Two /i/ or Not Two /i/?

Hearing aid delay and coloration pitch for vowel sounds.

By Christopher Slugocki, PhD; Francis Kuk, PhD; and Petri Korhonen

Introduction

Awareness concerning the perils of untreated hearing loss has become increasingly widespread, most notably with regard to the increased risk of developing dementia.[1] As such, individuals experiencing self-perceived hearing deficits may now be more likely to seek early treatment when their sensorineural losses would be considered mild-to-moderate. At the same time, with a relatively high degree of residual hearing, these listeners can easily feel discouraged when the audio quality of hearing aids does not meet their expectations.[2] To facilitate adjustment, clinicians often prescribe hearing aids with open or vented instant fit ear-tips, which can accommodate residual low-frequency hearing, provide adequate amplification for mild-to-moderate losses, and minimize the unnatural percepts due to the occlusion effect experienced with closed fittings.[3] Still, wearers of open/vented hearing aids often complain that their devices sound hollow, unnatural, or like a hearing aid.[2]

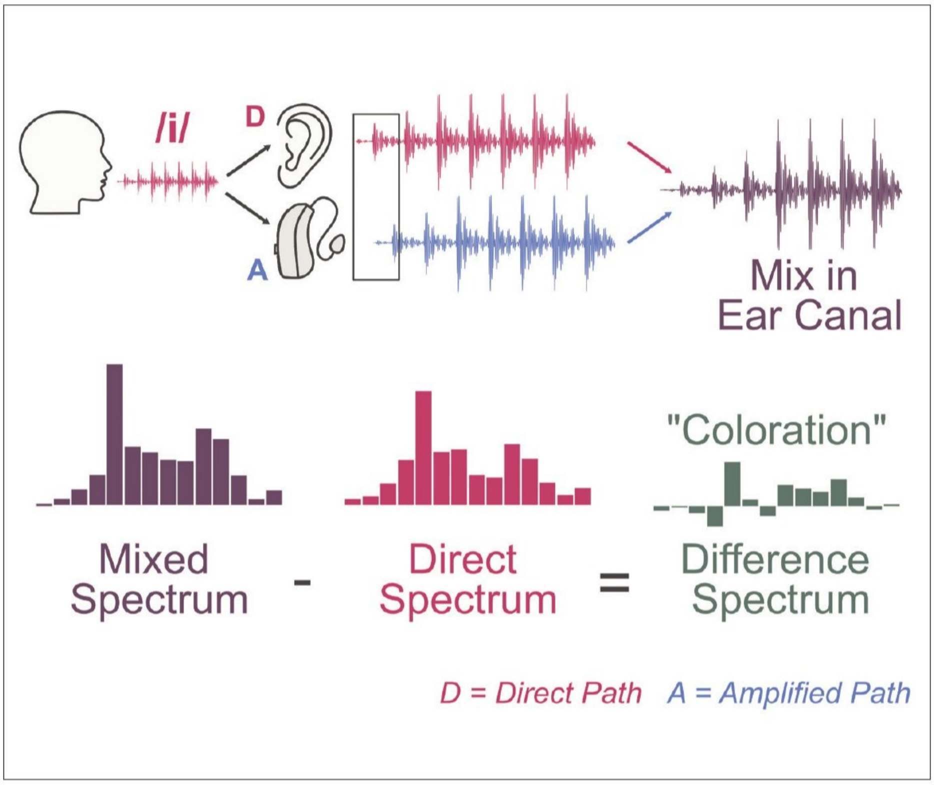
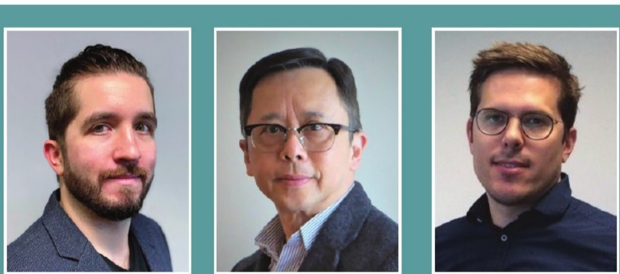


Figure 1. Schematic showing the effect of an 8 ms hearing aid delay on the acoustics of the vowel sound /i/.

A primary source of acoustic distortion in open/vented fittings is known as the "comb-filter" effect.[4] Comb filtering refers to the spectral distortion that results from a timing mismatch between the arrival of direct unamplified sound into the listener's ear canal via the open or vented ear-tip and that of amplified sound, which is delayed by the signal processing pathway of the hearing aid. The delayed amplified signal interacts with the direct sound to create patterns of alternating constructive and destructive interference, leading to peaks and troughs in the gain-frequency curve which resemble the teeth of a comb. Listeners perceive comb filtering as a secondary pitch or "coloration" of the original sound. The percept has been termed "coloration pitch," where the perceived pitch is related to the duration of the processing delay (**Figure 1**).

Few sounds imprint themselves on us so powerfully as the familiar voices of friends and family. Indeed, a surprising amount of information related to the identity of a talker can be derived from units of speech as short as a single vowel.[5] Familiar voices have been shown to help improve speech intelligibility in challenging listening environments[6] and can even enhance how strongly listeners' brains respond to hearing their own names.[7] Yet, the degree to which coloration pitch might influence these familiar voice effects remains an open question.

Research has already shown that listeners with a mild-to-moderate hearing loss are sensitive to the effects of hearing aid delay in open fittings. For example, in double-blind A-B comparisons across a range of indoor and outdoor real-life scenarios, listeners overwhelmingly preferred the Widex PureSound program featuring ZeroDelay technology (0.5 ms delay) over devices with a longer processing delay of 2.5 ms.[8] In a second study, listeners were better able to discriminate between listening positions within a reverberant room when listening with the Widex PureSound program compared to other top-of-the-line



Christopher Slugocki, PhD, is a research scientist, **Francis Kuk, PhD,** is the director, **and Petri Korhonen** is a senior research scientist at the WS Audiology Office of Research in Clinical Amplification (ORCA) in Lisle, Ill.

hearing aids with longer delay times of 5 and 8 ms.[9] This kind of spatial task relies on accurately resolving the natural coloration pitch of sounds that occurs when those sounds interact with their own reflections off of walls.

More recently, Stiefenhofer (2023,[10]) used a sophisticated program designed to precisely simulate the ear-canal acoustics of open-fit hearing aids with parametrically varied delay times. That study found that listeners with mild-to-moderate losses were able to use the coloration pitch to discriminate pink noise bursts processed with simulated delays as low as 0.6–1 ms from those processed with zero simulated delay.

Inspired by earlier work showing that the neural encoding of vowel sounds is facilitated by Widex ZeroDelay technology,[11,12]we applied the hearing aid delay simulator used in Stiefenhofer (2023,[10]) to ask whether listeners with mild-to-moderate hearing loss are able to detect coloration pitch when listening to more realistic stimuli, namely different vowel sounds.

Methods

Participants

Nineteen native English-speaking adults (mean age = 73 years, range 55–84 years) with symmetrical bilateral sensorineural hearing loss (**Figure 2**) and normal cognitive function participated in the study. Only five of the 19 listeners had previous experience with receiver-in-the-canal (RIC) style hearing aids (range 3 months to 8 years).

Hearing Aid Delay Simulator

Participants were tested in a simulated aided mode with synthetic vowel sounds processed by a hearing aid delay simulator10 that accurately re-creates the acoustic mixture of direct sound and the output from an open-fit hearing aid as would be measured at a KEMAR mannikin's "ear drum." The simulator considered each listener's audiometric thresholds and provided gain based on the NAL-NL2 fitting rationale. The simulated hearing aid did not have any advanced hearing aid features enabled (e.g., no noise reduction, directional microphone, or classifier). The final processed stimuli were presented to listeners via ER-2 ear-insert transducers, which are designed to accurately reproduce stimuli recorded through a KEMAR mannikin.

Procedure

The study followed a double-blind within-subjects design. Listener sensitivity to possible coloration pitch for five synthetically produced vowels (/i/, /æ/, /⊠/, /u/, and /⊠/) was assessed using a three-alternative forced choice (3AFC) task. In a given trial, listeners were presented with three instances of the same vowel. Two of the vowel sounds were processed with a simulated delay of 0 ms. The third vowel sound was processed with one of three longer delay times: 0.5, 5.0, or 8.0 ms. The order of the three stimuli was randomized, and listeners were asked to identify which stimulus interval sounded different from the other two by pressing corresponding buttons on a touchscreen monitor (i.e., '1', '2', or '3'). Each vowel and processing delay time combination was repeated five times for a total of 100 trials presented per listener.

Results

On this kind of 3AFC task, we would expect the discrimination performance of someone who is guessing (i.e., chance performance) to be about 33%. If listeners are sensitive to coloration pitch for different vowel sounds caused by the simulated delay, then we would expect their discrimination scores to be higher than 33%. On the other hand, discrimination scores closer to 33% would indicate that listeners had difficulty identifying the simulated delay condition from the "natural" 0 ms delay condition.

On average, the results showed that listeners performed above chance levels in all simulated delay conditions. However, performance was closest to chance for the 0.5 ms (i.e., PureSound) condition at 42.5%. Discrimination performance then increased with increasing delay time, from 52% at 5 ms of delay to 57% at 8 ms of delay.

Statistical analysis confirmed that delay time had a significant effect on listeners' overall abilities to discriminate vowel sounds processed with a non-zero delay

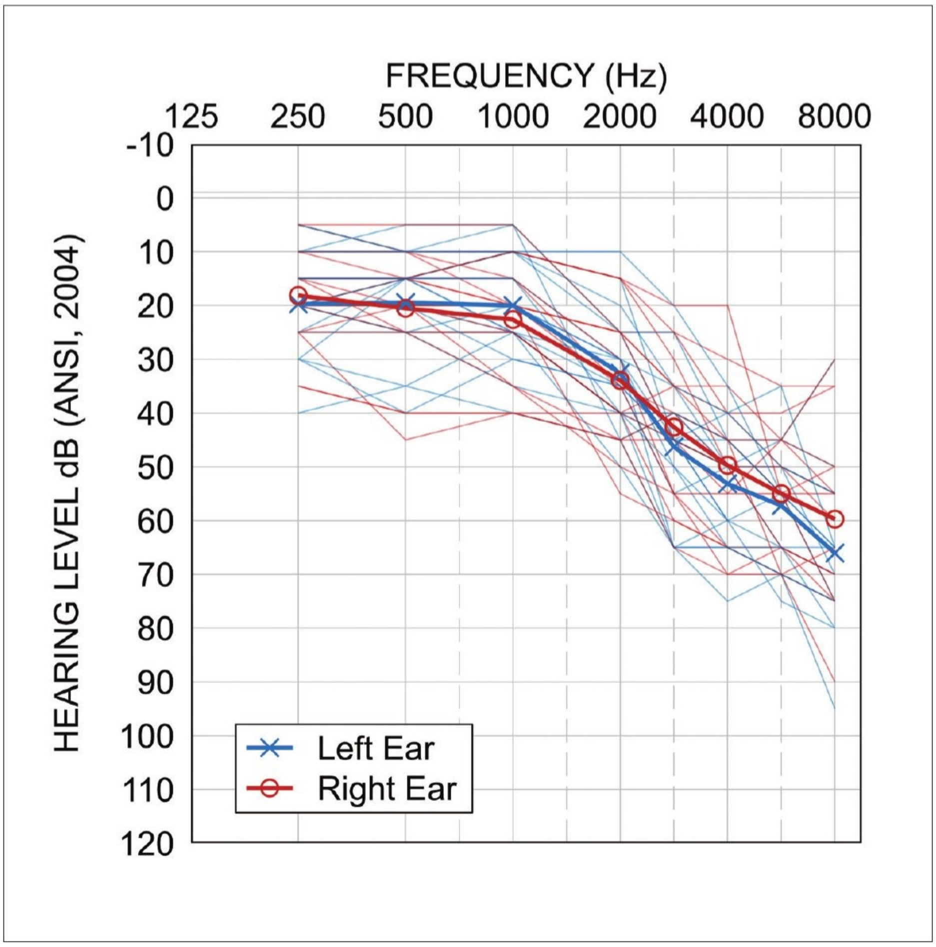


Figure 2. Air conduction thresholds for each listener (thin lines) measured using insert earphone transducers. The bold lines show the mean hearing loss across subjects.

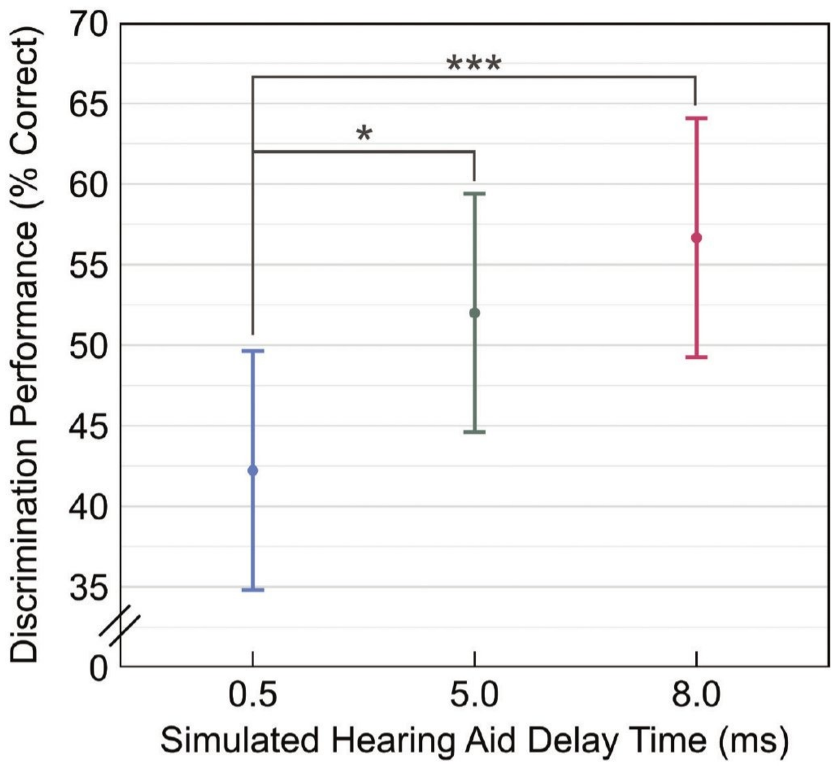


Figure 3. Post-hoc analysis comparing vowel discrimination performance across three different simulated delay conditions. Points represent estimated marginal means and error bars represent the 95% confidence intervals of those means. Horizontal bars with asterisks denote significant contrasts after Tukey adjustment for multiple comparisons, * $p < 0.05$, *** $p < 0.001$.

from those processed with no delay ($\chi 2(2) = 18.04$, $p < 0.001$). Specifically, listeners were better able to discriminate the vowels processed with delay times of 5 and 8 ms from the zero-delay condition than those processed with a delay time of 0.5 ms (**Figure 3**). This means that stimuli processed with more than 5 ms of delay sounded different, while those processed with the 0.5 ms delay sounded most similar to the natural 0 ms reference vowels.

Discussion

According to MarkeTrak surveys, the leading determiner of listeners' satisfaction with their hearing aids is "performance and sound quality." Moreover, a top contributor to this factor is that the hearing aids are natural sounding.2 Though it may mean different things to different people, a common understanding of naturalness is the absence of obvious human intervention. In this sense, any audible distortion, such as coloration pitch, that reminds wearers they are wearing a hearing aid may be considered unnatural.

In this study, we have shown that delay times of 5 and 8 ms can cause coloration-pitch distortions for vowel sounds that make them sound significantly different from the more "natural" vowels processed with 0 ms delay. Conversely, vowels processed with the delay time of 0.5 ms from the Widex PureSound program were significantly more difficult to differentiate from the "natural" 0 ms delay vowels.

Whereas it was once held that hearing aid delays below 10 ms are acceptable for open fittings,4 our results contribute to a growing body of recent work showing that delay times shorter than 10 ms can still influence how wearers with open fittings qualitatively experience the sound processed through their hearing aids. By minimizing audible coloration of sounds in open fittings, the Widex PureSound program may help new hearing aid users adjust to their devices and perhaps, for even a moment, forget they are wearing a hearing aid. ◗

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