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Differences in a Musician's Advantage for Speech-in-Speech Perception Based on Age and Task

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ABSTRACT

Purpose: This study investigates the debate that musicians have an advantage in speech-in-noise perception from years of targeted auditory training. We also consider the effect of age on any such advantage, comparing musicians and nonmusicians (age range: 18–66 years), all of whom had normal hearing. We manipulate the degree of fundamental frequency (f_o) separation between the competing talkers, as well as use different tasks, to probe attentional differences that might shape a musician's advantage across ages.

Method: Participants (ranging in age from 18 to 66 years) included 29 musicians and 26 nonmusicians. They completed two tasks varying in attentional demands: (a) a selective attention task where listeners identify the target sentence presented with a one-talker interferer (Experiment 1), and (b) a divided attention task where listeners hear two vowels played simultaneously and identify both competing vowels (Experiment 2). In both paradigms, f_o separation was manipulated between the two voices (Δf_o = 0, 0.156, 0.306, 1, 2, 3 semitones).

Results: Results show that increasing differences in f_o separation lead to higher accuracy on both tasks. Additionally, we find evidence for a musician's advantage across the two studies. In the sentence identification task, younger adult musicians show higher accuracy overall, as well as a stronger reliance on f_o separation. Yet, this advantage declines with musicians' age. In the double vowel identification task, musicians of all ages show an across-the-board advantage in detecting two vowels—and use f_o separation more to aid in stream separation—but show no consistent difference in double vowel identification.

Conclusions: Overall, we find support for a hybrid *auditory encoding-attention account* of music-to-speech transfer. The musician's advantage includes f_o, but the benefit also depends on the attentional demands in the task and listeners' age. Taken together, this study suggests a complex relationship between age, musical experience, and speech-in-speech paradigm on a musician's advantage.

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In everyday life, listeners often contend with sources of competing background noise to hear their interlocutor, known as speech-in-noise perception. A common, challenging listening scenario is trying to comprehend a talker when there are other overlapping speech signals or speech-in-speech perception (e.g., listening to a friend in a crowded restaurant). Yet, for young adults with normal hearing, the auditory system is surprisingly robust to environmental perturbations (Assmann & Summerfield, 2004). For example, listeners can use small differences in fundamental frequency (f_o; Assmann & Summerfield, 1990; Bregman, 1990; Summers & Leek, 1998), onset timing (Lee & Humes, 2012), and vowel spectral peaks (Assmann & Summerfield, 1989) to separate competing speech signals.

A growing body of work has examined the extent to which musical training might drive changes in auditory perception (Bidelman & Yoo, 2020; Kraus & Chandrasekaran,

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2010; Münte et al., 2002; Strait & Kraus, 2014). However, the search for a musician's advantage in speech-in-noise has produced decidedly mixed results in prior work (for a review, see Coffey et al., 2017). On the one hand, a cohort of studies have found a musicianship advantage for perceiving speech-in-speech, when a target talker's productions are obscured by one or more other talkers (Başkent & Gaudrain, 2016; Clayton et al., 2016; Kaplan et al., 2021; Morse-Fortier et al., 2017; Parbery-Clark, Skoe, Lam, & Kraus, 2009; Parbery-Clark et al., 2011; Slater & Kraus, 2016; Zendel & Alain, 2012; Zendel et al., 2015). For example, musicians show higher accuracy in recognizing words embedded in a four-talker babble (e.g., Parbery-Clark, Skoe, Lam, & Kraus, 2009). Yet, other studies, sometimes even using identical paradigms, have shown no difference between musicians and nonmusicians (e.g., Anaya et al., 2016; Başkent et al., 2018; Boebinger et al., 2015; Couth et al., 2020; Deroche et al., 2017; Madsen et al., 2017; Mandikal Vasuki et al., 2016; Mussoi, 2021; Ruggles et al., 2014; Yeend et al., 2017). That we see differences across studies suggests that the musician's advantage may be relatively small and overwhelmed by between-listener and task-related variation (see Supplemental Material S1 for overview). Here, we will discuss possible sources of variation in any musician's advantage in the perception of speech-in-speech, both within and between listeners.

Age-Related Variation

Age-related changes are perhaps one of the largest contributors to between-speaker variation in speech-in-speech perception. Older adults (OAs) with hearing loss face additional challenges in speech-in-speech perception (Arehart et al., 1997; Dubno et al., 1984; Helfer & Wilber, 1990; Lee & Humes, 2012; Lentz & Marsh, 2006; for a review, see Helfer et al., 2017). Even OAs with normal hearing show increased difficulties perceiving a talker in the presence of a background talker, an effect attributed to age-related declines in centralized auditory processing, attention, and working memory (Heidari et al., 2020; Helfer & Freyman, 2014; for a review, see Akeroyd, 2008). For example, OAs (ages 67–81 years) show greater interference by linguistically meaningful maskers than younger adults (YAs; ages 17–19 years), suggesting that speech-in-speech difficulties might be attributed to possible declines in auditory inhibition (Tun et al., 2002). Age-related declines in speech perception also start to emerge in middle adulthood (Bergman et al., 1976; Helfer, 2015; Helfer & Jesse, 2021). For example, Başkent et al. (2014) found worse speech reception thresholds for adults ages 51–63 years (all of whom had normal audiometric thresholds) than YAs (ages 19–26 years) when listening to sentences with a competing talker. Accordingly, there is much interest in determining what types of experience might improve speech-in-speech perception across age, such as via musical training.

There have been some comparisons of musicians and nonmusicians for specific age groups that suggest age-related factors in an advantage. For example, Başkent et al. (2018) tested adolescents (ages 11–14 years) and found no difference between the groups in perceiving sentences with a one-talker interferer. Yet, using the identical paradigm, Başkent and Gaudrain (2016) found a musician's advantage in YAs (ages 19–27 years), suggesting that the advantage might emerge with development. Indeed, there is other support for a YA musician's advantage: Bidelman and Yoo (2020) found that YA musicians (ages 19–33 years) showed higher accuracy in recognizing a target sentence amidst an increasing number of competing talkers (or "maskers"). Others have provided some evidence for a later-emerging advantage. Comparing adults across a wide age range (from ages 19–91 years), Zendel and Alain (2012) observed that nonmusicians have a steeper decline in keyword perception in four-talker babble with increasing age, relative to musicians. For YA listeners, on the other hand, musicians' and nonmusicians' thresholds appear to be largely overlapping until after 40 years of age (see Zendel & Alain, 2012, Figure 4, p. 415). Similarly, Tierney et al. (2020) found less of an age-related decline for musicians (ranging from ages 18 to 66 years) in perceiving a target sentence amidst a one-talker interferer. Together, these findings suggest that a musician's advantage for speech-in-speech perception might not emerge until young adulthood or middle age, possibly due to cumulative years of musical experience.

The Role of Task on a Musician's Advantage

Most studies testing a musician's advantage for speech-in-speech perception examine a single type of task (e.g., sentence or words in multitalker babble), and the task most commonly tests selective attention, wherein listeners hone in on one target speaker while ignoring competing talker (e.g., Boebinger et al., 2015; Parbery-Clark et al., 2011; Zendel & Alain, 2012). This requires that listeners are able to (a) separate the talkers and (b) direct their attention to the target while inhibiting interfering speech. Indeed, a growing body of work has shown that musicians often show enhanced selective auditory attention (e.g., Medina & Barraza, 2019; Strait & Kraus, 2011; Zendel & Alain, 2014), which might underlie their improvements in speech-in-speech perception.

While less studied than selective attention, it might also be illuminating to compare musicians and nonmusicians in tasks where attention is divided, such as when listeners are asked to recognize information from multiple speech streams simultaneously. For example, in double vowel paradigms, listeners hear two vowels simultaneously and are asked to identify both vowels they heard. Moreover, such a divided attention task might be particularly relevant for detecting a musician's advantage. Double vowel perception has been shown to be especially difficult for OAs (Vongpaisal & Pichora-Fuller, 2007), thought to be due to age-related difficulties in attending to multiple sources of incoming information at once. Meister et al. (2013) directly compared selective and divided attention by younger (ages 18–27 years) and middle-age/older (ages 58–79 years) listeners: In one task, participants were asked to repeat words from a target talker (selective), while in another task, they were asked to repeat words from two talkers (divided). They found no difference by age in the selective attention task, but a sizable decrease for older listeners in the divided attention task. Therefore, we might be better able to detect differences in a musician's advantage in the current study in tasks that require divided attention.

Role of f_o Difference Between Voices in a Musician's Advantage

In addition to age and task, the properties of the target and competing voice(s) themselves might play a role in a musician's advantage. As mentioned, listeners use f_o separation between voices to tease them apart, a critical first step in speech-in-speech perception (auditory stream separation; Bregman, 1990). f_o is related to the psychoacoustic perception of pitch; as f_o increases, listeners perceive an increase in pitch. Musicians, in particular, receive specific instruction, feedback, and training related to the accurate perception and discrimination of pitch (Schlaug, 2011), and musicians have higher perceptual acuity in perceiving small differences in f_o than nonmusicians (Bianchi et al., 2016; Kishon-Rabin et al., 2001; Micheyl et al., 2006). While prior studies examining a musician's advantage compare talkers (e.g., a male target with a female masker in Boebinger et al., 2015), the majority do not control for differences in f_o between the voices. This might be one source of the mixed results observed. For example, previous studies using large f_o differences (e.g., $\Delta f_o = 0$, 2, 4, 6, & 8 semitones [STs][1] in Madsen et al., 2017) show no difference for musicians and nonmusicians. Furthermore, natural fluctuations of f_o in speech intonation support stream segregation, making additional f_o separation unnecessary if f_o contours are sufficiently large (Darwin et al., 2003). When controlling for both f_o separation and fluctuation, Başkent and Gaudrain (2016) found evidence for a musician's advantage in younger listeners (ages 19–27 years) perceiving a target sentence with a one-talker interferer. Similarly, Cohn (2018b) found that younger musicians (ages 18–40 years) showed an advantage in perceiving a sentence with a one-talker interferer (the same talker) when controlling for f_o separation and fluctuation. An additional consideration, in the mixed results for the musician's advantage, is that listeners' ability to use f_o separation between voices changes by age. For example, Vongpaisal and Pichora-Fuller (2007) found that younger listeners (ages 21–34 years) could tease apart and identify double vowels at smaller f_o differences than older listeners (ages 65–83 years). Thus, f_o separation is a particularly relevant feature to examine when investigating changes in any potential musicianship advantage by age.

Theoretical Accounts of a Possible Musician's Advantage

There are varying accounts for possible mechanisms underlying the purported musician's advantage. *Shared auditory encoding* accounts (Bidelman et al., 2014; Shahin, 2011) propose that musical experience tunes how the brain perceives auditory features shared by both music and speech. For example, musicians show an improved frequency following response, indicating improved subcortical encoding of f_o, for music and speech sounds (Bidelman & Krishnan, 2010; Wong et al., 2007). Others have shown that musicians show higher fidelity representations of harmonics in speech (Tierney et al., 2015) and duration of speech properties (e.g., voice onset time in Kühnis et al., 2013). Some *shared auditory encoding* accounts place restrictions on what features could transfer from music to speech. For example, Patel (2011, 2012, 2014) proposes that only features that have more fine-grained distinctions in music than in speech are possible candidates. Pitch is thought to be one such feature, as tonal distinctions are argued to be more fine-grained in music than in speech (Zatorre et al., 2002; while the converse is argued for spectral distinctions). In the current study, a *shared auditory encoding* prediction is that musicians show better speech-in-speech perception on the basis of f_o differences across tasks.

Domain-general attention accounts (Besson et al., 2011; Strait & Kraus, 2011) propose that musical training strengthens general attentional mechanisms; that is, the benefits that come with musical training are not limited to the auditory domain. For example, Medina and Barraza (2019) found that musicians showed better performance than nonmusicians, and that this was consistent with better executive attention in a vision task wherein they had to ignore an irrelevant stimulus (all YAs; 17–33 years of age). Similarly, Tierney et al. (2020) found a relationship between an auditory attention task—attending to one stream of tones while inhibiting another—and improved speech perception in the presence of a one-talker interferer. In the current study, a *domain-general attention* prediction is for an across-the-board musician's advantage in tasks that require greater attentional demands (e.g., divided attention).

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[1] An ST is the relative distance between two tones (in log-2 Hz) in Western musical scales (e.g., C to a C#).

A hybrid *auditory encoding-attention* account (Kraus & Nicol, 2014; Kraus & White-Schwoch, 2015) would predict an interaction between enhanced subcortical encoding of speech and top-down cognitive processes. For example, Kraus and Nicol (2014) conceive of auditory training, including musical experience, as an attentional "mixing board," increasing subcortical representation for certain types of inputs, while dampening others. In the current study, finding an advantage only for a cue (e.g., f_o) in one type of attentional task, but not in the other, would be in line with a hybrid *encoding-attention* account.

Current Study

The current study consists of two speech-in-speech experiments to test for a musician's advantage: (a) competing sentences and (b) competing vowels. In both, we use identical voices for both target(s) and masker and manipulate the degree of f_o separation for competing talkers, holding f_o fluctuation constant by monotonizing the stimuli. For the handful of previous studies that do control for f_o, we see that sufficiently large f_o separation levels often show no musician's advantage (e.g., Δf_o = 0, 2, 4, 6, & 8 ST in Madsen et al., 2017; Δf_o = 0, 2, 8 ST in Deroche et al., 2017). Therefore, we selected smaller f_o separation (Δf_o = 0, 0.156, 0.306, 1, 2, 3 ST) based on the just-noticeable-difference (JND) in f_o in pure tones for musicians (Δf_o = 0.156 ST) and nonmusicians (Δf_o = 0.306 ST; Kishon-Rabin et al., 2001; see Supplemental Material S2. for ST calculations). While the majority of prior experiments examine one type of attentional demand and often one age group, this present study[2] tests how musicians and nonmusicians (ranging in age from 18 to 66 years) use f_o differences across two speech perception tasks varying in attentional demands: (a) a selective attention task where listeners identify the target sentence presented with a one-talker interferer (Experiment 1), and (b) a divided attention task where listeners hear two vowels played simultaneously and identify both competing vowels (Experiment 2). This cross-sectional approach can reveal if listeners, varying in musicianship and age, differ in their performance based on f_o separation of the voices across varying attentional demands.

General Method

Participants (Experiments 1 and 2)

A total of 72 participants were recruited for the study, consisting of native English speakers in four groups based on their age and whether they received musical training or not. Based on related work showing an advantage emerging around 40 years of age (Zendel & Alain, 2012), we recruited YA (YA < 40 years) and middle-aged/OA (≥ 40 years) age groups. Musicians were recruited if they had at least 9 years of musical training and were practicing on a weekly basis at the time of the study. Nonmusicians were recruited if they reported having minimal musical training (< 1 year in duration that had occurred at least 7 years ago, following Parbery-Clark, Skoe, Lam, & Kraus, 2009). While participants were recruited based on not having "hearing impairments or any auditory disorders," *n* = 2 participants (*n* = 1 OA musician, *n* = 1 OA nonmusician) were excluded as they did not pass an in-lab pure-tone hearing screening (described in General Procedure section in more detail). Participants who did not complete both Experiments 1 and 2 (*n* = 15 participants[3]) were also excluded from analysis (described in more detail in Stream Separation section).

The retained participants consisted of *N* = 55 adults, ranging in age from 18 to 66 years (median age = 40.0 years), who completed both experiments. Musician (*n* = 29) and nonmusician (*n* = 26) groups did not differ in terms of age or years of education (shown in Table 1).

Musicians had an average of 26.1 years of musical training (*SD* = 15.7, range: 9.5–63 years) and practiced on a weekly basis at the time of the study ($\bar{x}$ = 10.7 hr/week, *SD* = 7.9). Musicians varied in the family of their primary instrument(s): *n* = 3 brass (e.g., trombone, French horn, trumpet), *n* = 8 keyboard (e.g., piano), *n* = 8 string (e.g., violin, guitar, cello, double bass), *n* = 10 woodwind (e.g., flute, clarinet, saxophone). Slightly more than half of musicians (58.6%) additionally had voice training (*n* = 17). None of the subjects reported prior experience with a tonal language (e.g., Mandarin Chinese, Thai, Punjabi). All participants completed informed consent in accordance with the University of California, Davis Institutional Review Board.

General Procedure

Participants came into the lab for an hour-long session in which they completed both Experiment 1 (Experiment 1: Sentence Perception With a Competing Sentence section) and Experiment 2 (Experiment 2: Double Vowel Perception section) in a sound-attenuated booth wearing over-ear headphones (Sennheiser 280 PRO; experiment order counterbalanced across subjects).

After completing the experiments, participants completed the hearing screening (adapted from Reilly et al., 2007). To pass the hearing screening, participants needed an average of ≤ 25 dB HL at each of the frequencies

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[2] This project is an extension of material collected from a doctoral thesis (Cohn, 2018a) and an adaptation of a proceedings paper (Cohn, 2018b).

[3] *n* = 5 OA musicians, *n* = 2 OA nonmusicians; *n* = 2 YA musicians, *n* = 6 YA nonmusicians.

Table 1. Age and education of musician and nonmusician groups.

Variable	Musician group (n = 29)	Nonmusician group (n = 26)	Group comparison t test
Age	$\bar{x}$ = 39.7 years old (SD = 15.2)	$\bar{x}$ = 39.7 years old (SD = 14.8)	$t(60.82) = 0.24$, $p = .8$
Education	$\bar{x}$ = 16.6 years (SD = 2.6)	$\bar{x}$ = 16.4 years (SD = 2.2)	$t(56.21) = 0.39$, $p = .7$

tested (250–8000 Hz). Participants were compensated with a $15 giftcard for their time.

Experiment 1: Sentence Perception With a Competing Sentence

In Experiment 1, listeners completed a sentence-in-speech task where they are instructed to attend to one signal and ignore the other. The task consisted of sentences from the Coordinate Response Measure (CRM) corpus (Bolia et al., 2000). CRM sentences all have the same form: "Ready <call sign> go to <color> <number> now." Following Brungart (2001), target sentences used in the current study were cued by the call sign "baron," and participants were asked to identify the color/number from that sentence (e.g., "Ready baron go to green three now"), while ignoring a masking sentence that has a different call sign, color, and number (e.g., "Ready arrow go to red one now"). This paradigm has been widely used to assess speech-in-speech perception (Bidelman & Yoo, 2020; Carlile & Corkhill, 2015; Darwin et al., 2003; Johnsrude et al., 2013), including investigations of age and/or hearing loss (Gygi & Shafiro, 2014; Lee & Humes, 2012).

Stimuli

Stimuli consisted of sentences produced by a single male talker (Talker 1) from the CRM corpus (Bolia et al., 2000), monotonized at 100 Hz and amplitude normalized to 70 dB[4] in Praat (Boersma & Weenink, 2021). Target sentences (n = 16), indicated by the call sign "baron," were monotonized at six f_o levels relative to 100 Hz (Δf_o = +0, 0.156, 0.306, 1, 2, 3 ST). Masker sentences, which contained six different call signs ("arrow," "eagle," "hopper," "laker," "ringo," and "tiger") were monotonized at 100 Hz. We pseudorandomly mixed the target sentences with the masker sentences spoken by the same talker, at a signal-to-noise ratio[5] of 0 dB. Sentences were mixed with the constraint that the target and masker contained different call signs, colors, and numbers.[6] Each masker call sign, color, and number occurred an equal number of times. In total, 96 stimuli were generated (16 baron sentences × 6 f_o levels).

Procedure

Participants began with 12 pretest trials, where they heard all possible "baron" target sentences in isolation (randomly presented; see Figure 1A). They were asked to click the color–number combination from the target sentence. After subjects made a response, they were shown immediate feedback on their performance ("Correct" or "Incorrect"; intertrial interval [ITI] = 1 s). Subjects' accuracy was calculated at the end of the pretest block; in order to continue on to the experimental trials, subjects needed to correctly identify the target sentences at 90% accuracy or higher. If they did not reach the 90% requirement, they repeated the single sentence pretest block again (up to 2 additional times).

Next, participants completed the experimental trials consisting of a target and masker sentence presented simultaneously (see Figure 1B; ITI = 1 s). Subjects began with a short practice block consisting of four stimuli randomly selected at each of the six f_o levels (total of 24 trials). No feedback on performance was provided. Next, they completed 192 experimental trials (16 sentences × 6 f_o levels × 2 repetitions), presented across eight (24 trials each; order randomized) lasting roughly 20 min.

Analysis

Trial responses were scored binomially as to whether participants correctly identified both the target color and number from the sentence (= 1), or not (= 0). We modeled accuracy with a Bayesian multilevel logistic regression model using the *brms* package (Bürkner, 2017) in R (Version 4.0.5; R Core Team, 2021) using the *bernoulli* family (8,340 iterations; warm-up = 1,000; thin = 3). Fixed effects included f_o separation (centered), age (centered), group (musician, nonmusician), and their interactions. We also included fixed effects of block number (centered) and subject single sentence accuracy (standardized; model structure provided in Equation 1). Random effects included by-sentence and by-subject random intercepts, and by-subject random slopes for f_o separation and block number. Contrasts were sum coded.

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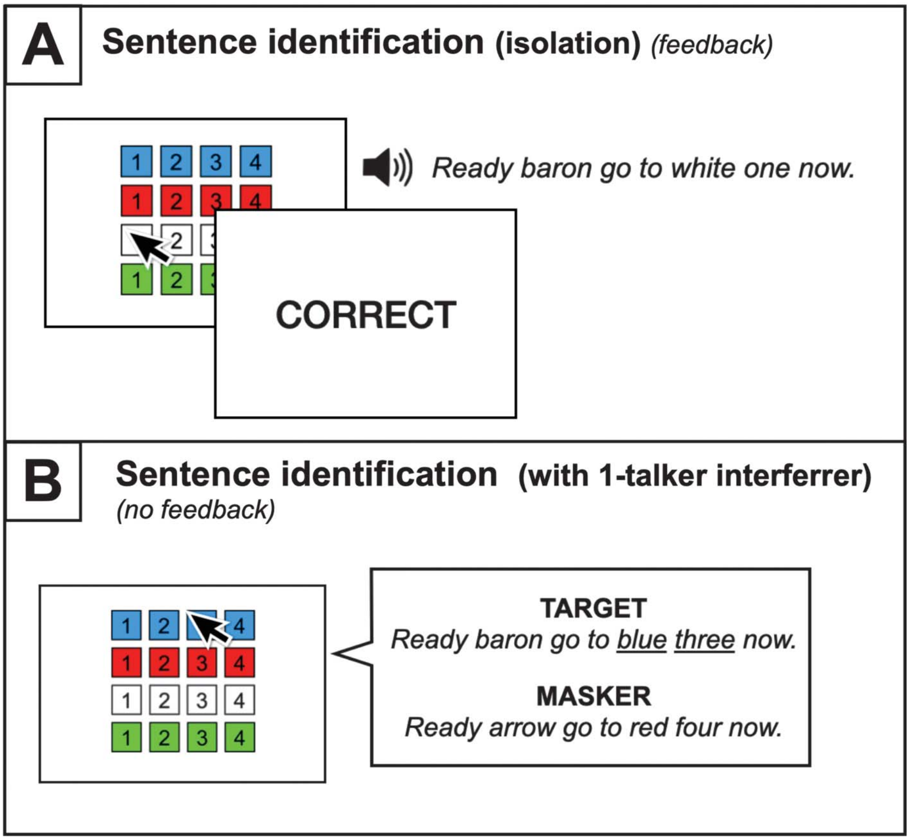
[4] Relative to 2e−05 Pascal, the "normative auditory threshold for a 1000-Hz sine wave" (Praat default).

[5] Also referred to as a target-to-masker ratio for speech-in-speech.

[6] Note that as the sentences were naturally recorded and used different call signs, colors, and numbers, there are small differences in timing across the target/masker sentences.

Figure 1. One-sentence talker interference paradigm for Experiment 1, based on the Coordinate Response Measure paradigm. (A) Participants started with sentence identification in isolation (i.e., without a masking sentence), where they clicked on the color/number from the target sentence. They heard six sentences and received immediate feedback on their accuracy after each trial. (B) Participants then completed sentence identification with a one-talker masker (0 dB SNR). Their task was to click on the color/number box associated with the target (cued by the call sign "baron"). No feedback was given.



$$\begin{aligned} \text{correct} \sim f_o \times \text{Age} \times \text{Group} + \text{Block} \\ + \text{SingleSentenceAcc} + (1|\text{Sentence}) \\ + (f_o + \text{Block}|\text{Subject}). \end{aligned} \tag{1}$$

Results

All participants reached the requisite 90% accuracy for target word identification when listening to sentences in isolation. There was no difference in accuracy in single sentence identification across the musician (98.1%) and nonmusician groups (96.9%) [$X^2(1, n = 55) = 0.51, p = .48$]. Investigating group and age (< 40, 40+ years), based on the median age of our participants, we see highest average accuracy for younger nonmusicians (100%), then older musicians (98.2%), followed by younger musicians (98.0%) and older nonmusicians (94.4%).

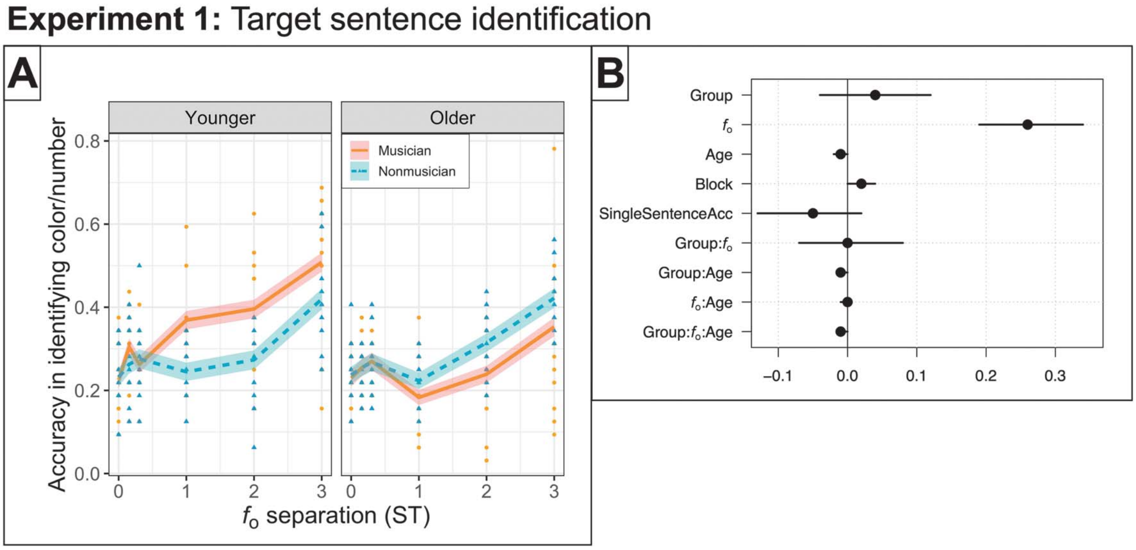
Mean proportion of trials in which the target color/number were identified in the experimental trials is plotted in Figure 2A. Figure 2B presents posterior means and credible intervals for all of the fixed effects in our model, and Table 2 presents the full model output. The model revealed an effect of f_o separation, with higher accuracy with a larger f_o separation. The effect for block number indicated that participants improved over time. There was also an effect for age, where participants' accuracy decreases with advanced age. An interaction between age and group revealed steeper age-related declines in accuracy for older musicians. Finally, there was a three-way interaction between group, f_o separation, and age, where older musicians show less of a benefit of f_o separation.

Post Hoc Analyses and Results

Age Category

To ascertain whether the age-related effects for musicians in Experiment 1 reflect (a) a general decline with age or (b) the presence of a YA musician's advantage, but one that is lost with age, we conducted a post hoc analysis examining effects across age categories. We modeled accuracy in the CRM task with a *brms* model

Figure 2. (A) Mean accuracy in correctly identifying the color and number from the target ("baron") sentence by group (musicians = orange solid line, dots; nonmusicians = blue dashed lines, triangle) at each f_o separation level (in semitones [ST]). Accuracy is faceted by age category (< 40 years, 40+ years based on median age of our sample). Shading indicates the standard error of the mean. (B) Posterior means and credible intervals for all of the fixed effects in the model. f_o = fundamental frequency.



(Bürkner, 2017) in R (Version 4.0.5; R Core Team, 2021; Bernoulli family; 8,340 iterations; warm-up = 1000; thin = 3). The model structure was the same as the main analysis, except for age. Here, we used an age category predictor (< 40, 40+ years old, sum coded) based on the median age in our sample (*Mdn* = 40.0 years; (96.9%), = 39.9 years).[7]

Model output is provided in Supplemental Material S3. We see credible effects for f_o separation and block, increasing accuracy with f_o separation and over the course of the experiment. Additionally, there are several effects of age category. First, YAs show higher accuracy overall in the task. An interaction between age category and group showed that this boost was even higher for YA musicians. Furthermore, a three-way interaction between age category, group, and f_o showed that this YA musician's advantage increased with increasing f_o separation. No other effects or interactions were observed.

Interim Discussion

In Experiment 1, we find that f_o separation improves listeners' ability to identify a target sentence when presented alongside a one-talker interferer, consistent with prior work showing intelligibility gains with increasing f_o separation for competing sentences (Lee & Humes, 2012) and vowels (Vongpaisal & Pichora-Fuller, 2007). In comparing performance by listener age, we see that YAs overall show higher accuracy on the task than OAs, consistent with age-related declines in speech-in-speech perception (e.g., Heidari et al., 2020).

Additionally, we find some support for a musician's advantage in speech perception for perceiving a sentence with a competing talker. However, this advantage is modulated by age. Specifically, YA musicians perform the best, and part of their improvement is rooted in their ability to leverage the f_o separation between competing sentences. This finding differs from that of Zendel and Alain (2012), who observed an advantage that emerges after 40 years of age. Our finding suggests that f_o separation might have played a role in younger musicians' advantage observed in other studies that did not control for the voice characteristics of competing talkers (e.g., Morse-Fortier et al., 2017; Parbery-Clark, Skoe, Lam, & Kraus, 2009). Taken together, we see a possible transfer for increased pitch sensitivity—from music to speech-in-speech perception—supporting *shared auditory encoding* accounts (Bidelman et al., 2014; Patel, 2014; Shahin, 2011).

Thus, while we do find evidence for a musician's advantage, there appear to be limitations to this benefit. For one, middle-aged/OAs in the current study do not exhibit a musician's advantage for sentence-in-sentence perception. While understudied, some work has shown a reduced ability for OAs to tease apart competing vowels at smaller f_o differences, compared to YAs (Vongpaisal & Pichora-Fuller, 2007; though musical background was not reported in that study). At the same time, older musicians (ages 65+ years)

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[7] correct ~ f_o × Age Category × Group + Block + SingleSentenceAcc + (1 | Sentence) + (f_o + Block | Subject).

Table 2. Sentence identification (Experiment 1): posterior means (estimate), standard deviation of the posterior (error), 95% credible intervals (Q2.5, Q97.5), and percent of posterior distribution above or below zero, for fixed effects.

Predictor	Estimate	Error	Q2.5	Q97.5	% Distribution < 0	% Distribution > 0
Intercept	**–0.79**	**0.26**	**–1.29**	**–0.29**	**100**	**0**
Group (Musician)	0.04	0.04	–0.04	0.12	16	84
f_o	**0.26**	**0.04**	**0.19**	**0.34**	**0**	**100**
Age	**–0.01**	**0.00**	**–0.02**	**0.00**	**100**	**0**
Block	**0.02**	**0.01**	**0.00**	**0.04**	**1**	**99**
SingleSentenceAcc	–0.05	0.04	–0.13	0.02	92	8
Group(Musician):f_o	0.00	0.04	–0.07	0.08	48	52
Group(Musician):Age	**–0.01**	**0.00**	**–0.01**	**0.00**	**98**	**2**
f_o:Age	0.00	0.00	–0.01	0.00	88	12
Group(Musician):f_o:Age	**–0.01**	**0.00**	**–0.01**	**0.00**	**98**	**2**

Note. Effects whose credible intervals do not include zero or those with 95% of their distribution on one side of zero are in bold. Num. observations = 10,560; Num. participants = 55; Num. sentences = 16; f_o = fundamental frequency.

in other studies show improved frequency discrimination, compared to age-matched nonmusicians (e.g., Grassi et al., 2017), suggesting that the type of task might shape whether a musician's advantage emerges for OA listeners.

Experiment 2: Double Vowel Perception

While Experiment 1 investigated the ability of listeners to hone in on a target sentence, amidst an interfering sentence, Experiment 2 employs a double vowel paradigm (Assmann & Summerfield, 1990; Vongpaisal & Pichora-Fuller, 2007), where participants hear two synthetic vowels varying in degree of f_o separation. Given that the vowels are presented with very small f_o separation levels (the same as in Experiment 1), it is likely that the vowels could perceptually fuse into one "auditory object." Experiment 2 tests the extent to which musicians and nonmusicians might leverage f_o differences to tease apart the competing vowels—and also if this varies by age. Additionally, we ask listeners to identify both vowels they heard, testing their divided attention (i.e., attending to both streams simultaneously).

Given prior work showing that musicians display enhanced subcortical representations of the spectrum in speech (e.g., /ba/ vs. /ga/ in Kraus et al., 2014; Parbery-Clark, Skoe, & Kraus, 2009), even with advanced listener age (Bidelman & Alain, 2015), we also take into account the spectral distance between the double vowels (Euclidean distance of first [F1] and second formants [F2] Bradlow et al., 1996). As listeners do not perceive isolated (naturally produced) vowels 100% correctly (e.g., Peterson & Barney, 1952), we began the study with a single vowel identification task. Furthermore, we account for each participant's accuracy in identifying each vowel in the full model to account for differences attributable to vowel identification in general.

Stimuli

Five steady-state vowels (260 ms; f_o = 100 Hz) were synthesized in R with the *phonTools* package (Barreda, 2015): /i, ɛ, æ, ɑ, u/ (formant frequency values are provided in the Appendix) based an acoustic analysis of California English vowels (Holland, 2014). We generated six versions of each vowel, varying in f_o separation levels from 100 Hz (Δf_o = +0, +0.156, +0.306, +1, +2, +3 ST), all at 60 dB. To create the double vowels, all possible vowel combinations were combined (excluding combination with itself, e.g., no /u/ + /u/), with the vowel presentation levels matched (and double vowel stimuli amplitude normalized to 60 dB[8]). In each double vowel combination, one vowel had a higher f_o than the other, for a total of 120 stimuli (20 vowel pairs × 6 f_o levels).

Participants

The same participants from Experiment 1 completed Experiment 2 (see Participants (Experiments 1 and 2) section for details).

Procedure

Participants first completed a vowel familiarization task, illustrated in Figure 3A (Vongpaisal & Pichora-Fuller, 2007), with the labeled button box containing five

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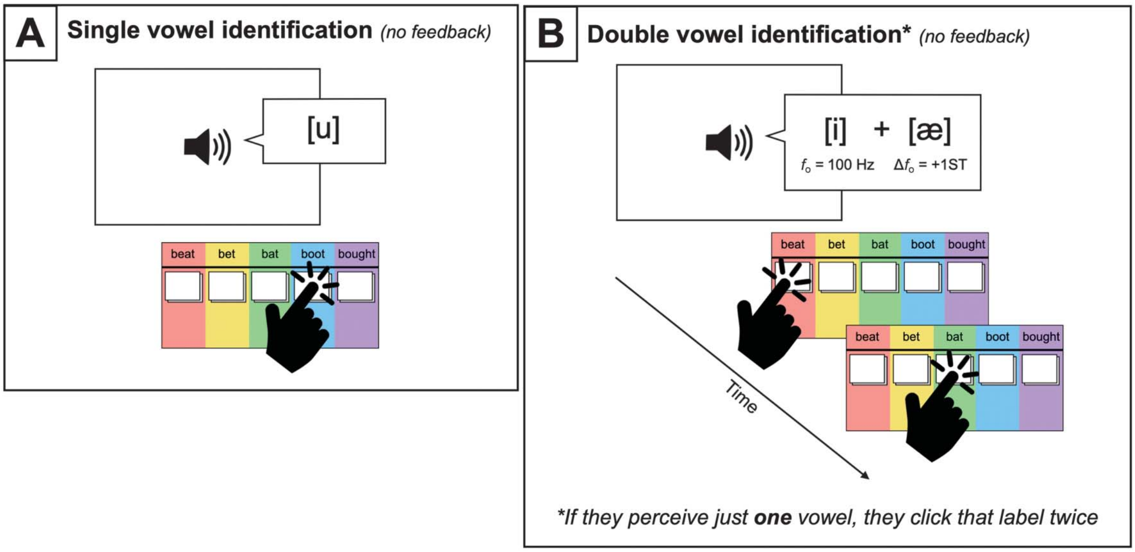
[8] Presentation level for stimuli was 70 dB SPL in Experiment 1 and 60 dB SPL in Experiment 2. Both are within a reasonable range for comfortable listening in a sound-attenuating booth, wearing over-ear headphones. Additionally, as our research question aimed to test the impact of the relative difference in f_o between two sounds (identical in intensity), we would not expect these small differences in presentation level to shape the effects we observe.

Figure 3. Vowel identification paradigms. (A) Participants begin with a single vowel identification block; they hear each synthesized vowel in isolation and select the representative word using a labeled button box. (B) Participants then complete a double vowel identification task. They hear a blend of two vowels (0 dB SNR) varying in f_o separation. If they perceive two vowels, they identify each vowel with a button press (order of button presses does not matter). If they perceive just one vowel, they click that vowel button twice. f_o = fundamental frequency; ST = semitone.



*If they perceive just **one** vowel, they click that label twice

example words for the vowels ("beat," "bet," "bat," "boot," and "bought"; button-label correspondence was counterbalanced across participants). They heard each of the vowels (at each f_o level) presented individually in a total of 30 trials (5 vowels × 6 f_o levels; randomly presented). If, after three attempts, participants did not reach 90% accuracy in identifying the vowels, they did not participate in the experimental trials.

In the double vowel trials, listeners were told that they might hear one or two vowels (following Vongpaisal & Pichora-Fuller, 2007) and instructed to identify the vowel(s) they heard via two button presses (schematized in Figure 3B). If they perceived two different vowels, they were instructed to identify each vowel in the pair. If they perceived just one vowel, they were instructed to press that vowel button twice. While there were always two vowels presented in the experimental trials, this allows us to test how the vowels might "perceptually fuse" at small f_o separation levels.

The double vowel portion began with 24 practice trials (four randomly selected vowel pairs from each of the six f_o levels); no feedback was given. Then, they saw the instructions repeated again before starting the experimental trials where they heard each of the 120 double vowel stimuli (20 vowel pairs × 6 f_o levels) twice, for a total of 240 trials presented across eight blocks (30 trials per block). Assignment of stimuli to block was randomized. After each block, participants were shown their progress (e.g., "Block 1/8 Complete"). In total, the double vowel experiment took roughly 25 min to complete.

Single Vowel Identification: Analysis and Results

Of the total of $N = 72$ participants recruited, $n = 14$ participants ($n = 4$ OA musicians, $n = 2$ OA nonmusicians; $n = 2$ YA musicians, $n = 6$ YA nonmusicians) did not reach the required 90% accuracy in the single vowel identification after three blocks and therefore did not complete Experiment 2. A vowel confusion matrix (see Supplemental Material S4) sheds some light on the source of this difficulty for these participants. They identify /ɑ/ as "bat" 66.7% of the time. Additionally, they show confusions about vowel height, identifying /æ/ as "bet" 22.7% of the time and /i/ as "bet" 15.9% of the time. Finally, they identify /u/ as "bought" 22.7% of the time (perhaps due to the "u" letter in the word).

All other participants passed the single vowel identification portion with an average accuracy of 90% or greater (in a single block, with three attempts). We did see differences in single vowel identification accuracy, which was higher for musicians (95.9%) than nonmusicians (91.4%) [$X^2(1, N = 50) = 14.16, p < .001$]. Investigating age groups (< 40, 40+ years), we see lower average accuracy for both younger nonmusicians (90.5%) and older nonmusicians (92.1%), than younger musicians (97.3%) and older musicians (94.3%). Vowel confusion matrices for each age/musician group (provided in Supplemental Material S5–S8) reveal sources for these differences, summarized in Table 3. For example, all groups show confusions in identifying /ɑ/ as "bat" (rather than "bought"). Vowel height confusions were also common, such as identifying /æ/ as "bet,"

Table 3. Summary of single vowel confusions.

Confusion	YA nonmusician	YA musician	OA nonmusician	OA musician
Selected "bat" for /ɑ/	23.1%	11.5%	10.7%	16.7%
Selected "bet" for /æ/	10.3%	2.5%	6.0%	2.4%
Selected "bet" for /u/	5.1%	0.0%	1.2%	4.8%

Note. YA = younger adult; OA = older adult.

indicating perception of a lowered vowel. YA nonmusicians and OA musicians also mistook /u/ for "bet," attributing the fronted /u/ as a front vowel.

Double Vowel Identification: Analyses and Results

In addition to the participants who did not complete the experimental trials, data were excluded for $n = 4$ listeners who performed at floor in the double vowel identification task (mean accuracy < 5%; resulting in removal of two middle-aged/older musicians and two middle-aged/older nonmusicians). Data were also excluded due to a computer error for one participant (one younger nonmusician), where the single vowel portion crashed and they completed it more than 3 times. Accordingly, $n = 50$ participants[9] were included in the Experiment 2 analysis (summarized in Table 4).

Stream Separation

We coded stream separation binomially (identifying that two vowels were presented = 1, or not = 0) and modeled it with a Bayesian logistic regression using the *brms* R package (Bürkner, 2017; 8,340 iterations; warm-up = 1,000; thin = 3). The model included fixed effects of f_o separation (centered), age (centered), and group (musicians, nonmusicians), and all possible interactions. Additionally, we included a fixed effect of F1/F2 Vowel Euclidean Distance (log Hertz) to account for the degree of spectral difference between the vowels. The model also included interactions between F1/F2 distance with age and with group. Furthermore, we included block (centered) as a fixed effect to account for changes over time. Contrasts were sum coded. Random effects included random intercepts for participants and vowel pair. We also included by-participant random slopes for f_o separation, F1/F2 distance, and block. The model syntax is shown in Equation 2.

$$\begin{aligned} & f_o \times \text{Age} \times \text{Group} + \text{F1F2.Distance} \times \text{Age} \\ & \quad \times \text{Group} + \text{Block} \\ & \quad + (f_o + \text{F1F2.Distance} + \text{Block}|\text{Subject}) \\ & \quad + (1|\text{VowelPair}). \end{aligned} \tag{2}$$

Figure 4A plots the proportion of trials in which two vowels were identified, the credible intervals are plotted in Figure 4B, and the model output is provided in Table 5. The model revealed an effect of f_o separation, where likelihood of perceiving two vowels increases with a larger f_o difference between the vowels. There was also an overall effect of group, as seen in Figure 4A, wherein musicians are more likely to detect two vowels (than just one vowel). Additionally, F1/F2 distance was a predictor, such that a larger F1/F2 distance between the vowels was associated with a higher likelihood they hear two versus just one vowel. Over the course of the block, participants also showed overall improvements in detecting two vowels. We also observe an interaction between group and f_o separation: Musicians show stronger stream separation on the basis of increasing f_o separation. No other effects or interactions were observed.

Double Vowel Identification

Participants' identifications of the two vowels in the experimental trials was binomially coded (1 = both vowels correctly identified, 0 = not) and modeled with a Bayesian multilevel logistic regression model using the *brms* R package (Bürkner, 2017; 8,340 iterations; warm-up = 1,000; thin = 3). Fixed effects included f_o separation (centered), age (centered), group (musician, nonmusician), and F1/F2 Vowel Euclidean Distance (log Hertz). The three-way interaction between f_o separation, age, and group was included, as well as one between F1/F2 vowel distance, age, and group. We also included a predictor of joint single vowel accuracy for each vowel in the pair based on pre-experiment single vowel identification accuracy as a measure for how well they perceived

Table 4. Participant breakdown.

Originally recruited	*N* = 72	
Retained	*N* = 55	*n* = 2 did not pass hearing screening *n* = 14 did not pass single vowel portion and did not complete Experiment 2 *n* = 1 left study before the end of Experiment 2
Experiment 1	*n* = 55	
Experiment 2	*n* = 50	*n* = 4 had double vowel accuracy at floor (< 5%) *n* = 1 computer error

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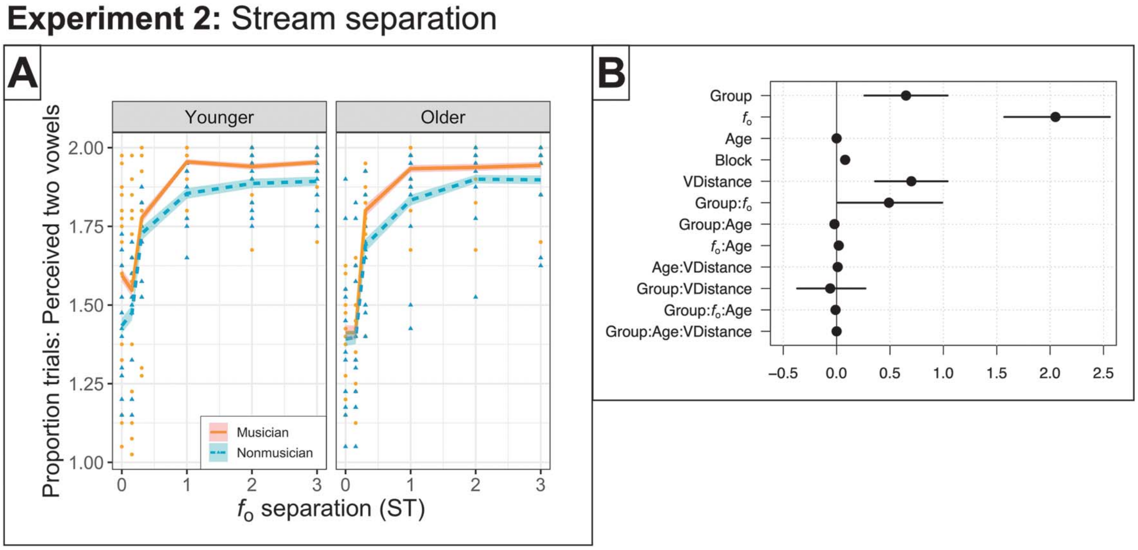
[9] All participants performed above 5% accuracy in Experiment 1.

Figure 4. (A) Mean number of vowels perceived (1 or 2) by group (musicians = orange solid line, dots; nonmusicians = blue dashed lines, triangle) at each f_o separation level (in semitones [ST]). Accuracy is faceted by age category (< 40 years, 40+ years based on median age of our sample). Error ribbons show the standard error of the mean. (B) Posterior means and credible intervals for all of the fixed effects in the stream separation model. f_o = fundamental frequency.



each of the synthetic vowels (logit of product of the Vowel-1 and Vowel-2 probabilities). Finally, we included the predictor of block number (centered). Contrasts were sum coded. Random effects included by-subject random intercepts and by-subject random slopes for f_o separation, F1/F2 distance, and block number, and random intercepts for vowel combination. The model syntax is provided in Equation 3.

$$\begin{aligned}&\text{correct} \sim f_o \times \text{Age} \times \text{Group} + \text{F1F12.Distance}\\&\quad \times \text{Age} \times \text{Group} + \text{JointSingleVowelAcc} + \text{Block}\\&\quad + (f_o + \text{F1F2.Distance} + \text{Block}|\text{Subject})\\&\quad + (1|\text{VowelPair}).\end{aligned} \tag{3}$$

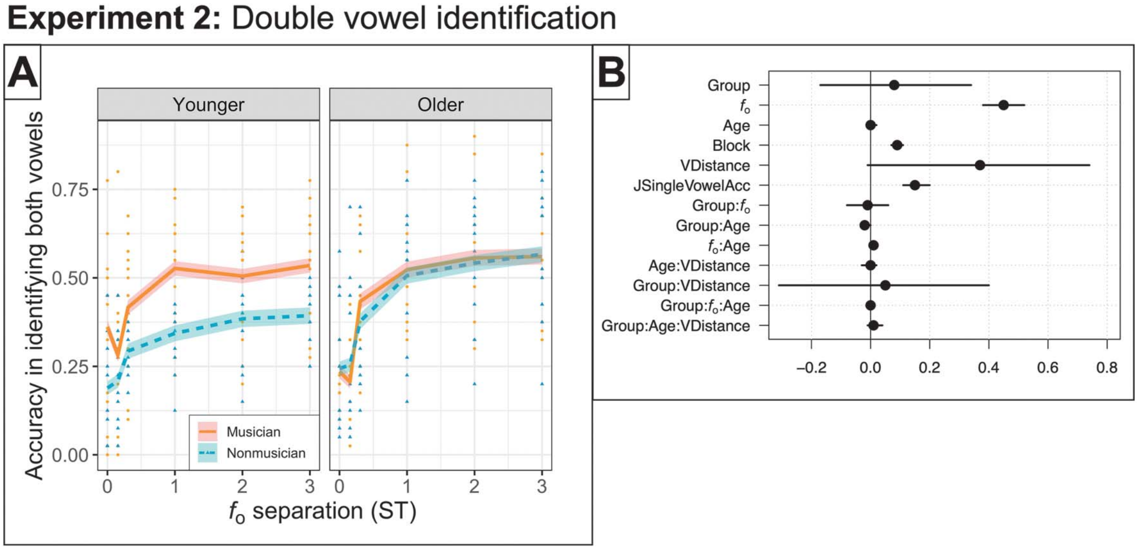
Mean accuracy for the task is plotted in Figure 5A. Table 6 and Figure 5B present posterior means and credible intervals (between the 2.5th and 97.5th percentiles) for all of the fixed effects in our model. Effects whose credible intervals do not include zero or have 95% of their distribution on one side of zero are bolded. Results indicate a credible effect for f_o separation, where identification accuracy increases as a function of f_o separation between voices. Similarly, F1/F2 vowel distance reliably affected accuracy, wherein listeners are more accurate in identifying both vowels the more spectrally distinct they were. There was also an effect for block number resulting in an increase in

Table 5. Stream separation (Experiment 2).

					% Distribution	
Predictor	**Estimate**	**Error**	**Q2.5**	**Q97.5**	**< 0**	**> 0**
Intercept	**1.88**	**0.24**	**1.41**	**2.37**	**0**	**100**
Group(Musician)	**0.65**	**0.20**	**0.26**	**1.04**	**0**	**100**
f_o	**2.05**	**0.25**	**1.57**	**2.56**	**0**	**100**
Age	0.00	0.01	−0.03	0.03	45	55
Block	**0.08**	**0.02**	**0.05**	**0.12**	**0**	**100**
VowelDistance	**0.70**	**0.17**	**0.36**	**1.04**	**0**	**100**
Group(Musician):f_o	**0.49**	**0.25**	**0.01**	**0.99**	**2**	**98**
Group(Musician):Age	−0.02	0.01	−0.04	0.01	87	13
f_o:Age	0.02	0.02	−0.01	0.06	9	91
Age:VowelDistance	0.01	0.01	−0.02	0.03	24	76
Group(Musician):VowelDistance	−0.06	0.16	−0.37	0.27	64	36
Group(Musician):f_o:Age	−0.01	0.02	−0.04	0.03	70	30
Group(Musician):Age:VowelDistance	0.00	0.01	−0.02	0.02	56	44

Note. Posterior means (estimate), standard deviation of the posterior (error), 95% credible intervals (Q2.5, Q97.5), and percentage of posterior distribution above or below zero, for fixed effects. Effects whose credible intervals do not include zero or those with 95% of their distribution on one side of zero are in bold. Num. observations = 12,000; Num. participants = 50; Num. vowel pairs = 20; f_o = fundamental frequency.

Figure 5. (A) Mean accuracy for correctly identifying both vowels by group (musicians = orange solid line, dots; nonmusicians = blue dashed lines, triangle) at each f_o separation level (in semitones [ST]). Accuracy is faceted by age category (< 40 years, 40+ years based on median age of our sample). Error ribbons show the standard error of the mean. (B) Credible intervals for double vowel identification. f_o = fundamental frequency.



accuracy over time for all groups. Furthermore, listeners' performance identifying each of the vowels presented in isolation (prior to the double vowel experimental trials) is positively related to their ability to perceive those same vowels in the double vowel stimuli (joint single vowel accuracy). We also see an interaction between group and age, where musicians show lower accuracy with increasing age. As group is sum coded, the converse is also true; nonmusicians show higher accuracy with increasing age. Finally, age and f_o separation interacted, such that the effect of f_o separation is weaker for YAs. No other effects or interactions whose 95% credible intervals did not overlap with zero were observed. While Figure 5A appears to show a musician's advantage for YAs, when we account for listeners' accuracy in correctly identifying each of the synthetic vowels in isolation, the model confirms that this is not a reliable musician group–level difference (see Table 6).

Double Vowel Identification: Post Hoc Analysis and Results

To confirm there is no YA musician's advantage in double vowel identification, we conducted a post hoc

Table 6. Double vowel identification (Experiment 2): posterior means (estimate), standard deviation of the posterior (error), 95% credible intervals (Q2.5, Q97.5), and percent of posterior distribution above or below zero, for fixed effects.

					% Distribution	
Predictor	**Estimate**	**Error**	**Q2.5**	**Q97.5**	**< 0**	**> 0**
Intercept	**−1.17**	**0.21**	**−1.59**	**−0.75**	**100**	**0**
Group (Musician)	0.08	0.13	−0.17	0.34	26	74
f_o	**0.45**	**0.04**	**0.38**	**0.52**	**0**	**100**
Age	0.00	0.01	−0.01	0.02	30	70
Block	**0.09**	**0.01**	**0.07**	**0.11**	**0**	**100**
VowelDistance	**0.37**	**0.19**	**−0.01**	**0.74**	**3**	**97**
JointVowelAcc	**0.15**	**0.02**	**0.11**	**0.20**	**0**	**100**
Group(Musician):f_o	−0.01	0.04	−0.08	0.06	59	41
Group(Musician):Age	**−0.02**	**0.01**	**−0.03**	**0.00**	**96**	**4**
f_o:Age	**0.01**	**0.00**	**0.00**	**0.01**	**0**	**100**
Age:VowelDistance	0.00	0.01	−0.03	0.02	53	47
Group(Musician):VowelDistance	0.05	0.18	−0.31	0.4	40	60
Group(Musician):f_o:Age	0.00	0.00	−0.01	0.00	63	37
Group(Musician):Age:VowelDistance	0.01	0.01	−0.01	0.04	11	89

Note. Effects whose credible intervals do not include zero, or those with 95% of their distribution on one side of zero are in bold. Num. observations = 12,000; Num. participants = 50; Num. vowel pairs = 20; f_o = fundamental frequency.

analysis, fitting accuracy with a *brms* model (bernoulli family; 8,340 iterations; warm-up = 1,000; thin = 3). We used the identical model structure as in the main analysis, but with age category (< 40, 40+ years), in lieu of continuous age.[10]

The model (provided in Supplemental Material S9) revealed largely parallel results as in the main model, including less of a reliance of f_o separation for YAs than OAs. Yet, we did not see an effect of group or its interaction with age category. Indeed, as previously mentioned (Single Vowel Identification: Analysis and Results section), YA nonmusicians in the study—while ultimately able to pass the 90% accuracy for single vowel identification—still have lower single vowel accuracy than the other groups. Accounting for this lower accuracy allowed us to correctly attribute their difficulty perceiving the vowels in general, rather than a musician's advantage per se.

Interim Discussion

In Experiment 2, we see that increasing f_o separation between the voices improves listeners' ability to tease apart and identify two competing vowels, in line with prior work (de Cheveigné et al., 1997; Vongpaisal & Pichora-Fuller, 2007). Furthermore, degree of F1/F2 Euclidean distance between the vowels also supports vowel separation and identification. Vowels that had larger vowel-space differences (e.g., /i/ + /ɑ/) are better recognized than vowels that are closer together (e.g., /i/ + /ɛ/). This finding aligns with reduced intelligibility for speech produced with a reduced vowel space observed in other studies (Bradlow et al., 1996).

We see some support for a musician's advantage, but critically only for stream separation. That is, musicians (all ages) are more likely to perceive two separate vowels, relative to nonmusicians. This finding aligns with work showing musicians' enhanced ability to tease apart two complex (nonspeech) harmonic sounds (Zendel & Alain, 2009). Furthermore, we see that musicians are better at separating the two vowels with increasing f_o. Yet, for both separation and identification, we saw no difference in how musicians use spectral differences (here, degree of vowel space expansion). Together, these findings support *shared auditory* accounts that propose more constrained transfer from music-to-speech: for pitch, but not for features that music places less "precision" on, such as the spectrum (Patel, 2012; Zatorre et al., 2002).

Age category also played a role in the double vowel experiment independently of musicianship, specifically in how listeners are able to identify the competing vowels. In particular, YAs leverage f_o separation less than middle-aged/OAs. That is, with increasing age, adults show a steeper increase in accuracy as f_o separation increases. Why is this the case? We might predict the opposite based on the prior literature: OAs (ages 65–83 years) show less of a benefit of f_o separation (Vongpaisal & Pichora-Fuller, 2007). Here, it is important to note that our OAs ranged from ages 40 to 66 years, largely occupying middle-adulthood, which could mean that declines in f_o encoding are not as prevalent as those for elderly listeners. Indeed, some work has shown similar or decreased speech-in-speech perception for middle aged adults (ages 49–59 years) compared to college-age adults (ages 19–24 years), but better than OAs (ages 60–83 years; Helfer & Freyman, 2009). While speculative, our OAs (ages 40–66 years) might be using f_o as a compensatory strategy to offset the start of age-related difficulties perceiving speech-in-speech. Taken together, our pattern of results suggests that both age and musical training shape the way listeners both separate and identify competing vowel sounds in independent, but nuanced, ways.

Discussion

This study investigated listeners' speech-in-speech perception across two tasks: perception of a sentence with a one-talker interferer (selective attention) and perceiving two competing vowels (divided attention). We compared musicians and nonmusicians varying in age to test the purported musician's advantage, investigating their reliance on f_o separation to perform both tasks.

Across both experiments, one of the strongest predictors of speech-in-speech perception is f_o separation. All listeners—musicians and nonmusicians alike—use f_o differences to separate competing voices, and identify the target stream(s), consistent with prior work (Lee & Humes, 2012; Summers & Leek, 1998; Vongpaisal & Pichora-Fuller, 2007). Furthermore, when separating and identifying two vowels, all listeners use their spectral distance (in F1/F2 vowel space).

Additionally, in both studies, we see support for a musician's advantage for speech-in-speech perception (e.g., Parbery-Clark, Skoe, Lam & Kraus, 2009; Parbery-Clark et al., 2011; Zendel & Alain, 2012). In the case of sentence perception (Experiment 1), YA musicians consistently show higher accuracy. In stream separation of vowels (Experiment 2), we see a consistent musician's effect across ages. However, we do not see *identical* musician's advantages across the experiments. Both f_o separation, age, and task shape the way an advantage emerges, highlighting potential sources for the mixed results observed in the literature for speech-in-speech perception (cf. Coffey et al., 2017).

Why do we see a musicians' advantage for speech-in-speech in the current study, while other studies report

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[10] correct ~ f_o × Age × Group + F1F2.Distance × Age Category × Group + JointSingleVowelAcc + Block + (f_o + F1F2.Distance + Block | Subject) + (1 | VowelPair).

no difference between musicians and nonmusicians? Our results suggest that one factor is f_o. f_o appears to be a particularly useful cue for musicians, likely due to their enhanced perception of pitch (e.g., Kishon-Rabin et al., 2001). Supporting our predictions, we see that our musicians' advantage is supported by their ability to leverage f_o separation between the voices: to identify the target sentence (Experiment 1) or separate the competing streams (Experiment 2). These findings point to the importance of controlling f_o characteristics of competing voices when assessing speech-in-speech (cf. Başkent & Gaudrain, 2016; Başkent et al., 2018; Deroche et al., 2017; Madsen et al., 2017) and suggest that an advantage might only emerge when two voices have very similar f_o values. In studies that examine voices that vary widely in f_o separation and other speaker indexical characteristics (e.g., Boebinger et al., 2015; Ruggles et al., 2014), it is possible that both musicians and nonmusicians alike are able to use these cues equivalently given sufficiently large differences.

Another possible source of the mixed findings in the speech-in-speech literature is due to listener age. In the current study, we see a younger musician's advantage (ages 18–39 years) in Experiment 1 (perceiving a sentence with a one-talker interferer), and part of their advantage is in using f_o separation between the target and masker sentences. This finding is consistent with related work with YAs (ages 19–27 years) that also controlled for f_o separation and fluctuation and found an advantage (Başkent & Gaudrain, 2016). In a related study of slightly younger participants (ages 11–14 years) who began training early (around age 7 years) and had more than 5 years of musical training, no advantage was detected (Başkent et al., 2018). One possibility is that a musician's advantage *emerges* with age, based on cumulative years of musical training. For example, Zendel and Alain (2012) find an advantage emerging around 40 years of age, while others show it occurring earlier. It might be fruitful to think of an advantage as emerging around young adulthood (from around 18 years old through around 40 years old), but with the caveat that there is no precise "age" at which an advantage occurs for any one person. This idea of a gradual—and highly individualistic—emergence of a musician's advantage can also help explain the mixed results in the literature; studies examining college-age cohorts (ages 18–22 years) might be sampling too young of participants to catch it.

On the flip side, our results suggest an advantage might also *wane* with increased age, particularly for selective attention tasks. For example, the ability to inhibit a competing talker decreases with age (Tun et al., 2002). At the same time, other work has shown that a musician's advantage persists for OAs. For example, Parbery-Clark et al. (2011) found that musicians (ages 45–65 years) showed consistent advantages in perceiving both words and sentences in four-talker babble, relative to their nonmusician (age-matched) counterparts. In our study, we do see a consistent musician's advantage for f_o separation for the competing vowels. Therefore, it might be more appropriate to think of multiple types of musician advantages—ones based on acoustic properties and attentional demands—that emerge and wane with age. Indeed, as nearly all studies are cross-sectional, the role of individual differences among participants cannot be understated. However, that is not to say that beneficial effects of musical training are limited to a younger age range. For example, Zendel et al. (2019) found that nonmusician OAs (ages 55–75 years) who received 6 months of musical training show greater improvement in speech-in-speech (relative to control groups), suggesting that with new training, neuroplastic changes are possible across a wide range of ages.

That we see a nuanced musician's advantage—one that is shaped by f_o, participant age, as well as task—sheds light on theories of music-to-speech transfer. In both experiments, musicians closely attend to f_o to improve performance. That the advantages we see are tied to f_o (but less so for other acoustic properties) supports accounts that propose a music-to-speech transfer for distinctions that have greater "precision" in music (i.e., pitch) than speech (Patel, 2011, 2012, 2014), but not the other way around (e.g., speech has more spectral distinctions than music; Zatorre et al., 2002). Additionally, the type of task, in providing varying attentional demands (e.g., selective attention), shapes the way listeners leverage acoustic cues (here, f_o; Kraus & Nicol, 2014; Kraus & White-Schwoch, 2015). Taken together, these findings support a hybrid *shared auditory encoding* and *domain-general attentional* account of music-to-speech transfer.

Limitations and Future Directions

There are several limitations of this study that can serve as avenues for future research. First, we see that participants show difficulty in perceiving synthetic vowels in isolation. While we modeled the vowels based on the California Vowel System (CVS; Eckert, 2008; Holland, 2014; Podesva, 2011; Villarreal, 2018), the English variety our participants were most familiar with, we see systematic confusions. One feature of the CVS is the backing of the /æ/ vowel in "bat" (known as TRAP-backing). Indeed, we see confusions of /æ/ for /ɑ/ for participants who completed the task (23.1% YA nonmusicians, 11.5% YA musicians, 10.7% OA nonmusicians, 16.7% OA musicians) and by far the most common confusion for the excluded individuals who did not pass with 90% accuracy (66.7%). Another feature of the CVS is front lax vowel lowering (e.g., for the vowels /ɪ/ and /ɛ/ in "bit" and "bet," respectively). In this study, nonmusicians confused /æ/ as /ɛ/ (10.7%) at a much higher rate than YA musicians (2.5%), OA nonmusicians (6%), and OA musicians (2.4%), suggesting that they are hearing a further CVS-shifted vowel. Indeed, perceiving a CVS-lowered vowel was the source of many "errors" for the participants who did not pass with 90% accuracy: 22.7% confused /æ/ as "bet." A third feature of CVS is back vowel fronting (e.g., the vowel /u/ in "boot" is fronted). While all age/musician groups display above 93% accuracy in identifying the intended /u/ vowel as "boot," the most common confusion was with "bet," indicating that they did not always perceive it as a back vowel (5.1% YA nonmusicians, 0% YA musicians, 1.2% OA nonmusicians, 4.8% OA musicians). Therefore, we see that perception of CVS features from the synthesized vowels is not consistent across the vowel space, and might also vary by both age and musical background. Future work can test whether a musician's advantage might be present for more peripheral vowels, as is common in singing (e.g., for female speakers/singers in Marczyk et al., 2022). Furthermore, future work providing more phonetic context (e.g., playing longer samples of the talker) can better signal the speaker as belonging to a particular language/dialect variety than isolated words. Finally, our findings suggest that strict "cutoff" points (e.g., 90% single vowel identification accuracy) and lack of feedback can result in a large number of participants who are excluded from the task.

Furthermore, the difficulty YA nonmusicians in particular faced with the synthetic vowels underscores the importance of accounting for accuracy in perceiving vowels in isolation in models of speech-in-noise perception. To our knowledge, studies generally do not include a baseline accuracy measure directly in the models (e.g., Madsen et al., 2017; Parbery-Clark, Skoe, & Kraus, 2009). Here, without accounting for YA nonmusicians' difficulty, we could have incorrectly attributed their lower accuracy to a YA musicians' advantage. We additionally control for single sentence accuracy in Experiment 1; indeed, we see that YA nonmusicians perceive naturally recorded (but flattened f_o) sentences equally well as their musician counterparts, suggesting that the unnatural stimuli made the double vowel identification task even more challenging. Future work using naturally recorded vowels can further probe whether a musicians' advantage in stream separation might extend to identification.

Another limitation was our age range. Our division of the YA and OA age groups was centered around age 40 years, consistent with age differences found in related work (Zendel & Alain, 2012), giving us more of a middle-aged "OA" group (Alain et al., 2001). While understudied, the interaction between age, musicianship, and task appears to be complex. In addition, it appears to be large enough to have a meaningful effect on observed outcomes and influences efforts to replicate findings across age groups and experimental tasks. Most studies examine college-age students, and those that examine older cohorts vary in their age ranges. The current study suggests that age-related differences might not always go in the expected direction—and more cross-age category research is needed to better elucidate these differences.

Furthermore, we used small f_o separation levels based on the JNDs for pure tones for musicians and nonmusicians (Δf_o = 0.156 and 0.306 ST, respectively; Kishon-Rabin et al., 2001). We see that increasing f_o separation beyond these levels—up to 3 ST—confers a benefit in sentence-in-speech perception (Experiment 1). As in other work (e.g., Assmann & Summerfield, 1990; Vongpaisal & Pichora-Fuller, 2007), increasing f_o separation beyond 1 ST for double vowels is less advantageous (Experiment 2). Yet, we see that at musician's JND for tones (Δf_o = 0.156 ST), musicians appear to show a small dip in both stream separation and double vowel identification, potentially indicating that the unexpected interval led to interference. Indeed, one musician participant reported that the "dissonance" between talkers was distracting at times, suggesting that the musician's advantage might be constrained to musical intervals they have trained on (e.g., a half step [1 ST], but not +0.156 ST). Still, another possibility is that these f_o separation levels were too small for linguistic stimuli. Related work has shown JNDs for participants (musical training not reported) that are larger for syllables, ranging from Δf_o = 1.23 ST for a child voice and Δf_o = 2.68 ST for a male voice (Gaudrain & Başkent, 2015). Taken together, these findings suggest that the JNDs vary for pure tones and across different levels of linguistic content (vowel, syllable, word, etc.). Future work directly comparing f_o separation, with and without the presence of meaningful stimuli (e.g., tones vs. vowels) and at an individual's JND and speech reception threshold, can start to tease this apart.

In addition, we see that while YAs show an advantage for the one-talker interferer (Experiment 1), OA musicians appear to show a disadvantage. While the majority of studies examining speech-in-speech report a musician's advantage (e.g., Başkent & Gaudrain, 2016; Parbery-Clark, Skoe, & Kraus, 2009), or equal performance across musician and nonmusician groups (e.g., Başkent et al., 2018; Boebinger et al., 2015), there is some work suggesting possible sources for a disadvantage. For example, Tufts and Skoe (2018) found that college-age musicians have greater noise exposure than nonmusicians, particularly due to their experience in orchestras and bands. While all participants in the current study passed a pure-tone hearing screening (Reilly et al., 2007), some work has shown that OAs and musicians have increased noise exposure and subclinical hearing loss, resulting in lower performance in speech-in-noise tasks (Drennan, 2022; Skoe et al., 2019). In the current study, some participants mentioned that they perform in front of loud instruments (e.g., brass, woodwind) in an orchestra or marching band setting, which is consistent with this interpretation. Future work both measuring subclinical hearing loss (e.g., using auditory brainstem responses; Skoe

& Tufts, 2018), as well as directly asking participants about their noise exposure (e.g., Guest et al., 2018), can shed light on possible sources of an age-related disadvantage for musicians.

Relatedly, while there is increased interest in effects of specific types of musical training (e.g., pianists and violinists in Carey et al., 2015), musician participants in the current study were heterogeneous in terms of the instruments they play, how they play (alone vs. in group ensembles), as well as their background in singing (i.e., voice training). Future work examining a specific type of experience (e.g., singing only, string instruments only) might better translate to f_o separation in speech perception, particularly for vowels (which are the focus of singing as the most sonorant elements).

While this study examined the role of musical experience by nontonal language speakers, other work has shown the impact of linguistic experience on f_o perception (Bidelman et al., 2013). For example, a recent paper provided support for a Cantonese advantage for prosodic prominence perception in English (Choi, 2022), particularly for falling pitch. The extent to which we observe similar language-based advantages for stream separation (e.g., on the basis of f_o separation) are avenues for future study.

Finally, while we can think of an advantage as "emerging" around young adulthood (sometime between ages 18 and 39 years), we know that children show tremendous plasticity in learning language and music (e.g., Chobert et al., 2014; Ilari et al., 2016). Increasingly, there are parallels drawn between "sensitive periods" for language and music acquisition, as well as cross-domain transfer (music-to-speech and vice versa; Chen et al., 2022; White et al., 2013). While speculative, these possibilities are ripe for future research and can shed light on the nature—and interplay—of differing types of complex auditory experience.

Conclusions

A musician's advantage for speech-in-speech perception depends on many factors, including the f_o properties of the competing voices, as well as the age of listeners and type of task. This work broadens our understanding of the impact—as well as limitations—of nonlinguistic experience on speech perception, and contributes to our understanding of cross-domain plasticity (e.g., music-to-speech).

Data Availability Statement

All data generated or analyzed during this study are included as supplemental materials.

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Appendix

Formant Frequency Values Used to Synthesize Vowel Tokens

Vowel	F1	F2	F3	F4	F5	Reference word
/i/	350	2400	2500	3500	4500	beat
/ɛ/	550	1850	2500	3500	4500	bet
/æ/	800	1780	2500	3500	4500	bat
/ɑ/	850	1380	2500	3500	4500	bought
/u/	400	1600	2250	3500	4500	boot

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