lng. = Number of spoken languages, including native language.

[c]MoCA = Montreal Cognitive Assessment. Higher scores indicate better cognitive functions.

[d]GDS = Geriatric Depression Scale. The GDS includes 15 yes/no questions. The normal score is 3 ± 2, a score of 7 ± 3 suggests a mild depression, and a score of 12 ± 2 indicates a severe depression. No participant scored above 7.

[e]Health = Self-reported physical health status on a scale of 0–7 (0 being the lowest physical health level).

[f]Dementia risk = To control for the risk of dementia, we developed a dementia risk factor (DRF) based on the 2020 *Lancet* Commission for dementia prevention, intervention, and care.[51] The details of the calculation are provided in Supplementary Material 2.

[g]PTA = Pure tone average thresholds measured in decibels at 0.5, 1, 2, 3, 4, and 6 kHz for each ear.

[h]Better ear PTA = Pure tone average thresholds (PTA) at 0.5, 1, and 2 kHz for the better ear, measured in decibels (dB).

[i]Practice of phy. act. = Currently practicing a physical (aerobic) activity regularly (0 = No, 1 = Yes).

[j]Intensity of phy. act. = Number of hour/week dedicated to a physical (aerobic) activity.

[k]Practice of cogn. act. = Currently practicing a cognitive activity regularly (0 = No, 1 = Yes).

[l]Intensity of cogn. act. = Number of hour/week dedicated to a cognitive activity.

[m]Practice of social act. = Currently practicing a social activity regularly (0 = No, 1 = Yes).

[n]Intensity of social act. = Number of hour/week dedicated to a social activity.

[o]Years of experience = Total years of active practice of singing, playing a musical instrument, or practicing a cognitive-motor activity.

[p]Experience ratio (ER) = Ratio between Years of practice and Age.

[q]Intensity of practice = Mean number of hours spent singing, playing a musical instrument, or practicing a cognitive-motor activity (principal activity) each week over the past 5 years.

[r]Age of onset = Age at which singers, instrumentalists, or control participants began to practice their activity.

[s]The global experience score (GES) combines the age of onset of the activity (musical or cognitive motor) and the ratio of practice of the main activity. It consists of the multiplicative inverse of the subtraction between the age of onset and the product of the age of onset and the ratio of practice 1/(AO−(AO x ER)). A higher score indicates that a person started practicing early and has practiced for a large proportion of his/her life.

[t]X^2 of Chi^2 test.

(digit span test), a test of inhibitory control and cognitive flexibility (color-word interference test; CWIT), and a test of auditory selective attention (test of attention in listening; TAiL). The WM and the CWIT tests were completed in a quiet interview room. The hearing assessment and the TAiL were completed in a double-walled sound-attenuated room. The participants wore circumaural headphones (DT 770 Pro, Beyerdynamic Inc.). The tests were run on an ASUS desktop computer (Intel Core i7–6700K CPU; 16 GB RAM) running Windows 10. For the TAiL, the volume was adjusted to a comfortable level prior to beginning each task. The tasks detailed here represent a subset of a larger project.

Hearing assessment and auditory frequency sensitivity (d′)

Pure-tone thresholds in dB HL were measured with a calibrated clinical audiometer (AC40, Interacoustic) at the following frequencies: 0.5, 1, 2, 3, 4, and 6 kHz. These measurements were used to compute a better ear (i.e., lowest thresholds between the two ears) pure-tone average (PTA). The groups did not differ in better ear PTA ($p = 0.52$). Because hearing can affect the performance in auditory cognitive tasks, better ear PTA was included as a covariate in all statistical analyses.

In addition to measuring PTA, we calculated an auditory frequency discrimination score (sensitivity or d′) score based on the signal detection theory framework.[46] Discrimination was calculated from the TAiL. Specifically, we used the trials in the attend frequency (AF) task (see below), which includes 40 trials in which two pure tones are presented. In this case, d′ measures the ability to correctly recognize whether the pairs have the same or a different pitch. The formula used was: Z (hit rate) − Z (false alarm rate), where hit rate is the proportion of identical trials to which subjects responded "identical" and false alarm rate is the proportion of identical trials to which subjects responded "different." A high d′ value indicates a good auditory frequency discrimination capacity. This measure was included as a (very indirect) proxy of musical skills. We expected this measure to be maximally different across musicians and the active control group given its proximity to musical aptitude.

Tests of executive functions

We chose to examine four abilities: processing speed, selective attention, inhibitory control, and verbal WM. These abilities were selected because they are more likely to be associated with musical activities compared to higher-order executive functions such as reasoning, problem-solving, and planning, given the nature of musical activities and because each has been investigated in previous work on the relationship between musical activities and cognition.

Processing speed and auditory attention

Auditory attention was evaluated using a French version of the TAiL,[47] which is based on Posner's Attention System view[48,49] and the Load Theory of attention.[50] The TAiL is a Windows-based computer program that measures two aspects of auditory attention (involuntary orienting and conflict resolution). To capture these abilities, the listener is required to assess the relationship between two sequentially presented tones with respect to either their location (same or different ear), or their frequency (same or different frequency). The TAiL includes three tasks, each involving the diotic presentation of 40 pairs of two pure tones varying in two dimensions: pitch (range is 476–6188 Hz, with the constraint that the spectral gap between any two tones was at least 2.1 equivalent rectangular bandwidths) and location (right ear, left ear). The first task (Cued RT) simply evaluates participants' ability to detect the signal (speeded reaction time [RT]) by pressing a key on a computer keyboard as quickly as possible when the second sound is presented, independently of frequency and location. In the other two tasks (AF and attend location [AL]), participants are asked to indicate as quickly as possible whether two pure tones have the same Frequency or Location (depending on the task), while the other dimension (Frequency or Location) is ignored. A summary of the conditions and associated outcome measures is presented in Supplementary Material 3. The average RTs on correct trials and error rate are calculated for each task. RTs higher or lower than $\pm$ 3 SD from the participant's mean were excluded for each task. Two composite scores were calculated (involuntary orienting and conflict resolution). The involuntary orienting score describes the effect of an incongruence in the unattended dimension on performance (e.g., the effect of a difference in tone location when the listener attends to frequency). A higher value indicates an increase in the cost in dealing with distracting information (increased distraction). The conflict resolution score considers differences between trials with tones varying in one (attended or unattended) dimension (conflict) and those in which tones agree on both or neither dimension (no conflict). A higher value indicates an increase in the cost for resolving conflict.

Inhibitory control

A French version of the DKEFS CWIT[51] was used. The CWIT is derived from the Stroop test;[52] it measures inhibitory control and cognitive flexibility. The test has four conditions: color naming (C1), word reading (C2), inhibition (C3), and inhibition/switching (C4). In each condition, the participant is presented with a single page containing 50 stimuli. In the color naming condition, stimuli are a series of green, red, and blue squares whose color has to be named as quickly and accurately as possible. In the word reading condition, stimuli are black-on-white printed words of color names ("green," "red," "blue"). The participant is asked to read the words aloud as quickly and accurately as possible. In the inhibition condition, the same color names ("green," "red," "blue") are used as stimuli, but printed in a color that does not match their meaning (e.g., the word "red" printed in green). The participant is asked to name the color of the ink of each word as quickly and accurately as possible. In the inhibition/switching condition, color names ("green," "red," "blue") are printed in a mismatching ink as in the inhibition condition. Half the words are in boxes. The participant must name the ink color of each word, except for words presented in a box, which must be read as quickly and accurately as possible. The first two conditions serve to measure fundamental skills of color naming and word reading. The third and fourth conditions measure executive functioning (inhibition and cognitive flexibility). For each of the four conditions, two dependent variables were used: completion time and total number of errors (corrected and uncorrected).

Working memory

WM was assessed with the digit span subtest of a French version of the Wechsler Adult Intelligence Scale (WAIS-III).[53] The test includes forward and backward conditions. On both conditions, the participant is asked to repeat a series of numbers of increasing length (from 2 to 8), either in the same order as the experimenter (forward condition) or in the reverse order (backward condition). The number of correct responses was calculated for each condition, as well as the total score.

Statistical analyses

Data were analyzed using R version 4.0.3.[54] For each variable of interest, outliers, defined as values above or below the interquartile range (IQR), were first removed (Q1 − 1.5 × IQR or above Q3 + 1.5 × IQR). On average, the data contained less than 10% outliers. Next, the cleaned data were inspected using density plots and by calculating kurtosis and skewness measures to ensure that the distributions were normally or relatively normally distributed. The continuous independent variables (Age, Experience) and covariates (hearing, measured as PTA) were mean centered.

Data were analyzed using either linear models (sensitivity) or linear mixed models (TAiL main outcomes, CWIT, and WM). For sensitivity, we used *regsubsets* (part of the *leaps* library[55]) to identify the best regression model using the backward selection option, beginning with the full least squares model containing all predictors, and then iteratively removing the least useful predictor, one at a time. The full model included the factors Group (singers, instrumentalists, and controls), Age (continuous factor), and Experience (continuous factor), as well as hearing and biological sex as covariates: Score ~ Group * Age * Experience + Hearing + Sex. In the R modeling language, the symbol * denotes all main effects and interactions among the variables it connects. Consequently, our model tested for interactions between all variables of interest.

For the TAiL main outcomes, the CWIT and the WM, each model was fitted using the *buildmer*[56] and the *lme4* packages.[57] The *buildmer* package starts with the full model and determines the order of the fixed and random effects that best explains the variance.[58] The effects are then systematically reduced with backward stepwise elimination based on likelihood ratio tests to arrive at the final converging model with the best fit. The full model included the fixed factors Group (singers, instrumentalists, and controls), Task/Condition, Age (continuous factor), and Experience (continuous factor), as well as Hearing and (biological) Sex as covariates and a maximal random effects structure: Score ~ Group * Age * Experience * Condition/Task + Hearing + Sex + (1|SID) + (1|Group).

For all analyses, effects and interactions were decomposed using the *emmeans*[59] and *interactions*[60] packages. The residuals of each model were inspected using QQ plots. Collinearity in the final model was assessed using the *performance*[61] package in R.

TABLE 2 Results for auditory frequency sensitivity (extracted from the attend frequency task of the TAiL).

Predictors	*b*	*β*	*SE*	*CI*	*p*
(Intercept)	2.158	−0.474	0.139	−0.751 to −0.198	**0.001**
Age	−0.023	−0.448	0.081	−0.609 to −0.288	**<0.001**
Group [Instr.]	0.711	0.799	0.197	0.409–1.189	**<0.001**
Group [Singer]	0.183	0.409	0.213	−0.012 to 0.831	0.057
Exp	0.673	0.163	0.167	−0.167 to 0.494	0.329
Group [Instr.] × Exp	−0.329	−0.08	0.198	−0.471 to 0.312	0.687
Group [Singer] × Exp	−2.528	−0.614	0.285	−1.178 to −0.049	**0.033**
Observations	112				
R^2/R^2 adjusted	0.381/0.345				
AIC	260.712				

Note: The reference group is the Control group. Bold values denote statistically significant results.
Abbreviations: *b*, unstandardized estimate; *β*, standardized estimate; CI, confidence interval of *β*; SE, standard error of *β*.

RESULTS

In this section, for the sake of concision, the results for the main analysis are reported only narratively, with inferential statistics reported in the tables and descriptive statistics reported in the Supplementary Materials. The statistics reported in the text complement the main analyses, focusing on the comparison of singers and instrumentalists (not reported in the main tables, where the comparisons are reported for each group against the control group) as well as post-hoc analysis.

Auditory frequency sensitivity (d′)

Auditory frequency sensitivity was calculated from the AF task of the TAiL. The final model did not include hearing or sex. The results (Table 2) indicate statistically significant main effects of Age, Group, as well as an interaction between Group * Experience. The main effect of Age (Figure 2A) on sensitivity revealed that sensitivity was negatively associated with age. The main effect of Group (Figure 2B) was decomposed using pairwise contrasts, which revealed that sensitivity was significantly higher (better) for the instrumentalists compared to the controls, and for the singers compared to the controls. There was no difference between the instrumentalists and the singers (p = 0.071 [not shown in Table 2]). Decomposition of the Group * Experience interaction (Figure 2C) using simple slope analyses revealed that above-average experience was marginally negatively associated with d′ in singers (b = −1.855, SE = 0.97, p = 0.058), with no association in instrumentalists (b = 0.344, SE = 0.44, p = 0.436) or controls (b = 0.672, SE = 0.6876, p = 0.329). This led to a significant difference between Singers and Controls (b = 2.528, SE = 1.172, p = 0.033) and between Singers and Instrumentalists (b = 2.199, SE = 1.062, p = 0.04). Descriptive statistics and marginal means are found in Supplementary Material 3.

Auditory attention and processing speed

Three attention-related constructs were extracted from the TAiL: auditory processing speed, auditory involuntary attention (RT and error rate), and auditory conflict resolution (RT and error rate), for a total of five dependent variables (see Supplementary Material 3 for the marginal means and descriptive statistics). For processing speed, there was no group difference. In contrast, for involuntary attention, we found evidence of a disadvantage for singers while, for conflict resolution, there was evidence of an advantage for instrumentalists. The detailed findings are reported below.

Processing speed

For processing speed, the results revealed only a main effect of Age (b = 0.001, SE = 0.0001, p = 0.009), with processing speed becoming slower with age.

Involuntary attention

For Error rate, the final model did not include hearing or sex. The results (Table 3A) indicate statistically significant main effects of Age and Task, as well as a two-way Age * Task interaction. The main effect of Age on error rate for involuntary attention revealed that distraction was higher in older compared to younger adults. The main effect of Task revealed that distraction was higher in the AF compared to the AL task. Decomposition of the Task * Age interaction using simple slope analysis (Figure 3A) shows an age effect in the AF task, with older adults more distracted than younger adults (b = 0.34, SE = 0.05, p < 0.0001). There was no age effect in the AL task (b = 0.2, SE = 0.05, p = 0.68).

For RT, the final model did not include hearing or sex. The results (Table 3B) indicate a statistically significant main effect of Task as well as a two-way interaction between Task and Age, between Group and

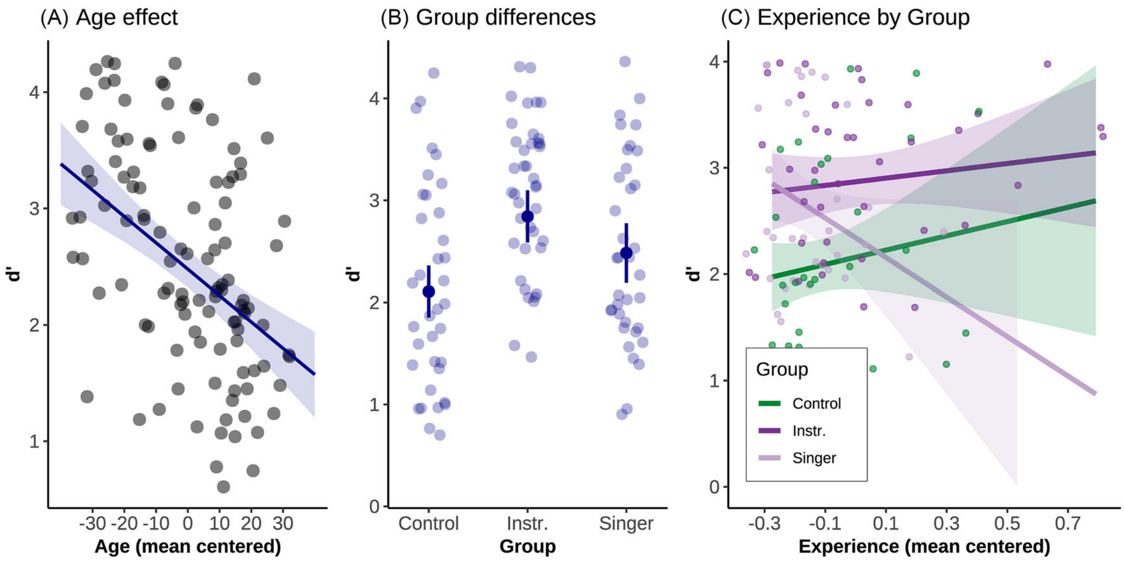

FIGURE 2 Results for the analysis of auditory sensitivity (d') extracted from the AF task of the TAiL. (A) The scatterplot displays the significant effect of Age on d' in this task. The shaded area around the regression line represents the 95% confidence interval of the regression line. Each dot represents one participant. (B) The boxplots display the significant group differences on d'. (C) The scatterplot displays the significant interaction between Group (Instrumentalist, Singer, Control) and Experience on auditory sensitivity. Instr., instrumentalists.

TABLE 3 Results for the auditory involuntary attention construct extracted from the TAiL.

	A. Errors					B. RT				
Predictors	*b*	*β*	*SE*	*CI*	*p*	*b*	*β*	*SE*	*CI*	*p*
(Intercept)	14.64	0.52	0.08	0.37–0.68	**<0.001**	0.13	0.26	0.13	0.00–0.52	**0.046**
Task [AL]	−13.25	−1.04	0.11	−1.26 to −0.82	**<0.001**	−0.08	−0.75	0.12	−0.99 to −0.51	**<0.001**
Age	0.34	0.49	0.08	0.34–0.65	**<0.001**	0	0.11	0.12	−0.13 to 0.36	0.354
Task [AL] × Age	−0.31	−0.46	0.11	−0.68 to −0.24	**<0.001**	0	−0.27	0.12	−0.51 to −0.03	**0.029**
Group [Instr.]						0.01	0.11	0.16	−0.20 to 0.42	0.491
Group [Singer]						0.04	0.31	0.17	−0.03 to 0.65	0.072
Exp						0.05	0.07	0.14	−0.20 to 0.35	0.603
Age × Group [Instr.]						0	0.27	0.15	−0.04 to 0.57	0.084
Age × Group [Singer]						0	0.77	0.18	0.42–1.12	**<0.001**
Age × Exp						0.01	0.3	0.12	0.07–0.53	**0.01**
Group [Instr.] × Exp						−0.07	−0.12	0.16	−0.44 to 0.20	0.46
Group [Singer] × Exp						−0.02	−0.07	0.24	−0.53 to 0.40	0.784
(Age × Group [Instr.]) × Exp						−0.01	−0.27	0.14	−0.55 to 0.02	0.065
(Age × Group [Singer]) × Exp						0	0.18	0.25	−0.31 to 0.68	0.466
Observations	198					186				
R^2/R^2 adjusted	0.394/0.385					0.366/0.318				
AIC	1467.13					−365.667				

Note: The reference group is the Control group. Bold values denote statistically significant results.
Abbreviations: *b*, unstandardized estimate; *β*, standardized estimate; CI, confidence interval of *β*; SE, standard error of *β*.

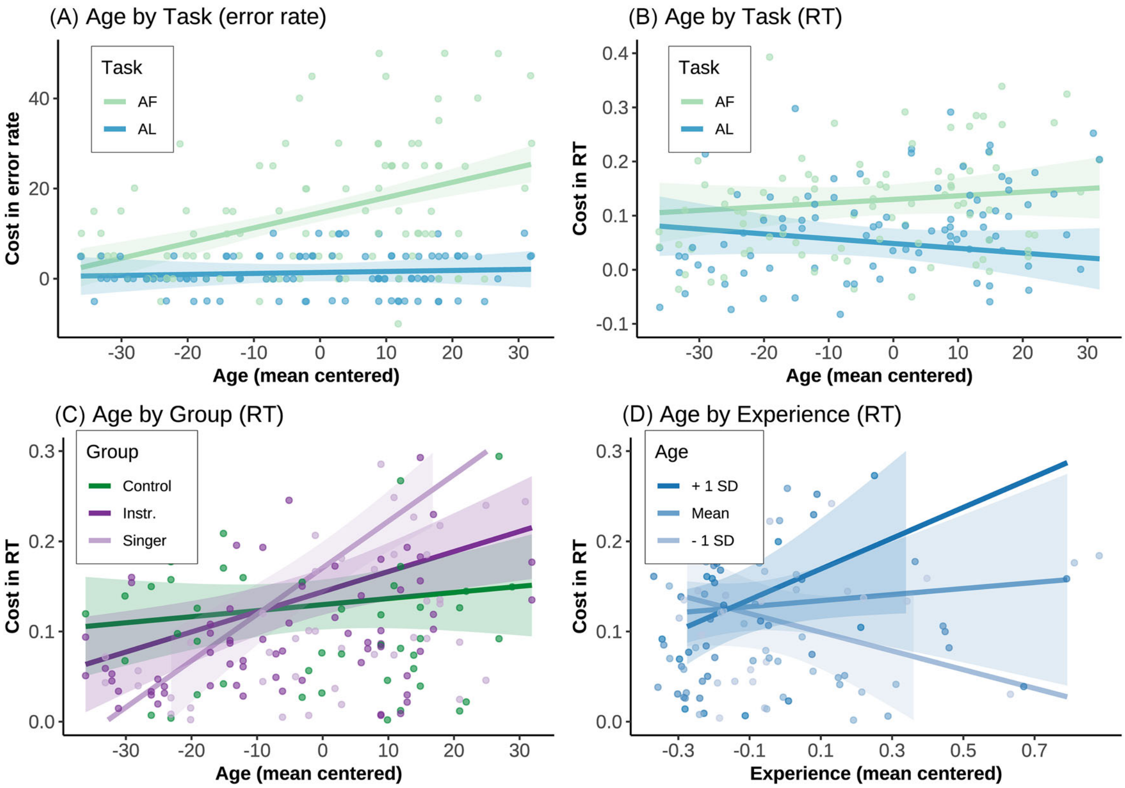

FIGURE 3 Results for the involuntary attention construct extracted from the TAiL. (A) The scatterplot displays the significant interaction between Age and Task (AF and AL) on the cost in error rate. The shaded area around the lines represents the 95% confidence interval of the regression lines. Each dot represents one participant. (B) The scatterplot displays the significant interaction between Age and Task on the cost of RT. (C) The scatterplot displays the significant interaction between Age and Group (Control, Instrumentalist, Singer) on the cost in RT. (D) The scatterplot displays the significant interaction between Age and Experience on the cost in RT.

Age, and between Age and Experience. The main effect of Task revealed that the cost of distraction was higher in the AF compared to the AL task. Decomposition of the Task * Age interaction using simple slope analysis (Figure 3A) shows higher RT with older age in the AF task ($b = 0.0007$, $SE = 0.0007$, $p = 0.354$), and the opposite in the AL task ($b = -0.0009$, $SE = 0.0007$, $p = 0.22$) (Figure 3B). For the Group * Age interaction (Figure 3C), simple slope analyses revealed an effect of Age in Instrumentalists ($b = 0.0022$, $SE = 0.0007$, $p = 0.0026$) and Singers ($b = 0.0052$, $SE = 0.0009$, $p \leq 0.0001$), but not in Controls ($b = 0.0007$, $SE = 0.0007$, $p = 0.3543$). This led to a significant difference in the effect of Age on Singers compared to Controls (Table 3B) and Instrumentalists ($b = -0.00293$, $SE = 0.001029$, $p = 0.0050$ [not shown in Table 3B]) meaning that older singers were disadvantaged compared to older controls. For the Age * Experience interaction (Figure 3D), simple slope analysis revealed that experience was positively associated with cost in RT only in older participants ($b = 0.1705$, $SE = 0.0853$, $p = 0.0472$), meaning that more experience was associated with higher cost in RT.

Conflict resolution

For Error rate, the final model did not include hearing or sex. The results (Table 4A) indicate statistically significant main effects of Age, Task, and Group as well as two-way interactions between Age and Task, Group and Task, and between Age and Group. The main effect of Age on error rate for conflict resolution revealed that the cost of conflict was higher with age. The Task effect revealed more errors in the AF compared to the AL task. The Group effect revealed that instrumentalists had a lower error rate compared to controls (Table 4A) and singers ($b = -6.25$, $SE = 2.2$, $p = 0.0052$ [not shown in Table 4A]). Singers and Controls did not differ from one another (Table 4A). For the Task * Age interaction, simple slope analysis revealed an effect of age in the AF task, with older adults less able to cope with conflicting information than younger adults ($b = 0.438$, $SE = 0.084$, $p < 0.0001$). There was no age effect in the AL task ($b = 0.053$, $SE = 0.084$, $p = 0.527$) (Figure 4A). For the Age * Group interaction (Figure 4B), simple slope analysis revealed an effect of age in all groups, but this effect was lower in the instrumentalists (controls: $b = 0.438$, $SE = 0.084$, $p < 0.0001$; instrumentalists: $b = 0.207$, $SE = 0.094$, $p = 0.029$; singers: $b = 0.489$, $SE = 0.101$, $p < 0.0001$). Finally, decomposition of the Group * Task interaction (Figure 4C) revealed no group differences in the AL task (all p's > 0.05). In contrast, pairwise contrasts in the AF task revealed that the instrumentalists differed significantly from the controls ($b = -13.31$, $SE = 2.89$, $p < 0.0001$) and from the singers ($b = -12.52$, $SE = 3.08$, $p = 0.0003$). The controls and the singers did not differ from one another.

TABLE 4 Results for conflict resolution construct extracted from the TAiL.

	A. CRE					B. CRT				
Predictors	***b***	***β***	***SE***	***CI***	***p***	***b***	***β***	***SE***	***CI***	***p***
(Intercept)	16.81	0.66	0.13	0.40–0.93	**<0.001**	0.07	0	0.07	−0.14 to 0.14	**<0.001**
Task [AL]	−14.48	−0.97	0.19	−1.34 to −0.59	**<0.001**					
Age	0.44	0.57	0.11	0.36–0.79	**<0.001**					
Group [Instr.]	−13.78	−0.94	0.2	−1.34 to −0.54	**<0.001**					
Group [Singer]	−1.69	−0.13	0.2	−0.53 to 0.27	0.53					
Task [AL] × Age	−0.38	−0.5	0.12	−0.74 to −0.27	**<0.001**					
Task [AL] × Group [Instr.]	10.41	0.74	0.29	0.17–1.30	**0.011**					
Task [AL] × Group [Singer]	−0.12	−0.01	0.28	−0.57 to 0.55	0.976					
Age × Group [Instr.]	−0.23	−0.3	0.14	−0.58 to −0.02	**0.035**					
Age × Group [Singer]	0.05	0.07	0.15	−0.23 to 0.36	0.651					
BE						0	0.27	0.07	0.12–0.41	**<0.001**
Observations	186					174				
R^2/R^2 adjusted	0.404/0.374					0.072/0.067				
AIC	1438.224					−397.014				

Note: The reference group is the Control group. Bold values denote statistically significant results.
Abbreviations: *b*, *unstandardized* estimate; *β*, standardized estimate; CI, confidence interval of *β*; SE, standard error of *β*.

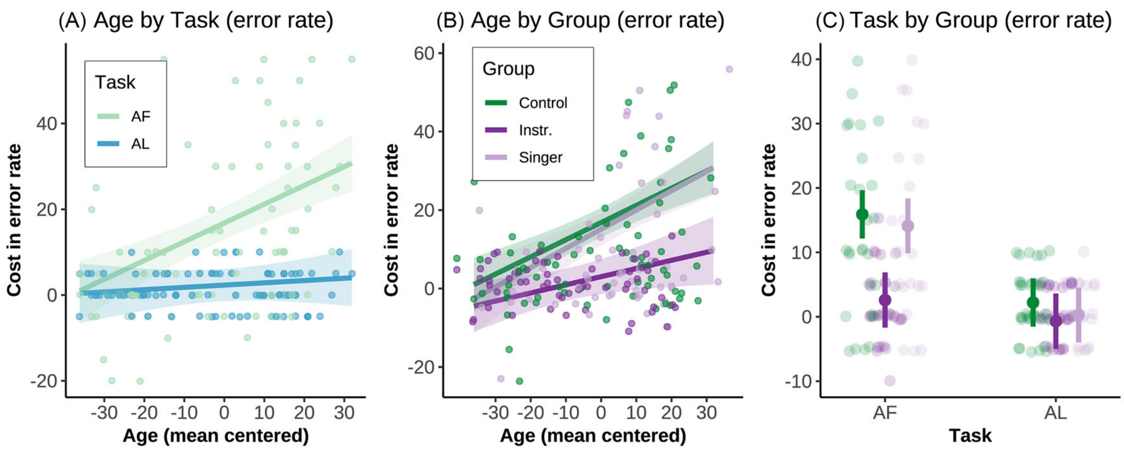

FIGURE 4 Results for the conflict resolution construct extracted from the TAiL. (A) The scatterplot displays the significant interaction between Age and Task (AF and AL) on the cost of resolving conflict in error rate. The shaded area around the lines represents the 95% confidence interval of the regression lines. (B) The scatterplot displays the significant interaction between Age and Group on the cost in resolving conflict in error rate. (C) The boxplots display the significant effect of Group (Instrumentalist, Singer, Control) on the cost of resolving conflict in error rate as a function of Task.

For RT, the final model only included hearing. The results (Table 4B) indicate that higher hearing threshold was associated with worse conflict resolution.

Inhibitory control (CWIT)

For the CWIT, errors and RTs were analyzed (see Supplementary Material 4 for the marginal means and descriptive statistics). There was evidence of a musician advantage, in the form of lower RTs for singers and instrumentalists, independent of age, but with no benefit on accuracy. The detailed findings are reported below.

For Errors, the final model did not include hearing or sex. The results (Table 5A) indicate a statistically significant main effect of Condition, which revealed that conditions 3 and 4 were more difficult than conditions 1 and 2 (see full details in Supplementary Material 4). For Reaction time (RT), the final model shown in Table 3B indicates statistically significant effects of Condition, Age, Group as well as a Condition by Age interaction. The effect of Group (Figure 5A and Table 5) revealed

TABLE 5 Results for the color-word interference test.

	A. Errors					B. RT				
Predictors	***b***	***β***	***SE***	***CI***	***p***	***b***	***β***	***SE***	***CI***	***p***
(Intercept)	0.54	−0.27	0.09	−0.45 to −0.09	**<0.001**	29.77	−0.48	0.05	−0.59 to −0.38	**<0.001**
Condition [C2]	−0.36	−0.31	0.13	−0.57 to −0.06	**0.015**	−7.46	−0.42	0.06	−0.53 to −0.30	**<0.001**
Condition [C3]	0.86	0.74	0.13	0.49–0.99	**<0.001**	23.54	1.29	0.06	1.18–1.41	**<0.001**
Condition [C4]	0.76	0.65	0.13	0.40–0.90	**<0.001**	28.21	1.59	0.06	1.47–1.70	**<0.001**
Age						0.14	0.14	0.04	0.06–0.23	**0.001**
Group [Instr.]						−3.59	−0.2	0.05	−0.30 to −0.10	**<0.001**
Group [Singer]						−3.08	−0.17	0.05	−0.28 to −0.07	**0.001**
Condition [C2] × Age						−0.06	−0.06	0.06	−0.18 to 0.05	0.272
Condition [C3] × Age						0.43	0.43	0.06	0.32–0.55	**<0.001**
Condition [C4] × Age						0.11	0.11	0.06	−0.00 to 0.23	0.055
Observations	396					416				
R^2/R^2 adjusted	0.196/0.190					0.826/ 0.822				
AIC	1163.505					2864.002				

Note: When a row is empty, it means that the term was not included in the final model. The reference group is the Control group. The reference condition is Condition 1. Bold values denote statistically significant results.
Abbreviations: *b*, unstandardized estimate; *β*, standardized estimate; CI, confidence interval of *β*; Conditions, Experiment *conditions* for the tests; C1, color naming; C2, word reading; C3, inhibition; C4, inhibition/switching; DRF, dementia risk factor; Edu, education; Exp, composite score; Int., intensity of practice in the past 5 years; SE, standard error of *β*.

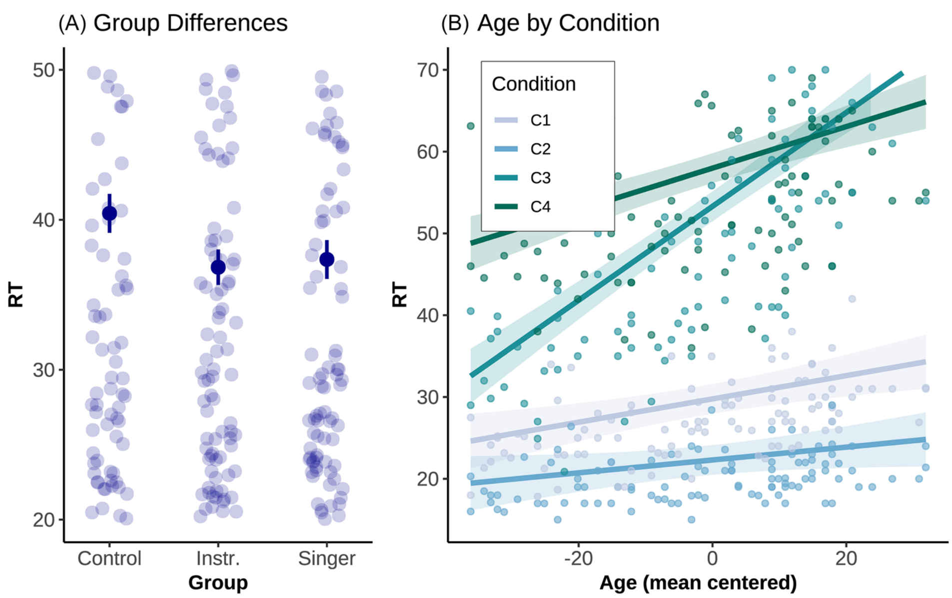

FIGURE 5 Results for the color-word interference test. (A) The boxplots illustrate the significant Group differences on RT. (B) The scatterplot illustrates the significant interaction between Age and Condition on RT. The shaded area around the lines illustrates the 95% confidence interval of the regression line. Each dot represents one participant.

that instrumentalists and singers were significantly faster than controls but did not differ from one another (b = 0.52, SE = 0.89, p = 0.5630; not shown in the table). The effect of Condition revealed that all conditions differed from one another ($p < 0.0001$; C2<C1<C3<C4). The effect of Age revealed that RT was higher in older participants. The Age by Condition interaction (Figure 5B) revealed that though RT increased as a function of age in all conditions, the slope of this relationship was steeper in C3 and C4 (C1: b = 0.14, SE = 0.04, p = 0.0006; C2: b = 0.08, SE = 0.05, p = 0.0577, C3: b = 0.57, SE = 0.04, p <0.0001, C4: b = 0.25, SE = 0.04, p <.0001).

TABLE 6 Results of the working memory test.

Predictors	*b*	*β*	*SE*	*CI*	*p*
(Intercept)	9.2974	0.4615	0.0991	0.2662–0.6568	**<0.001**
Task [Backward]	−3.4019	−1.3541	0.0972	−1.5458 to −1.1624	**<0.001**
Group [Instr.]	0.5254	0.2091	0.1189	−0.0253 to 0.4436	0.08
Group [Singer]	1.0849	0.4318	0.1227	0.1899–0.6737	**0.001**
Age	−0.0204	−0.1459	0.0501	−0.2447 to −0.0472	**0.004**
Observations	214				
R^2/R^2 adjusted	0.504/0.494				
AIC	862.627				

Note: The reference group is the Control group. Bold values denote statistically significant results.
Abbreviations: *b*, *unstandardized* estimate; *β*, standardized estimate; CI, confidence interval of *β*; SE, standard error of *β*.

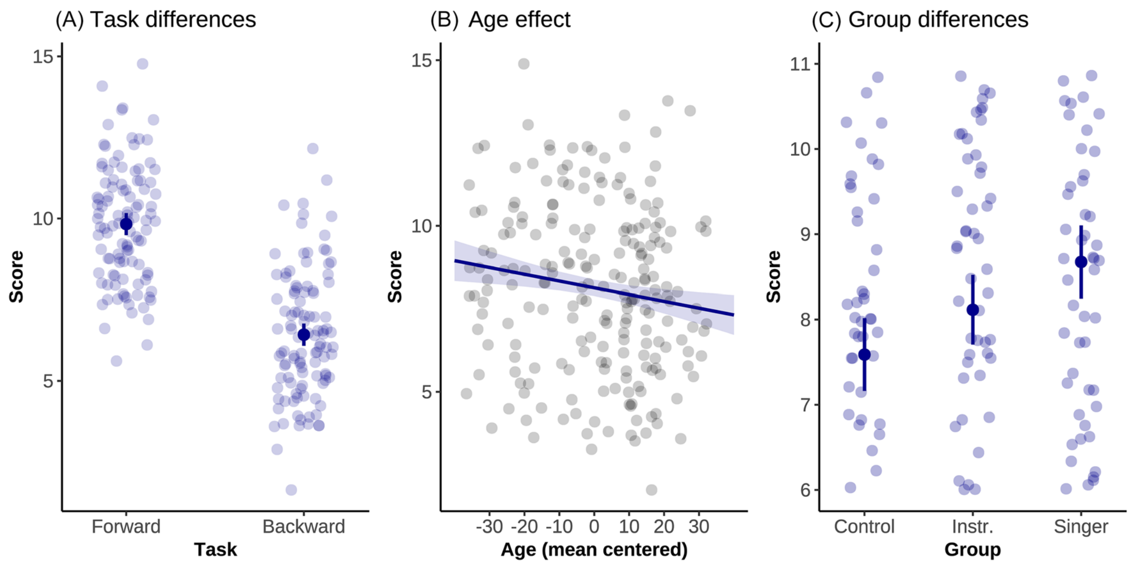

FIGURE 6 Results for the working memory test. (A) The boxplots display the significant task (forward/backward) difference on WM scores. Each dot represents one participant. (B) The scatterplot displays the significant effect of Age on overall working memory scores. The shaded area around the regression line represents the 95% confidence interval of the regression line. (C) The box plots display the significant group differences on score. Instr., instrumentalists.

Working memory

The scores of the forward and backward conditions were analyzed (see Supplementary Material 5 for the descriptive statistics and estimated marginal means). There was evidence of an advantage for singers compared to controls and instrumentalists.

The final model did not include hearing or sex. The results (Table 6) indicate statistically significant main effects of Age, Task, and Group. The main effect of Task (Figure 6A) revealed that the forward task was easier than the backward task. The main effect of Age revealed a negative association between WM performance with age (Figure 6B). The main effect of Group revealed that singers were better than controls (Figure 6C). No other differences reached significance.

DISCUSSION

The overall objective of the current study was to examine four core components of executive functions (processing speed, selective attention, inhibitory control, and WM) in healthy adult amateur singers and amateur instrumentalists in comparison to people involved in nonmusical cognitive-motor activities as part of a noncausal cross-sectional study. This comparison is critical to tease apart the actual contribution of musical activities to executive functions from the contribution of other kinds of activities. As can be seen in Figure 7, the results support our hypothesis regarding age, with broad age-related differences that are not simply reflected in a slowing in processing speed, but instead included increased error rates reflecting increased distractibility, more difficult management of conflicting information,

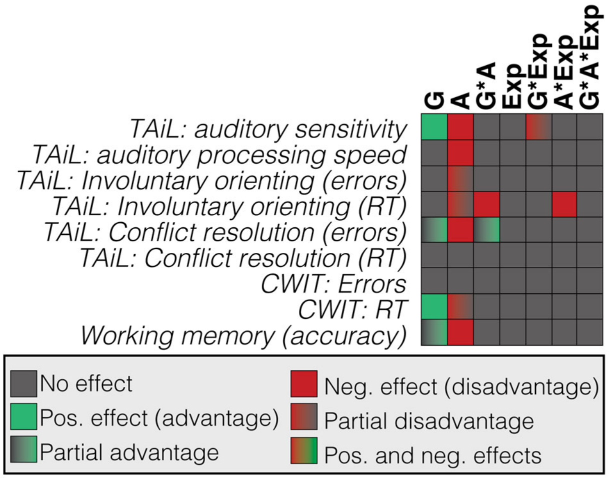

FIGURE 7 Summary of the main findings. A = age, G = group, Exp = experience. Beneficial effects are colored in green, detrimental ones are colored in red. Gray indicates the absence of an effect. For column A, a partially red cell indicates that the effect of Age was not found in all conditions (the A*C column is not displayed for the sake of clarity). For columns G and G*A, a green cell indicates an advantage for both musician groups (instrumentalists and singers) and a partially green cell indicates an advantage for one of the two groups.

and reduced WM capacity. Furthermore, our results support the general hypothesis that the practice of amateur-level musical activities is associated with better executive capabilities in adulthood compared to active controls in certain domains but not globally. Finally, our hypothesis that the amount of experience rather than the type of activity is the driving factor for these effects was not supported. These findings are discussed below.

Musician advantage in executive functions?

The cognitive reserve hypothesis proposes that environmental factors can predict—to a certain degree and in interaction with each person's genetic makeup—responses to brain disease, with increased reserve associated with reduced cognitive aging.[62–64] Based on this hypothesis, we predicted that there would be benefits associated with practicing musical activities, operationalized in terms of group differences (musicians> controls). Furthermore, we expected these benefits to be associated with age (interactions between Group and Age), reflecting a difference in the rate of age-related decline, consistent with Salthouse's differential preservation hypothesis.[9,65] Our results are not consistent with this hypothesis, as most of the advantages were independent of age. This suggests that the differences between amateur musicians and nonmusicians are stable throughout the adult lifespan, consistent with a recent study from our group with an independent cohort.[66] This suggests that at any age, musicians perform significantly better than nonmusicians on specific tests, but that the rate of change with age is not diminished by the practice of musical activities. Although this study is not causal in nature, these results suggest that practicing an amateur-level musical activity does not reduce cognitive aging, though it may provide cognitive reserve.

Among the age-independent advantages was a better WM for singers but not instrumentalists. Improvements on a verbal short-term memory task were reported by a study conducted in older adults who took part in a 12-week group-singing program.[20] Relatedly, others have found a positive association between WM and singing ability in a group of singers aged 17–59 years.[67] A lack of benefit on verbal short-term and WM in older instrumentalists, measured using the digit span test, has been reported in longitudinal[31–33] and cross-sectional[29,30] studies. Taken together, these results suggest that singing may be positively associated with verbal WM. A potential explanation is that, because only singing involves the memorization of verbal content (lyrics), which may enhance WM capabilities, an association with verbal WM represents a nearer transfer, while it would represent a farther transfer for instrumentalists. Far transfers are rare and controversial.[68,69]

One domain that appears to be responsive to musical training is inhibitory control/conflict resolution. We found evidence of a positive association between music training and inhibitory control in both the TAiL and the CWIT. First, instrumentalists (independent of their age) showed reduced cost of conflict resolution in terms of errors. Second, the effect of age on conflict resolution was lower in instrumentalists (cost in error rate). Last, both instrumentalists and singers showed higher scores in the CWIT. Together, these findings suggest better inhibitory control in amateur musicians, consistent with results from previous longitudinal[31] and cross-sectional[11,17] studies conducted in older adults. This is also consistent with a recent study in which better inhibitory control was found in amateur singers compared to controls (nonmusicians).[66] A benefit for instrument players has also been reported using the Trail Making Test,[70] which also involves cognitive flexibility,[11,16,18,29] and the Simon task in older[17] or younger musicians.[71,72] It should be noted, however, that some studies using similar tasks have failed to report such benefit in instrumentalists[33,73,74] or singers[20,21,28] of different ages, suggesting potential cohort effects, or, as suggested by others, that there is no good evidence of causality between music training and executive functions.[68]

One domain that did not show a positive association with musical training is distractibility (involuntary attention orientation). While instrument players showed no evidence of a lower distractibility, singers were significantly more distracted (in terms of cost in RT) than instrumentalists and controls. This is consistent with a previous study that was based on an independent sample.[66] It is difficult to interpret these findings. Choirs are social activities that provide intense multisensory stimulation in a social context. Exposure to complex environments can have a distracting effect, which could explain the present finding. Another possibility is that paying attention to other voices in the choir, and to the choir lead, is needed to perform optimally, as synchrony between singers is needed to produce an optimal melody. It is also possible that people with higher distractibility join choirs. Additional data is needed to disentangle these possibilities.

In sum, our results reveal circumscribed musicians' advantage in terms of increased WM capacity (singers) and greater inhibitory control (singers and instrumentalists), but not a broad association in a subset of executive functions that we consider to be closely associated with musical training, thus arguably reflecting near transfers. Importantly, a musician's advantage in our study reflects an advantage specific to the practice of a musical activity, because our control group was active, both cognitively and physically, unlike what has been done in most studies, for example, Refs. 14, 21, 27, 29, 74. The group differences that we report are unlikely to be associated with nonspecific aspects of musical activities (for instance, the social component). Nevertheless, given the cross-sectional nature of our study, no conclusion can be drawn regarding a potential causal effect of music training on executive functions. Indeed, there may be pre-existing differences (e.g., genetic) between individuals who choose to play a musical instrument or sing (i.e., those with high musical aptitudes will naturally engage in musical activities) and those who do not engage in musical activities. While we controlled for many such pre-existing differences, our results await empirical replication as part of randomized training studies that would include a careful assessment of initial musical aptitude (which is not necessarily associated with musical training[39]). Finally, there was only one instance of a reduced age effect in instrument players that was not found in singers, suggesting that musical training does not reduce the rate of age-related cognitive decline.

Does experience matter?

Based on the available empirical evidence and theoretical considerations, we predicted that the amount of experience—as a proxy of performance—rather than the type of musical activity would be the driving factor for the association between executive capabilities and musical activities. This hypothesis was not confirmed. We found no significant effect of experience alone. Experience interacted with Groups on d′ (singers with higher experience had worse performance), and it interacted with age on involuntary attention (RT) (older participants with more experience had a worse performance than those with low experience). These interactions suggest that having more experience is not always beneficial. In a previous study, with an independent sample, we found a similar relationship between experience, auditory WM, and processing speed.[66] One possibility is that the longer one trains a specific skill, the more proficient in that particular skill one becomes.[75] This expertise could limit the potential for transfer because of the high specificity of the processes—or operators in the PRIMs model[76]—involved, a phenomenon that has been referred to as the "curse of specificity."[77] In sum, the present finding suggests that, to reach their optimal transfer potential, amateur musicians do not need to have decades of experience or an early age of onset. From a perspective of preventing cognitive decline, this is key, because long-lasting interventions have limited applicability.

Instrumentalists versus singers

Another important and novel aspect of this work is the comparison of amateur instrumentalists and singers. We did not find a clear advantage for one musician group over the other. Both groups showed better conflict resolution capabilities compared to controls. Instrumentalists benefited a little more, showing reduced cost in terms of accuracy as well as RT. Singers, on the other hand, showed better accuracy in a WM task. However, they were more distracted than musicians in the auditory attention test. These findings reveal no clear overall advantage for instrumentalists compared to singers, but it suggests that the association between different musical activities and executive functions may be partly distinct.

One possibility is that our groups were not "pure" enough, in the sense that if instrumentalists sing and singers play an instrument, then the finding of limited group differences is to be expected. However, while some of the instrumentalists did sing, and some singers did play a musical instrument, the number of participants with both instrument and singing practice in the past 5 years was low (only 5/43 instrumentalists sang, and 9/39 singers played a musical instrument), and the main musical activity was dominant in each participant. Instrumentalists had a ratio of instrument playing (intensity of practice for the main activity/intensity of practice for all musical activities) of 0.99 in the past 5 years and one of 0.96 for the lifetime, and singers had a ratio of singing of 0.96 in the past 5 years and one of 0.91 for the lifetime. Hence, our groups were distinct in terms of their musical practice. Importantly, the instrumentalists and singers were comparable in terms of their education level, hearing, MoCA, dementia risk factor, and social activities. Thus, the finding of limited differences between instrumentalists and singers suggests that the association between music-making activities and executive functions may be partly general, partly activity-specific, but does not appear to be overall greater for either instrumentalists or singers. Although this result awaits replication, it is important, as it suggests that executive benefits may be achieved in certain domains through the practice of any music-related activity, leaving for people seeking an executive workout the choice of which activity to engage in to achieve this goal.

Limitations

The main limitation of this study is its cross-sectional nature, with the inherent selection bias associated with this design. Despite thoroughly controlling for group differences in social, physical, and cognitive activities, and cognitive level, there could be pre-existing differences, including in cognitive aptitudes not assessed in this study and musical aptitudes (e.g., pitch discrimination, beat perception, melody imitation), between those who enroll in musical activities compared to those who do not, and this could be associated with differences in executive functions, which could be the reason for the advantages seen in musicians in the present study. This also means that enrolling in musical activities for people with low musical aptitudes may not lead to enhanced executive functions. Another limitation is related to our approach of using a continuous sampling of age, which can be seen as a limitation given the relatively limited sample size. However, this method has the advantage of avoiding the artificial categorization of age into young and older adults. Nevertheless, our results warrant replication with a larger sample or via a carefully executed randomized training experiment.

CONCLUSIONS

The results of this study suggest specific musicians' advantages in executive functions, in terms of inhibitory control/conflict resolution, although the results do not support the notion of a global advantage in musicians. Critically, we showed that amateur musicians, even those with relatively late age of onset (especially the singers), show advantages on several executive domains compared to a carefully matched group of adults actively engaged in nonmusical activities. These findings are important for guiding future randomized cognitive training studies which should integrate measures of experience and proficiency to validate the current findings. An important dimension of the present study is the choice of amateur rather than professional musicians, that is, people engaged in musical activities as a hobby. Most previous studies recruited professional musicians. Yet, understanding the impact of amateur musical activities is critical because these forms of activities are much more accessible than professional-level activities, especially singing, thus increasing the potential impact of our results. A recent study revealed that Canada is home to 28,000 choirs, with 3.5 million people participating, representing about 10% of the population.[78] Clearly, musical hobbies are prevalent in the general population, therefore, understanding their impact should be a national priority given the fast aging of populations in Canada and in many other countries.

AUTHOR CONTRIBUTIONS

Marilyne Joyal: Project administration; investigation; methodology; supervision; validation; writing—reviewing and editing. **Alexandre Sicard**: Formal analysis; data curation; writing—reviewing and editing. **Philip L. Jackson**: Funding acquisition; writing—reviewing and editing. **Virginia Penhune**: Conceptualization; funding acquisition; writing—reviewing and editing. **Pascale Tremblay**: Conceptualization; funding acquisition; methodology; supervision; resources; project administration; formal analysis; visualization; data curation; writing—original draft preparation.

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CONFLICT OF INTEREST STATEMENT

The authors report no conflict of interest.

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