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RESEARCH

Musicianship modulates octave illusion perception differently across stimulation frequencies

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Abstract

The octave illusion is a well-known auditory phenomenon elicited by binaural octave-separated tones alternating between the ears that engages parallel processing pathways for sound localization and pitch perception. It has mainly been studied using the central frequencies of the musical spectrum (e.g., 400–800 Hz). However, in a previous study, we measured a shift in the distribution of percepts reported by non-musicians at the upper and lower boundaries of the musical spectrum, suggesting a reduced pitch perception accuracy. This study now aims to determine if musical training, which is known to improve pitch perception, affects the relative distribution of percepts across frequencies. 24 non-musicians and 19 professional musicians listened to the illusion evoked by pairs of frequencies ranging from 40 to 80 Hz to 2000–4000 Hz, and selected which percept they heard (octave, simple, complex). In non-musicians, the results replicate the previously reported shift in the distribution of percepts at higher and lower frequencies, but no such perceptual shift was measured in musicians. At lower frequencies, musicians were more likely than non-musicians to report the octave percept and less likely to report simple percepts. For the classic paradigm frequencies (400–800 Hz), musicians were more likely to report a complex percept that more closely matched the true pattern of stimulation used to elicit the illusion. In conclusion, musical training seems to preserve pitch representation at the lower boundaries of the musical spectrum, and musicians seem to have a more consistent distribution of percept elicited by the illusion across different frequencies.

Introduction

The complex acoustic signals present in everyday environments are processed by our peripheral and central auditory systems to construct mental representations of distinct auditory objects. This fascinating ability called auditory scene analysis (Bregman, 1990) revolves around the segregation or fusion of disparate sound sources based on their spectral and temporal characteristics. Auditory scene analysis enables several high-level auditory abilities, such as speech in noise understanding, spatial localization of sounds, or music perception. While extensive musical training is known to enhance auditory abilities related to musical processing such as discrimination of timbre, pitch, or rhythm (for a review, see Kraus & Chandrasekaran, 2010), fewer studies have investigated how musical training influences auditory scene analysis abilities (Nederlanden et al., 2020).

Auditory illusions offer a window to investigate the mechanisms underlying auditory scene analysis (Deutsch, 1974a; Pressnitzer et al., 2011). These illusions illustrate that the auditory system does not simply transmit sound information, but also rearranges the information as it is processed by the brain. This can lead to perceptions that are false (e.g., sound that do not exist), altered (e.g., sound that is modified from its original acoustic representation (McGurk &

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MacDonald, 1976) or impossible (e.g., pitch that increases forever (Shepard, 1964). Auditory illusions can also offer insight into the effects of musical training on auditory scene analysis. For instance, Smith et al. (1982) found significant differences in the perception of the musical scale illusion between musicians and non-musicians, observing that the perception of musicians was more resistant than that of non-musicians to modulations of the stimulation parameters (e.g., timbre, loudness). Among musicians, these perceptual differences appear to be primarily associated with degree of expertise with pitch perception abilities rather than duration of musical training (Choi et al., 2024). The effect of musical expertise on illusions also extends beyond the auditory modality. Musicians are notably less susceptible to the visual Solitaire illusion, which involves the Gestalt law of proximity and good continuation (Pecunioso & Agrillo, 2021), and to both audiovisual and audiotactile double-flash illusions (Bidelman, 2016; Landry et al., 2017), suggesting domain-general perceptual differences. However, musical training doesn't improve all forms of perceptual processing, as demonstrated by its lack of effects on the parchment skin illusion that involves multimodal integration of spectral information (Landry et al., 2017). Given musicians' enhanced pitch perception abilities and altered susceptibility to various illusions, it is relevant to explore how musicians perceive the octave illusion, which crucially involves pitch processing and sound localization.

The octave illusion is a well-known illusion often used to investigate auditory scene analysis (Deutsch, 1974a, b) in non-musicians. It is perceived when alternating high and low tones (high-low-high-low), typically separated by an octave, are presented through stereo headphones, with each ear receiving the opposite tone simultaneously (Fig. 1A). Instead of hearing both tones, non-musically trained listeners often report hearing a single tone that alternates between the ears while shifting between the high and low pitches, such that one ear only perceives high tones and the other only low tones. To explain this paradoxical perception, Deutsch has argued over the years that auditory information is processed in two parallel *what* (Fig. 1B) and *where* (Fig. 1C) pathways in the central auditory system (Deutsch, 1975, 1978, 1980, 1981a, b, 1988, 2004; Deutsch & Roll, 1976), with the illusory percept being created when both processing streams reunite (Fig. 1D). This phenomenon illustrates the interaction between key auditory scene analysis abilities: sound localization and binaural fusion/segregation.

Almost all individuals without musical training reported hearing the classic octave illusion when elicited through that classical paradigm of a 400–800 Hz stimuli pair. However, Craig (1979) found that only 50% of musicians reported

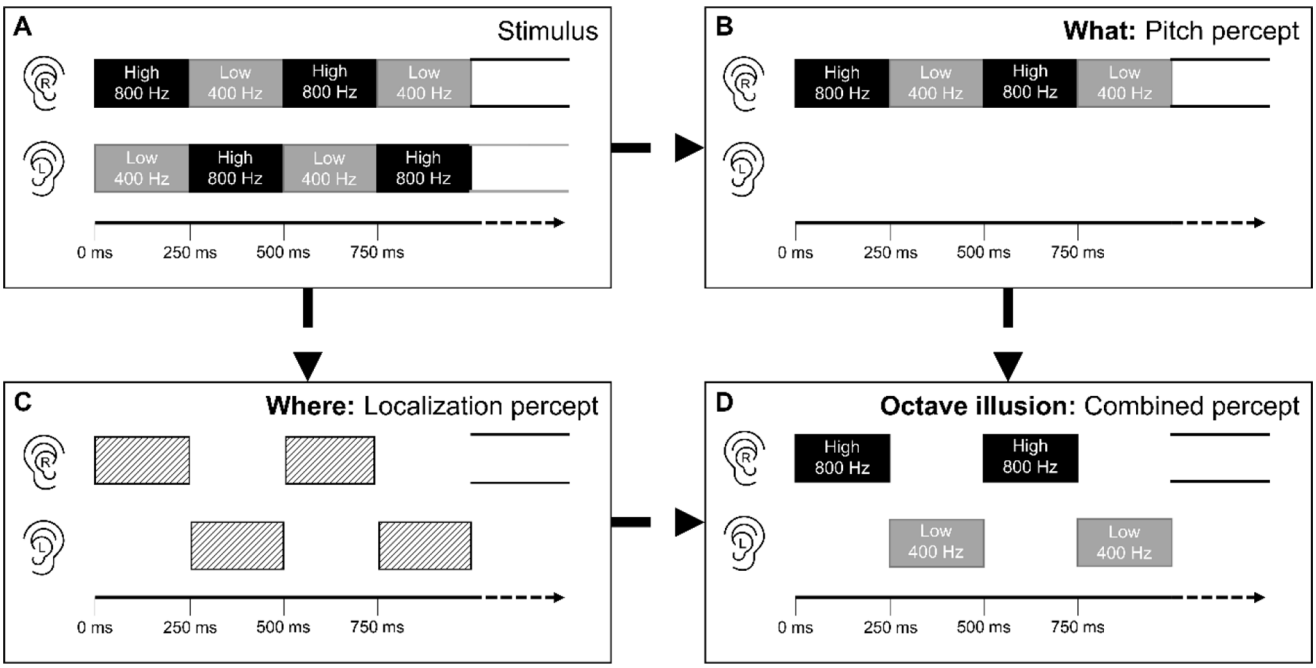

Fig. 1 Stimulation parameters and processing pathways giving rise to the perception of the octave illusion. **A**. The classical pattern of sounds used to elicit the octave illusion: a binaural pair of 400 and 800 Hz pure tones alternating every 250 ms. When one ear is receiving the high tone, the other is receiving the low tone (Deutsch, 1974a, b). **(B)** Pitch processing in the *what* pathway: the pitch sequence is processed by one (generally the right) ear. **(C)** Spatial processing in the *where* pathway: the sound is lateralized to the ear currently receiving the high tone. This also illustrates the simple percept, where a sound is heard alternating between the ears without a change in pitch. **(D)** The octave illusion: perception of a high tone on the right alternating with a low tone on the left. (Dashed lines represent the continuation of the signal or percept). Adapted from Whittom et al. (2023) with authors' permission

hearing the octave percept during the illusion. Brennan and Stevens (2002) further found that increased musical experience lowered the probability of perceiving the standard octave illusion. They also noted that musical expertise with an instrument possessing harmonic and spatial features similar to those of the octave illusion (i.e., the pipe organ) could allow individuals to perceive the illusion veridically, that is accurately recognizing the stimuli used to elicit the illusion. These results suggest that musical training can modulate the perceptual mechanisms underlying the illusion. This effect is noteworthy, given that the illusion is otherwise robust in non-musicians, persisting even when the acoustic parameters are changed, such as when the illusion is elicited using harmonic complex tones (McClurkin & Hall, 1981), other frequencies ratios (e.g., major seventh, minor ninth, minor tenth) (Brancucci et al., 2008) and narrow-spectrum noise (Brännström & Nilsson, 2011). Furthermore, these results suggest that the percept relies mainly on relative pitch rather than the exact frequency ratio between pure tones.

Pitch processing indeed appears to play an important role in the inhibitory mechanisms that are hypothesized to generate the octave illusion through the *what* and *where* pathways. For the *what* pathway, neural units responsible for pitch perception in the dominant ear are hypothesized to suppress conflicting pitch information in the non-dominant ear (Deutsch, 1980, 1981a). For the *where* pathway, inhibitory connections from the neural units sensitive to higher frequencies are hypothesized to suppress those sensitive to lower frequencies (Deutsch, 1981a, 1988). It is thus logical that musicianship can modulate the perception of the octave illusion, since extensive musical training can induce important functional and structural plastic changes in the brain, particularly in the primary and secondary auditory areas (Bermudez et al., 2009; Herholz & Zatorre, 2012), which are notably reflected in improved pitch perception abilities (Besson et al., 2007; Bianchi et al., 2016). For instance, musicians are better at detecting pitch deviations in melodies (Habibi et al., 2013) and have lower frequency discrimination thresholds (Kishon-Rabin et al., 2001; Liang et al., 2018).

While previous studies showed that musicianship can modulate the perception of the octave illusion, a previous study from our group found that using frequencies from the upper and lower boundaries of the musical spectrum, where pitch perception accuracy is known to be reduced, can also modulate the illusion (Whittom et al., 2023). Indeed, non-musicians reported the classic octave illusion percept less frequently at the two lowest (40–80 Hz and 100–200 Hz) and highest (1600–3200 Hz and 2000–4000 Hz) frequency pairs used compared to the classic 400–800 Hz stimulation paradigm. At these higher or lower frequencies, instead of hearing the octave percept participant reported hearing either a simple percept (i.e., a sound alternating between the ears without a change in pitch)[1] or a complex percept (i.e., other subjective percepts that didn't fit into predetermined categories and were reported in writing by participants). This result then suggests that the decline in pitch perception that occurs at these extremities of the musical frequency spectrum (Attneave & Olson, 1971; Moore, 1973; Semal & Demany, 1990) can lead to measurable alterations in the perception of the octave illusion in non-musicians. While both frequency and musicianship are known to modulate the perception of the octave illusion, it remains unclear how these two factors interact. The question thus remains whether using these lower and higher frequency pairs has a similar effect across musicians and non-musicians.

Resolving this question requires further investigating the relationship between pitch processing and the octave illusion in non-musicians and musicians. A 88 keys grand piano generally spans a frequency range from 27.5 Hz (A0) to 4186 Hz (C8). At the upper and lower bounds of the musical spectrum, even musicians have lower pitch perception. For example, Biasutti (1997) found that amateur musician failed to recognize minor and major triads below around 120 Hz and above around 3000 Hz, while Attneave and Olson (1971) found that pitch perception and the ability to make octave correspondences largely disappear above 5000 Hz. Thus, comparing the octave illusion between musicians and non-musicians across a wide frequency range can provide a better understanding of how musical training impacts the cognitive processes involved in pitch perception and auditory scene analysis. This current study thus aims to assess how professional musicians perceive the illusion across a broader musical frequency spectrum compared to non-musicians.

Materials and methods

Participants

The control group consisted of 24 adults (15 females, 9 males) with no significant musical training, defined as less than 1 year of musical training (excluding music classes received as part of the standard elementary or secondary school curriculum in Quebec (Beatty, 2007). Participants were recruited from the Quebec City metropolitan area through university mailing lists and social media.

[1] *Simple percept* is used here to refer to a perception that is simpler than the octave percept, as it lacks pitch variation. Our use is synonymous with *single pitch percept* from Oehler and Reuter (2013), but should also not be confused with *single percept*, which typically refers to situations where two acoustic elements are fused into a singular percept.

The musician group consisted of 19 professional musicians (9 females, 10 males). These professional musicians had multiple years of musical experience (M=18.16, SD=6.97), began playing music at a relatively young age (M=8.84, SD=3.82), and practiced for several hours per week (M=16.74, SD=9.82). Nine musicians reported some singing experience. All participants self-reported having a normal hearing and being right-handed. The hearing status of participants was confirmed with a screening procedure including external auditory canal visualization, tympanometry, and screening pure tone audiometry (0.25 to 8 kHz) conducted in a quiet room following guidelines for maximum permissible ambient noise level (Chung, 2023) using an AA222 middle ear analyzer and audiometer (Interacoustics, Assens, Denmark). The sample size of the current study is similar to previous studies comparing musicians to non-musicians on the octave illusion (Brennan & Stevens, 2002) or similar illusions (Davidson et al., 1987), which used groups of between 14 and 16 participants. The participant characteristics are further described in Table 1.

Procedure

We replicated the exact same paradigm as previously used in (Whittom et al., 2023). The experiment was conducted in a quiet room at the CERVO Brain Research Center. Stimuli were generated with the free open-source software Audacity® (Audacity Team, 2021) and were presented to the participants through headphones (Insert ER3C, Etymotic) at a comfortable sound level (65–70 dB SPL). Insert earphones were chosen as they better attenuate environmental sound compared to supra-aural earphones and since they are routinely used in audiology (Chung, 2023). The experimenter was trained by an audiologist to obtain a proper insertion of the foam tip, and the earphones were calibrated by a technician following ANSI/ASA S3.7 standard protocol (ANSI & ASA, 2020). The tones consisted of sine waves with a duration of 250 ms, similar to Deutsch's original experiment (Deutsch, 1974a), and were presented in alternance 120 times, for a total duration of 30 s. As in the original experiment, the stimuli were controlled to preserve phase continuity and avoid drops in amplitude during the transitions between.

frequencies. Seven pairs of frequencies were presented in a randomized order, covering a broad range of the musical spectrum: 40–80 Hz, 100–200 Hz, 200–400 Hz, 400–800 Hz, 800–1600 Hz, 1600–3200 Hz, 2000–4000 Hz.

After listening to each sequence, the participants indicated their perception by selecting one of four choices on a paper questionnaire using a pen: (1) a high-pitched sound on the right alternating with a low-pitched sound on the left, (2) a high-pitched sound on the left alternating with a low-pitched sound on the right, (3) a sound alternating between the ears without any change in pitch, and (4) none of these answers. These four categories of percept are based on the categories and descriptions used by Oehler and Reuter (2013). If this last option was selected, the participant had to briefly describe their perception in writing. Participants first completed the auditory screening, after which data for the octave illusion were collected. The experiment lasted approximately 10 min on average, as participants were given time to respond between each stimulation condition, with the next stimulus presented only when they indicated being ready. They were then given the option to participate in a second, separate experiment, which was entirely optional. No additional variables beyond those reported in this manuscript were collected during the octave illusion experiment.

Table 1 Participant characteristics

Characteristics	Non-musicians (n=24)	Musicians (n=19)	p
Age			0.188 [a]
Mean (SD)	25.9 (4.7)	28.3 (6.3)	
Sex			0.368 [b]
Female	15 (63%)	9 (47%)	
Male	9 (38%)	10 (53%)	
Level of education			0.141 [b]
Secondary	1 (4%)	0 (0%)	
College	9 (38%)	7 (37%)	
Bachelor	11 (46%)	7 (37%)	
Master	2 (8%)	4 (21%)	
PhD	1 (4%)	1 (5%)	
Main instrument			
Piano	-	6 (32%)	
String [c]	-	4 (21%)	
Brass	-	3 (16%)	
Singing	-	3 (16%)	
Woodwind	-	2 (10%)	
Violin	-	1 (5%)	

[a] Welch's unequal variances t-test; [b] Fisher's exact test. [c] Non bowed string instruments (e.g., guitar, harp)

Analysis

First, choices 1 and 2 from the questionnaire were merged into a single item, as they both represent the same percept (i.e., the classic octave illusion). Choices 1 and 2 relate to different lateralization possibilities of the octave illusion, which are typically associated with handedness (Oehler & Reuter, 2013). Since these two responses relate to the same underlying percept and since only right-handed participants were recruited for the study, choices 1 and 2 were merged to simplify the analysis. In summary, three categories of percept were defined: octave (answers 1 and 2), simple (answer 3) and complex (answer 4). The dependent variable was the responses (categorical: octave, simple, complex) with

octave as the reference category. The predictor variables were Group (categorical: control, musician) and Frequency (categorical: 40–80 Hz, 100–200 Hz, 200–400 Hz, 400–800 Hz, 800–1600 Hz, 1600–3200 Hz, 2000–4000 Hz). The relationship between the responses and the predictor variables was analyzed using a multinomial logistic regression, a common approach to model categorical dependent variables that is also able to handle categorical predictor variables and provide easy to interpret results in the form of odds ratios (Kwak & Clayton-Matthews, 2002). All analyses were conducted in R version 4.4.0 (R Core Team, 2024) using the packages nnet version 7.3 (Venables & Ripley, 2002), car version 3.1 (Fox & Weisberg, 2019), lmtest version 0.9 (Zeileis & Hothorn, 2002) and pscl version 1.5.9 (Jackman, 2024).

Results

A multinomial logistic regression was performed to determine the effects of musicianship and frequency on the likelihood of perceiving either the octave, simple, or complex percept during the octave illusion. A Likelihood Ratio (LR) Chi-Square test indicated that the multinomial logistic regression model was statistically significant, χ^2 (26, $N=301$) = 63.74, $p<.001$, Nagelkerke $R^2=0.22$, and correctly predicted 56% percepts. The Nagelkerke R^2 must be interpreted with caution, as it is not equivalent to R^2 for ordinary least square regressions and tend to be lower (Smith & McKenna, 2013). To confirm that the model has an adequate fit to the data, a multinomial Hosmer-Lemeshow goodness of fit test (Fagerland & Hosmer, 2012) was conducted and suggested no evidence of poor fit, $\chi^2(16)=14.25$, $p=.58$. Model coefficients are reported as Supplementary Material 1. The analysis of deviance showed a significant main effect of Frequency, $\chi^2(12, N=301)=38.28$, $p<.001$, and Group $\chi^2(2, N=301)=10.33$, $p=.006$, and a significant interaction between Frequency and Group, $\chi^2(12, N=301)=23.28$, $p=.025$.

Because of the significant two-way interaction, simple main effect analyses were conducted to evaluate the effect of group at each level frequency and of frequency at each level of group. Significant differences were observed in the distribution of percepts between groups at 40–80 Hz, $\chi^2(2, N=43)=10.33$, $p=.006$; 100–200 Hz, $\chi^2(2, N=43)=8.28$, $p=.016$; 200–400 Hz, $\chi^2(2, N=43)=6.23$, $p=.044$; and 400–800 Hz, $\chi^2(2, N=43)=9.00$, $p=.011$, but not for the other frequency conditions (Fig. 2). However, when correcting for multiple comparisons using false discovery rate (FDR; Benjamini & Hochberg, 1995), the 200–400 Hz contrast did not remain significant with a corrected p value of $p=.078$. At the lowest frequency pair (40–80 Hz), musicians were more likely than non-musician to report the octave percept (OR = 9.23, 95% CI = [1.98, 46.85]) and less likely to report the simple percept (OR = 0.19, 95% CI = [0.05, 0.77]). Musicians were also less likely to report the simple percept (OR = 0.12, 95% CI = [0.02, 0.67]) at the second-lowest frequency pair (100–200 Hz). At the classic stimulation paradigm of 400–800 Hz, musicians were also more likely to report a complex percept (OR = 10.62, 95% CI = [1.04, 108.45]), but less likely than non-musician to report the octave percept (OR = 0.13, 95% CI = [0.03, 0.62]).

Significant differences were also observed in the distribution of percepts between frequencies for the control group, $\chi^2(12, N=168)=38.28$, $p<.001$, but not for the musician group, $\chi^2(12, N=133)=11.45$, $p=.490$. This effect of frequency in the control group was further explored using multiple Fisher's exact tests with FDR correction (Benjamini & Hochberg, 1995). The distributions of responses that showed significant differences between frequency pairs are presented in Fig. 3. Overall, non-musicians rarely reported complex percepts across all frequency pairs. At the classic 400–800 Hz stimuli paradigm, non-musicians most often reported hearing the octave percept. However, at lower and higher frequencies, the likelihood of reporting the octave percept decreased while the likelihood of reporting the simple percept increased. In contrast, musicians showed a more consistent distribution of responses across frequencies: the octave percept was the most common for all frequency pairs, but simple and complex percepts were also commonly reported. While the lateralization of the octave percept was not analyzed in the present study, most musicians lateralized the octave percept to the right (9) compared to the left (4), while other musicians had variable lateralization depending on the frequency pair used (3) or never perceived the octave percept (3). Non-musicians equally lateralized the octave percept to the right (7) and to the left (7), but most had variable lateralization depending on the frequency pair used (10).

The written descriptions of the reported complex percepts were categorized based on whether the participants mentioned hearing different tones with distinct pitches (e.g., a low and high pitch alternating in the same ear), with the same pitches (e.g., a low pitch pulsing in both ears simultaneously), or with ambiguous pitches (e.g., unsure if the pitches were the same or distinct). The descriptions were also categorized based on the nature of other reported perceptual attributes, such as hearing a third sound (e.g., hearing a third ambient sound), pitch fluctuations (e.g., the pitch of a sound was felt as increasing over time), temporal effects (e.g., one sound appearing longer than the other), localization effects (e.g., hearing alternating tones in one ear only), or amplitude effects (e.g., sound that appeared louder in one ear). Responses could match multiple categories (e.g.,

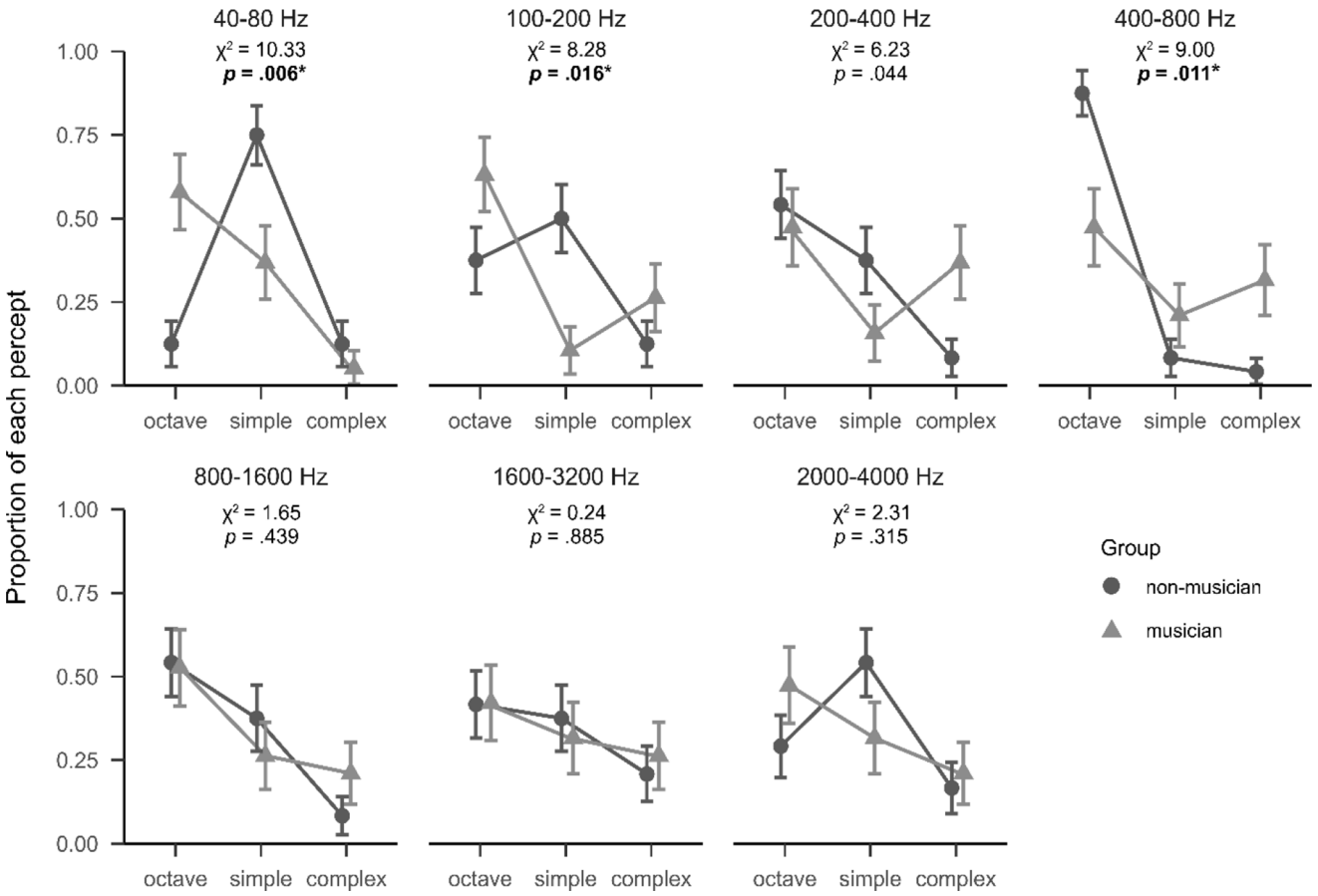

Fig. 2 Distribution of percepts (Octave, Simple, Complex) reported by non-musicians and musicians at each pair of frequencies. Dark grey circles represent non-musicians, light grey triangles represent musicians, error bars represent standard errors. Asterisks indicate *P* values that remained significant after FDR correction

distinct pitches + third sound). Responses that could not be categorized were classified as "other". The number of occurrences of each category are presented for the control and musician groups in Fig. 4. Musicians' complex percept often included hearing different pitches, hearing a third sound, and localization effects. Non-musicians' complex percept often included hearing sounds with the same or ambiguous pitches, sometimes with pitch fluctuations.

Discussion

The primary objective of this study was to examine the effect of musicianship on the distribution of percepts evoked by the octave illusion using frequency pairs covering a wide range of musical pitch perception. Specifically, the octave illusion was tested using frequency pairs ranging from 40 to 4000 Hz while maintaining constant the other acoustic parameters used to elicit the octave illusion (Deutsch, 1974a; Oehler & Reuter, 2013). The results suggest that musicians demonstrate a greater consistency in perceiving the octave illusion across frequency pairs, particularly at lower frequencies, where they were more likely to report the octave percept compared to non-musicians. This difference could be attributed to musicians' enhanced pitch perception abilities, which may allow them to maintain a stable percept even when pitch discrimination becomes more challenging.

The octave illusion in non-musicians

For the non-musician participants, we replicated the results from our previous study (Whittom et al., 2023). At the frequency pair typically used to elicit the illusion (400–800 Hz), the octave percept was the most common. This percept was reported by 88% of non-musicians, similar to the proportion reported by Whittom et al. (2023) and Deutsch (1988). For frequency pairs near the center of the musical scale (e.g., 200–400 Hz, 800–1600 Hz), our results are consistent with previous studies showing that the octave percept remains the most common (Deutsch, 1974a, 1988). Like Whittom et al. (2023), the current results show a greater variability in the distribution of percepts reported by non-musicians at

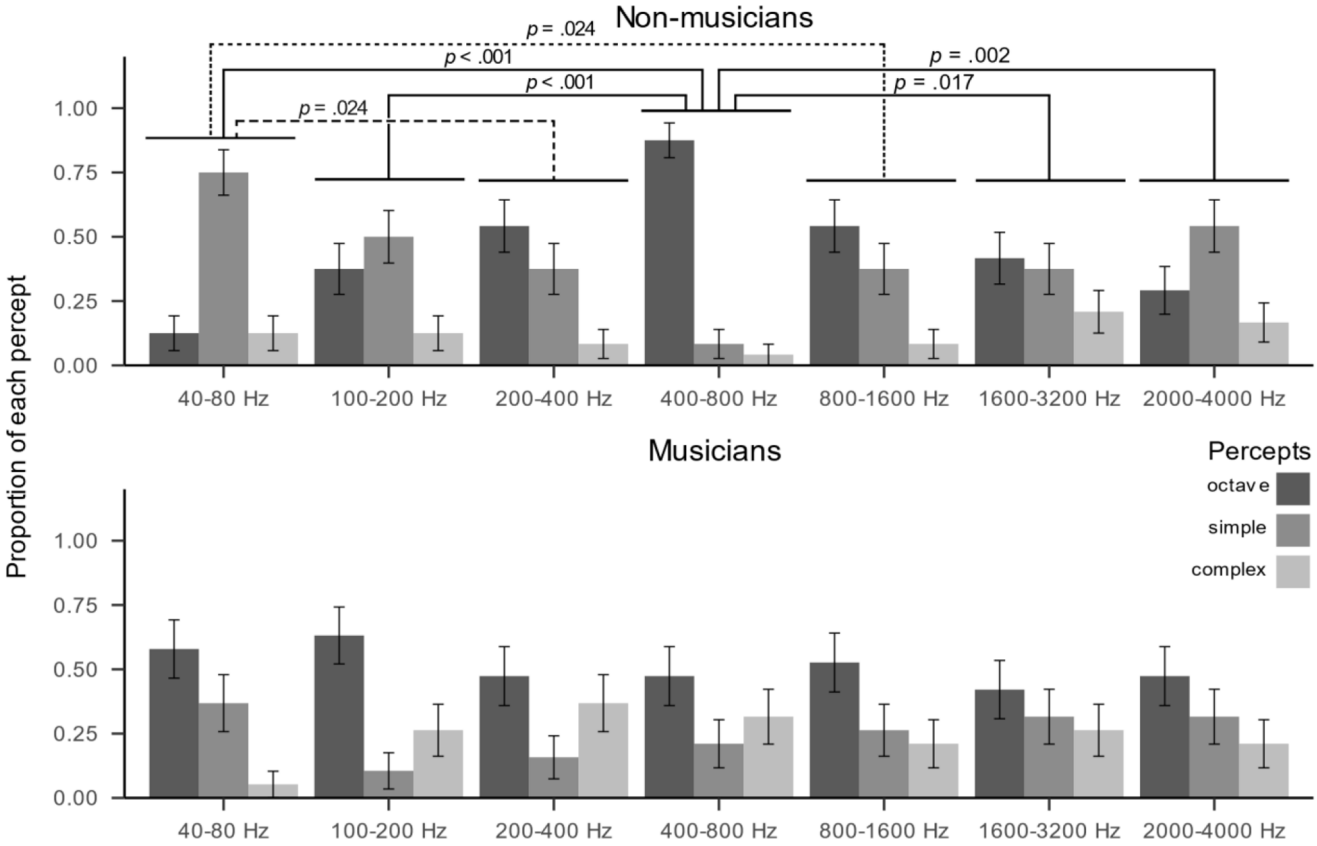

Fig. 3 Distribution of reported percepts (Octave, Simple, Complex) across each frequency pair by non-musicians and musicians. *P* values adjusted for FDR correction. Dark grey represents octave percepts, medium grey represents simple percepts, light grey represents complex percepts, error bars represent standard errors

the upper and lower bounds of the musical frequency spectrum (40–80 Hz, 100–200 Hz, 1600–3200 Hz, and 2000–4000 Hz), where the likelihood of reporting the octave percept decreases.

The simple percept was the most frequently reported by non-musicians at the lower frequency pairs (40–80 Hz and 100–200 Hz) and at the highest frequency pairs (2000–4000 Hz). Notably, at 40–80 Hz, 75% of non-musicians reported hearing the simple percept. This percept corresponds to a sound alternating between the ears without any change in pitch, suggesting that only the *what* component of the model is altered while the *where* component responsible for sound localization is preserved. For these lower frequencies, it is worth noting that stimuli of equal intensity like those used in the present study have greater differences in subjective loudness when presented monaurally due to the steep slope of equal loudness contours at low frequencies (Robinson & Dadson, 1956). In comparison, at higher frequencies, this slope flattens and differences in loudness should be minimal for monaural presentation. However, since all stimuli are presented dichotically, perception is generated by central interactions. Nonetheless, it is unclear if loudness could influence perception since the binaural loudness of dichotic tones remains an active field of research requiring further investigation (Sivonen & Ellermeier, 2011). Moreover, while loudness effects can modulate sound lateralization (Deutsch, 1981a), it is not obvious how differences in loudness could explain the prevalence of the simple percept at lower frequencies, since this percept appears to involve a preserved lateralization with degraded pitch information. Overall, the complex percept was the least often reported by non-musicians. While non-musicians were more likely to report a complex percept at higher frequency pairs (1600–3200 Hz, 2000–4000 Hz), it was still only reported by around a fifth of participants. These changes in the distribution of percepts are coherent with the idea that pitch perception declines at the lower and upper bounds of the musical spectrum for non-musicians (Attneave & Olson, 1971; Biasutti, 1997) and that the octave illusion is modulated by pitch processing (Brancucci et al., 2008; Brännström & Nilsson, 2011; McClurkin & Hall, 1981).

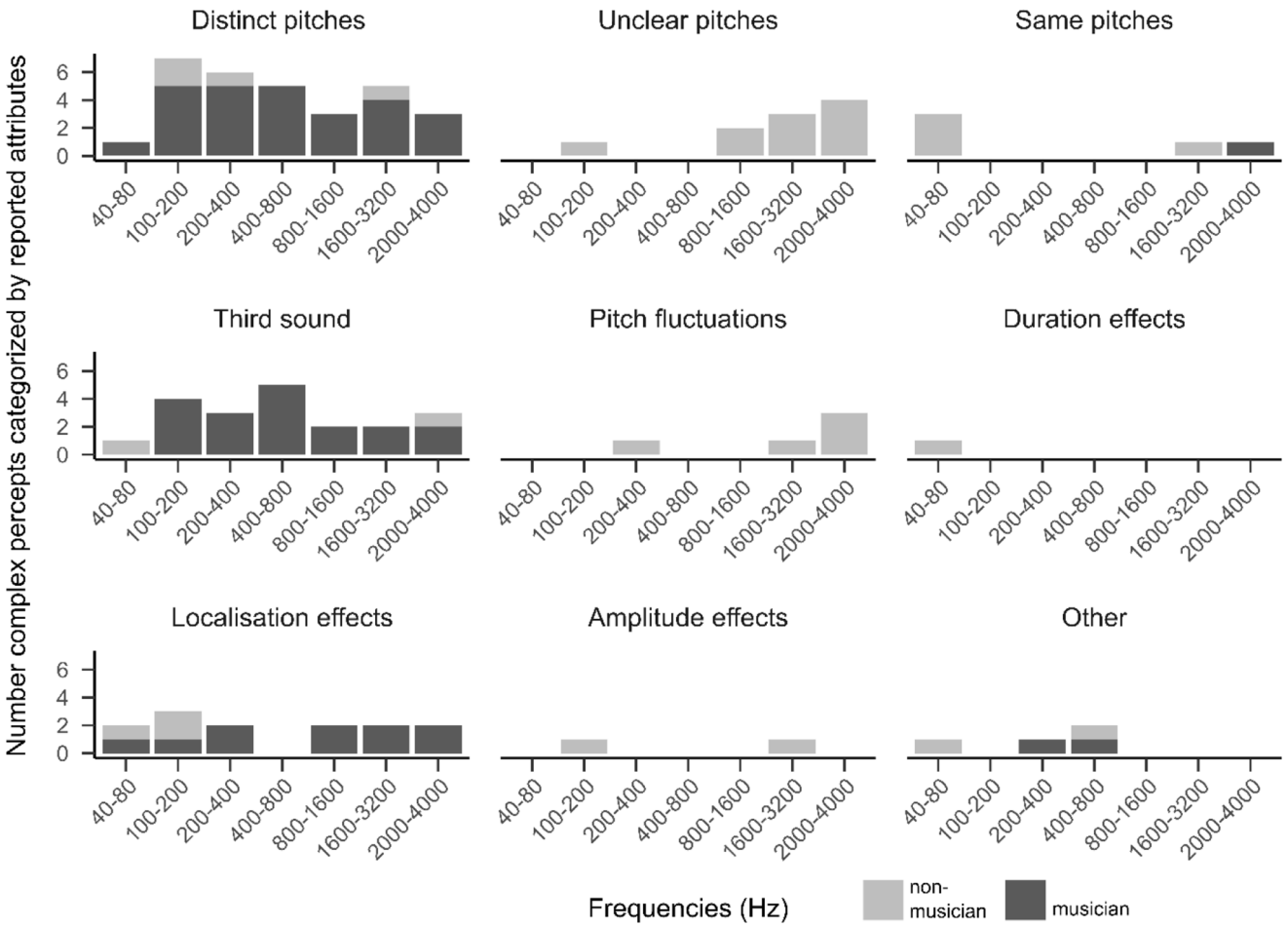

Fig. 4 Number of complex percepts categorized by their reported pitch (Distinct, Unclear, Same) and other reported perceptual attributes. Dark grey represents musicians, light grey represents non-musicians

The octave illusion in musicians

In contrast to non-musicians, where the distribution of percepts varied as a function of the frequency pairs used to elicit the illusion, the distribution of percepts reported by musicians was mostly consistent across all frequency pairs (Fig. 3). At the lowest frequency pair of 40–80 Hz, while only 13% of non-musicians reported hearing the octave percept, more than half of the musicians reported hearing this same percept (Fig. 2). A similar pattern was also observed at 100–200 Hz, where the octave percept was again more commonly reported by musicians (63%) compared to non-musicians (38%). However, at frequencies pairs higher than the classic paradigm of 400–800 Hz, there was no significant difference in the distribution of reported percepts between the musician and non-musician groups (Fig. 2). This suggests an asymmetry, where pitch perception abilities are better preserved by musicians at lower frequencies, but are similarly altered in both musicians and non-musicians at higher frequencies. Pitch discrimination has been shown to becomes particularly difficult at these higher frequencies for musicians and non-musicians (Attneave & Olson, 1971; Bachem, 1948; Moore, 1973; Semal & Demany, 1990; Shower & Biddulph, 1931), it is thus possible that pitch processing decreases at higher frequencies despite musical training. For instance, Ward (1954) found that octave judgments were more variable and less precise at higher frequencies for professional musicians. Some authors have proposed that this high frequency limit to pitch perception is due to changes in the way sound is coded in the cochlea with a shift in the relative efficiency of "place" and "temporal" coding after a certain frequency threshold (Attneave & Olson, 1971; Moore, 1973). Other authors have posited that this phenomenon has a cultural component since high frequency melodies a rare in music (Semal & Demany, 1990; Ward, 1954).

Nonetheless, a clear effect of musical training was observed for the classic octave illusion paradigm of 400–800 Hz and for lower frequencies. There is some data supporting the idea that musicians still have better pitch perception abilities than non-musicians even at lower frequencies (Bianchi et al., 2016). In our study, musicians

were less likely than non-musicians to report the octave percept at 400–800 Hz and were instead more likely to report a complex percept. However, when analyzing the written descriptions of the complex percepts from musicians, we found that most of them explicitly reported hearing different pitches, suggesting that pitch processing was not impaired when musicians reported complex percepts. It appears that many musicians selected the complex instead of the octave percept because they were hearing something that was closer to the veridical perception of the stimulation, such as hearing an additional third sound (Fig. 4). For instance, at 100–200 Hz, three musicians reported hearing a high pitch tone on the right alternating with a low pitch tone on the left, and a third unlocalized (center, ambient) lower pitch sound. Many musicians also reported complex percepts because of different localization patterns rather than altered pitch perception. For example, at 40–80 Hz, one musician reported hearing alternating low- and high-pitched sound in the left ear only. In contrast, non-musicians that reported complex percepts often perceived sounds with ambiguous, fluctuating or no pitch. This finding is coherent with the fact that non-musicians were also more likely to report a simple percept at lower frequencies compared to musicians (Fig. 2).

Previous research on the octave illusion among musicians is scarce. Craig (1979) found that only 50% of musicians reported hearing the octave percept when presented with the 400–800 Hz stimulation paradigm, which is similar to the proportion of musicians reporting the octave percept across all frequency conditions in the present study (Fig. 2). Brennan and Stevens (2002) showed that in musicians with extensive training, a small portion reported a veridical perception (i.e., where the listener's perception matches the true physical stimulus rather than an illusory percept). The veridical perception was not an explicit option in the present study to avoid involuntarily cueing the participants to the stimulation parameters. Instead, participants had to write down what they perceived if their perception did not match one of the pre-defined categories (octave or simple). When analyzing the written answers, we found that no participant reported a veridical perception. This is not unexpected, as Brennan and Stevens (2002) observed a veridical perception only in a minority of musical experts (with an associate diploma recognized by the Australian Music Examinations Board) and in only one other musician. In addition, the veridical perception was an explicit choice presented in musical notation to the participants in Brennan and Stevens (2002). This means that their participants could have selected a veridical perception because it was the closest to their actual perception even if it was not a perfect match, or that they could have achieved a veridical perception by explicitly trying to listen for it. Furthermore, the response choices in the present study were given in writing instead of musical notation, since non-musician participants would not have been familiar with sheet music. Of note, Brennan and Stevens (2002) also reported that pipe organ players were significantly more likely than other equally trained musicians to report a veridical perception. This is hypothesized to be due to shared harmonic and spatial features between pipe organ sounds and the stimuli used to elicit the octave illusion. These findings suggest that the extent of musical training and instrument types are two factors that can shape how the octave illusion is perceived.

Another of Deutsch's illusions that involves dichotic pitches is the scale illusion (Deutsch, 1974c), which uses a dichotic presentation of an ascending and descending scale alternating between the ears. Instead of hearing the scales, listeners often perceive a simultaneous high melody in one ear and low melody in the other. Smith et al. (1982) found that the percepts elicited by this illusion tended to vary in non-musicians when changing acoustic parameters such as the timbre or loudness. In contrast, musicians were more consistent in their choice of percept despite these modulations of the stimulation parameters, and mostly reported the percept in which pitch cues dominate binaural fusion. Butler (1979) also found that pitch was the main auditory attribute guiding the perception of the scale illusion in musicians, and that their perception was resistant to changes in timbre, loudness variations, imperfect attack time, and inconsistent durations. These results suggest that musicians may rely more on pitch for binaural fusion and segregation compared to other acoustic attributes. In our data, musicians were similarly more consistent in their perception despite changes in the stimulation parameter (i.e., frequency), which could be explained by their improved ability to process and use pitch information, particularly at lower frequencies. However, this particularity of musicians raises questions about which neural mechanisms involved in the octave illusion are also modulated by the training in musicians.

Neural correlates of the octave illusion

Exploring the neurophysiological correlates of the octave illusion could provide valuable insights into the central mechanisms involved in pitch processing and sound localization since the illusion is thought to arise from neural units integrating pitch and spatial information that has ostensibly been processed in parallel through the *what* and *where* pathways (Deutsch, 1981b). Neuroanatomical evidence of parallel processing pathways for sound identification (i.e., *what* pathway) and localization (i.e., *where* pathway) was first established by Romanski et al. (1999). This seminal study identified a ventral stream connecting the anterior auditory cortex to the ventral prefrontal cortex, and a dorsal stream connecting the posterior auditory cortex to the dorsolateral

prefrontal cortex through the posterior parietal cortex (Romanski et al., 1999; Belin & Zatorre, 2000). Subsequent investigations of these *what* and *where* pathways were done to clarify how they are involved in translating basic acoustic information into meaningful auditory objects (Rauscheker, 2009, 2011), with advances in neuroimaging now allowing us to map these hierarchical pathways in more details (Rolls et al., 2022). However, few studies have examined the neural mechanisms involved in the octave illusion using neurophysiological methods.

Some electroencephalography (EEG) (Ross et al., 1996) and magneto-electroencephalography (MEG) (Brancucci et al., 2017; Lamminmäki & Hari, 2000) studies have begun to uncover the network of activity associated with the octave illusion. Notably, Brancucci et al. (2017) conducted a MEG study to investigate the neural mechanisms responsible for the octave illusion. To achieve this, the authors compared the neural responses to the classic dichotic 400–800 Hz stimulation paradigm, to a similar stimulation paradigm altered to not evoke the illusion, and to a monaural sequence that mimicked the illusory percept. Their results suggested that the Heschl's gyrus, insular cortex, as well as frontal and parietal areas were involved in the perception of the octave illusion. The morphology and physiology of these regions are known to be modulated by musical training. For instance, Schneider (2002) reported that musicians had increased sound-evoked activity and grey matter volume in the Heschl's gyrus which strongly correlated with musical aptitude. Musical training has also been associated with functional neuroplasticity in insula-based brain networks (Zamorano et al., 2017), notably within the salience network (Luo et al., 2014). Bianchi et al. (2017) found that musicians had increased activity in the Heschl's gyrus and inferior frontal gyrus during pitch discrimination tasks, with an important cluster of enhanced activation being observed near the right Heschl's gyrus, extending to both the insular cortex and the inferior frontal gyrus (Bianchi et al., 2017). Correlations have also been found between the volume of the right inferior frontal gyrus and pitch perception ability in musicians (Palomar-García et al., 2020). Such brain areas that can be subject to neuroplasticity in musicians while also being activated during the octave illusion may provide regions of interest to investigate the differences in perception between musicians and non-musicians.

In their fMRI study, Tanaka et al. (2018) explicitly compared participants who heard the octave percept to participants who did not. The authors found a greater activation in the right premotor cortex in participants who did not hear the octave illusion, leading them to propose that not perceiving the classic octave illusion may be related to better musical meter perception. Grey matter volume in the right ventral premotor cortex has been associated with the age of onset of musical training and with performance in rhythm synchronization tasks (Bailey et al., 2014). Palomar-García et al. (2017) also reported increased resting state connectivity between the right auditory cortex and right ventral premotor cortex, as well as increased right auditory cortex volume, in musicians. This increased volume in auditory and premotor areas, coupled with the increased connectivity between these areas, could have a role in explaining why musicians report the classic octave percept less often than non-musicians.

This study suggests for the first time significant differences between the distribution of percepts across multiple frequency pairs reported by musicians and non-musicians. In line with these new findings, it is expected that musicians and non-musicians would show different patterns of neural activity in response to the octave illusion, particularly at lower frequencies where their distributions of reported percept differ the most. Exploring the impact of musical experience on perception of the octave illusion is helpful to better understand how neural plasticity linked to auditory and multisensory training can shape central auditory processing related to auditory scene analysis.

Conclusion

The study aimed to compare the distribution of percepts during the octave illusion between musicians and non-musicians across the wide frequency range associated with the sensation of pitch. We replicated previous results showing a shift in the most common percept reported by non-musicians when using pairs of stimuli towards the upper and lower boundaries of the musical spectrum where pitch processing becomes degraded. This result is consistent with the hypothesized importance of pitch for the perception of the octave illusion. Since musicians are known to have enhanced pitch perception abilities, we hypothesized that they would have a more consistent distribution of reported percept across frequencies. Our results suggest that it is indeed the case. Musicians are more likely to report the octave illusion and less likely to report simple percepts at lower frequencies. They are also more likely to report complex percepts that match more closely the true nature of the stimuli used to elicit the illusion. The study indicates for the first time that significant differences exist in the perception of the octave illusion under conditions where pitch processing is typically degraded. These findings are opening opportunities to explore the underlying mechanisms of the octave illusion and the functional organization of central auditory processing.

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Data availability The data and code that support the findings of this study are available from the corresponding author upon request.

Declaration

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Approval was granted from the Research Committee for sectorial research in neuroscience and mental health of the CIUSSS—Capitale Nationale.

Informed consent Informed consent was obtained from all individual participants included in the study.

Competing interests The authors declare no competing interests.

References

ANSI, & ASA (2020). *Method for Measurement and Calibration of Earphones* (No. ANSI/ASA S3.7-2016 (R2020)). Acoustical Society of America (ASA). https://asastandards.org/

Attneave, F., & Olson, R. K. (1971). Pitch as a medium: A new approach to psychophysical scaling. *The American Journal of Psychology*, *84*(2), 147–166.

Audacity Team (2021). *Audacity(R): Free Audio Editor and Recorder [Computer program]* (Version 3.0.0). https://www.audacityteam.org/

Bachem, A. (1948). Chroma fixation at the ends of the musical frequency scale. *The Journal of the Acoustical Society of America*, *20*(5), 704–705. https://doi.org/10.1121/1.1906428

Bailey, J. A., Zatorre, R. J., & Penhune, V. B. (2014). Early musical training is linked to Gray matter structure in the ventral premotor cortex and Auditory–Motor rhythm synchronization performance. *Journal of Cognitive Neuroscience*, *26*(4), 755–767. https://doi.org/10.1162/jocn_a_00527

Beatty, R. J. (2007). The history and development of elementary music education in Canada – Curricular perspectives. In K. Veblen, C. Beynon, S. Horsley, U. DeAlwiss, & A. Heywood (Eds.), *From sea to sea: Perspectives on music education in Canada*. Western Libraries, The University of Western Ontario. https://ir.lib.uwo.ca/musiceducationebooks/1

Belin, P., & Zatorre, R. J. (2000). What,' where' and how' in auditory cortex. *Nature Neuroscience*, *3*(10), 965–966. https://doi.org/10.1038/79890

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society Series B (Methodological)*, *57*(1), 289–300.

Bermudez, P., Lerch, J. P., Evans, A. C., & Zatorre, R. J. (2009). Neuroanatomical correlates of musicianship as revealed by cortical thickness and Voxel-Based morphometry. *Cerebral Cortex*, *19*(7), 1583–1596. https://doi.org/10.1093/cercor/bhn196

Besson, M., Schön, D., Moreno, S., Santos, A., & Magne, C. (2007). Influence of musical expertise and musical training on pitch processing in music and Language. *Restorative Neurology and Neuroscience*, *25*(3–4), 399–410.

Bianchi, F., Santurette, S., Wendt, D., & Dau, T. (2016). Pitch discrimination in musicians and Non-Musicians: Effects of harmonic resolvability and processing effort. *JARO: Journal of the Association for Research in Otolaryngology*, *17*(1), 69–79. https://doi.org/10.1007/s10162-015-0548-2

Bianchi, F., Hjortkjær, J., Santurette, S., Zatorre, R. J., Siebner, H. R., & Dau, T. (2017). Subcortical and cortical correlates of pitch discrimination: Evidence for two levels of neuroplasticity in musicians. *Neuroimage*, *163*, 398–412. https://doi.org/10.1016/j.neuroimage.2017.07.057

Biasutti, M. (1997). Sharp low- and high-frequency limits on musical chord recognition. *Hearing Research*, *105*(1–2), 77–84. https://doi.org/10.1016/s0378-5955(96)00205-5

Bidelman, G. M. (2016). Musicians have enhanced audiovisual multisensory binding: experience-dependent effects in the double-flash illusion. *Experimental Brain Research*, *234*(10), 3037–3047. https://doi.org/10.1007/s00221-016-4705-6

Brancucci, A., Padulo, C., & Tommasi, L. (2008). Octave illusion or Deutsch's illusion? *Psychological Research Psychologische Forschung*, *73*(3), 303–307. https://doi.org/10.1007/s00426-008-0153-7

Brancucci, A., Padulo, C., Franciotti, R., Tommasi, L., & Della Penna, S. (2017). Involvement of ordinary what and where auditory cortical areas during illusory perception. *Brain Structure and Function*, *223*(2), 965–979. https://doi.org/10.1007/s00429-017-1538-4

Brännström, K. J., & Nilsson, P. (2011). Octave illusion elicited by overlapping narrowband noises. *The Journal of the Acoustical Society of America*, *129*(5), 3213–3220. https://doi.org/10.1121/1.3571425

Bregman, A. S. (1990). *Auditory scene analysis: The perceptual organization of sound*. The MIT Press. https://doi.org/10.7551/mitpress/1486.001.0001

Brennan, D., & Stevens, C. (2002). Specialist musical training and the octave illusion: Analytical listening and veridical perception by pipe organists. *Acta Psychologica*, *109*(3), 301–314. https://doi.org/10.1016/S0001-6918(01)00063-4

Butler, D. (1979). A further study of melodic channeling. *Perception & Psychophysics*, *25*(4), 264–268. https://doi.org/10.3758/BF03198805

Choi, A., Bang, Y., Park, J. M., & Lee, K. (2024). The effects of musical factors on the perception of auditory illusions. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *46*(207–213).

Chung, K. (2023). Calibration matters: II. Measurement of ambient noise in test rooms/areas. *Journal of Communication Disorders*, *101*, 106293. https://doi.org/10.1016/j.jcomdis.2022.106293

Craig, J. D. (1979). The effect of musical training and cerebral asymmetries on perception of an auditory illusion. *Cortex; A Journal Devoted To the Study of the Nervous System and Behavior*, *15*(4), 671–677. https://doi.org/10.1016/S0010-9452(79)80055-6

Davidson, B., Power, R. P., & Michie, P. T. (1987). The effects of familiarity and previous training on perception of an ambiguous musical figure. *Perception & Psychophysics*, *41*, 601–608. https://doi.org/10.3758/BF03210492

Deutsch, D. (1974a). An auditory illusion. *Nature*, *251*(5473), 307–309. https://doi.org/10.1038/251307a0

Deutsch, D. (1974b). An auditory illusion. *The Journal of the Acoustical Society of America*, *55*(S1), S18–S19. https://doi.org/10.1121/1.1919587

Deutsch, D. (1974c). An illusion with musical scales. *The Journal of the Acoustical Society of America*, *56*(S1), S25. https://doi.org/10.1121/1.1914084

Deutsch, D. (1975). Musical illusions. *Scientific American*, *233*(4), 92–98. https://doi.org/10.1038/scientificamerican1075-92

Deutsch, D. (1978). Lateralization by frequency for repeating sequences of dichotic 400- and 800-Hz tones. *The Journal of the Acoustical Society of America*, *63*(1), 184–186. https://doi.org/10.1121/1.381710

Deutsch, D. (1980). Ear dominance and sequential interactions. *The Journal of the Acoustical Society of America*, *67*(1), 220–228. https://doi.org/10.1121/1.383731

Deutsch, D. (1981a). The octave illusion and auditory perceptual integration. In J. V. Tobias, & E. D. Schubert (Eds.), *Hearing research and theory* (Vol. 1, pp. 99–142). Academic.

Deutsch, D. (1981b). The octave illusion and the What—Where connection. In R. S. Nickerson (Ed.), *Attention and performance Viii* (1st ed., pp. 575–594). Psychology.

Deutsch, D. (1988). Lateralization and sequential relationships in the octave illusion. *The Journal of the Acoustical Society of America*, *83*(1), 365–369. https://doi.org/10.1121/1.396249

Deutsch, D. (2004). The octave illusion revisited again. *Journal of Experimental Psychology: Human Perception and Performance*, *30*(2), 355–364. https://doi.org/10.1037/0096-1523.30.2.355

Deutsch, D., & Roll, P. L. (1976). Separate what and where decision mechanisms in processing a dichotic tonal sequence. *Journal of Experimental Psychology Human Perception and Performance*, *2*(1), 23–29. https://doi.org/10.1037//0096-1523.2.1.23

Fagerland, M. W., & Hosmer, D. W. (2012). A generalized Hosmer-Lemeshow goodness-of-fit test for multinomial logistic regression models. *Stata Journal*, *12*, 447–453.

Fox, J., & Weisberg, S. (2019). *An R companion to applied regression* (3rd ed.). Sage Publications, Inc.

Habibi, A., Wirantana, V., & Starr, A. (2013). Cortical activity during perception of musical pitch: Comparing musicians and nonmusicians. *Music Perception*, *30*(5), 463–479. https://doi.org/10.1525/mp.2013.30.5.463

Herholz, S. C., & Zatorre, R. J. (2012). Musical training as a framework for brain plasticity: Behavior, function, and structure. *Neuron*, *76*(3), 486–502. https://doi.org/10.1016/j.neuron.2012.10.011

Jackman, S. (2024). pscl: Classes and Methods for R Developed in the Political Science Computational Laboratory (Version 1.5.9) [R package]. University of Sydney. https://doi.org/10.32614/CRAN.package.pscl

Kishon-Rabin, L., Amir, O., Vexler, Y., & Zaltz, Y. (2001). Pitch discrimination: Are professional musicians better than Non-Musicians? *Journal of Basic and Clinical Physiology and Pharmacology*, *12*(2), 125–144. https://doi.org/10.1515/JBCPP.2001.12.2.125

Kraus, N., & Chandrasekaran, B. (2010). Music training for the development of auditory skills. *Nature Reviews Neuroscience*, *11*(8), 599–605. https://doi.org/10.1038/nrn2882

Kwak, C., & Clayton-Matthews, A. (2002). Multinomial logistic regression. *Nursing Research*, *51*(6), 404–410. https://doi.org/10.1097/00006199-200211000-00009

Lamminmäki, S., & Hari, R. (2000). Auditory cortex activation associated with octave illusion. *Neuroreport*, *11*(7), 1469–1472.

Landry, S. P., Sharp, A., Pagé, S., & Champoux, F. (2017). Temporal and spectral audiotactile interactions in musicians. *Experimental Brain Research*, *235*(2), 525–532. https://doi.org/10.1007/s00221-016-4813-3

Liang, C., Houston, L. M., Samy, R. N., Abedelrehim, L. M. I., & Zhang, F. (2018). Cortical processing of frequency changes reflected by the acoustic change complex in adult cochlear implant users. *Audiology & Neuro-Otology*, *23*(3), 152–164. https://doi.org/10.1159/000492170

Luo, C., Tu, S., Peng, Y., Gao, S., Li, J., Dong, L., Li, G., Lai, Y., Li, H., & Yao, D. (2014). Long-Term effects of musical training and functional plasticity in salience system. *Neural Plasticity*, *2014*, 180138. https://doi.org/10.1155/2014/180138

McClurkin, R. H., & Hall, J. W. (1981). Pitch and timbre in a two-tone dichotic auditory illusion. *The Journal of the Acoustical Society of America*, *69*(2), 592–594. https://doi.org/10.1121/1.385376

McGurk, H., & MacDonald, J. (1976). Hearing lips and seeing voices. *Nature*, *264*(5588), 746–748. https://doi.org/10.1038/264746a0

Moore, B. C. J. (1973). Frequency difference Limens for short-duration tones. *The Journal of the Acoustical Society of America*, *54*(3), 610–619. https://doi.org/10.1121/1.1913640

Nederlanden, V. B. D., Zaragoza, C. M., Rubio-Garcia, C., Clarkson, A., E., & Snyder, J. S. (2020). Change detection in complex auditory scenes is predicted by auditory memory, pitch perception, and years of musical training. *Psychological Research Psychologische Forschung*, *84*(3), 585–601. https://doi.org/10.1007/s00426-018-1072-x

Oehler, M., & Reuter, C. (2013). The octave illusion and handedness: A replication of Deutsch's 1974 study. *Musicae Scientiae*, *17*(3), 277–289. https://doi.org/10.1177/1029864913493801

Palomar-García, M. Á., Zatorre, R. J., Ventura-Campos, N., Bueichekú, E., & Ávila, C. (2017). Modulation of functional connectivity in Auditory–Motor networks in musicians compared with nonmusicians. *Cerebral Cortex*, *27*(5), 2768–2778. https://doi.org/10.1093/cercor/bhw120

Palomar-García, M. Á., Hernández, M., Olcina, G., Adrián-Ventura, J., Costumero, V., Miró-Padilla, A., Villar-Rodríguez, E., & Ávila, C. (2020). Auditory and frontal anatomic correlates of pitch discrimination in musicians, non-musicians, and children without musical training. *Brain Structure & Function*, *225*(9), 2735–2744. https://doi.org/10.1007/s00429-020-02151-1

Pecunioso, A., & Agrillo, C. (2021). Do professional musicians perceive numerosity illusions differently? *Psychology of Music*, *49*(3), 631–648. https://doi.org/10.1177/0305735619888804

Pressnitzer, D., Suied, C., & Shamma, S. A. (2011). Auditory scene analysis: The sweet music of ambiguity. *Frontiers in Human Neuroscience*, *5*(158). https://doi.org/10.3389/fnhum.2011.00158

R Core Team. (2024). *R: A Language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rauschecker, J. P. (2009). Cortical processing streams and central auditory plasticity. In A. T. Cacace, & D. J. McFarland (Eds.), *Controversies in central auditory processing disorder* (pp. 61–82). Plural Publishing.

Rauschecker, J. P. (2011). An expanded role for the dorsal auditory pathway in sensorimotor control and integration. *Hearing Research*, *271*(1–2), 16–25. https://doi.org/10.1016/j.heares.2010.09.001

Robinson, D. W., & Dadson, R. S. (1956). A re-determination of the equal-loudness relations for pure tones. *British Journal of*

Applied Physics, *7*(5), 166–181. https://doi.org/10.1088/0508-3443/7/5/302

Rolls, E. T., Rauschecker, J. P., Deco, G., Huang, C. C., & Feng, J. (2022). Auditory cortical connectivity in humans. *Cerebral Cortex*, *33*(10), 6207–6227. https://doi.org/10.1093/cercor/bhac496

Romanski, L. M., Tian, B., Fritz, J., Mishkin, M., Goldman-Rakic, P. S., & Rauschecker, J. P. (1999). Dual streams of auditory afferents target multiple domains in the primate prefrontal cortex. *Nature Neuroscience*, *2*(12), 1131–1136. https://doi.org/10.1038/16056

Ross, J., Tervaniemi, M., & Näätänen, R. (1996). Neural mechanisms of the octave illusion. *Neuroreport*, *8*(1), 303–306. https://doi.org/10.1097/00001756-199612200-00060

Schneider, P., Scherg, M., Dosch, H. G., Specht, H. J., Gutschalk, A., & Rupp, A. (2002). Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nature Neuroscience*, *5*(7), 688–694. https://doi.org/10.1038/nn871

Semal, C., & Demany, L. (1990). The upper limit of musical pitch. *Music Perception*, *8*(2), 165–175. https://doi.org/10.2307/40285494

Shepard, R. N. (1964). Circularity in judgments of relative pitch. *The Journal of the Acoustical Society of America*, *36*(12), 2346–2353. https://doi.org/10.1121/1.1919362

Shower, E. G., & Biddulph, R. (1931). Differential pitch sensitivity of the ear. *The Journal of the Acoustical Society of America*, *3*(2A), 275–287. https://doi.org/10.1121/1.1915561

Sivonen, V. P., & Ellermeier, W. (2011). Binaural Loudness. In: M. Florentine, A. Popper & R. Fay, (Eds.) *Loudness.* Springer Handbook of Auditory Research, vol 37. Springer. https://doi.org/10.1007/978-1-4419-6712-1_7

Smith, T. J., & McKenna, C. M. (2013). A comparison of logistic regression Pseudo R2 indices. *Multiple Linear Regression Viewpoints*, *39*(2), 17–26.

Smith, J., Hausfeld, S., Power, R. P., & Gorta, A. (1982). Ambiguous musical figures and auditory streaming. *Perception & Psychophysics*, *32*(5), 454–464. https://doi.org/10.3758/BF03202776

Tanaka, K., Kurasaki, H., & Kuriki, S. (2018). Neural representation of octave illusion in the human cortex revealed with functional magnetic resonance imaging. *Hearing Research*, *359*, 85–90. https://doi.org/10.1016/j.heares.2018.01.001

Venables, W. N., & Ripley, B. D. (2002). Modern Applied Statistics with S (4th ed.). Springer. https://doi.org/10.1007/978-0-387-21706-2

Ward, W. D. (1954). Subjective musical pitch. *Journal of the Acoustical Society of America*, *26*(3), 369–380. https://doi.org/10.1121/1.1907344

Whittom, A., Couture, F., Chauvette, L., & Sharp, A. (2023). Octave illusion: Stimulation frequencies can modulate perception. *Psychological Research Psychologische Forschung*, *87*(7), 2183–2191. https://doi.org/10.1007/s00426-023-01805-z

Zamorano, A. M., Cifre, I., Montoya, P., Riquelme, I., & Kleber, B. (2017). Insula-based networks in professional musicians: Evidence for increased functional connectivity during resting state fMRI. *Human Brain Mapping*, *38*(10), 4834–4849. https://doi.org/10.1002/hbm.23682

Zeileis, A., & Hothorn, T. (2002). Diagnostic checking in regression relationships. *R News*, *2/3*, 7–10.