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Effects of Age on Concurrent Vowel Perception in Acoustic and Simulated Electroacoustic Hearing

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Abstract

Purpose—In this study, the authors investigated the effects of age on the use of fundamental frequency differences (ΔF_0) in the perception of competing synthesized vowels in simulations of electroacoustic and cochlear-implant hearing.

Method—Twelve younger listeners with normal hearing and 13 older listeners with (near) normal hearing were evaluated in their use of ΔF_0 in the perception of competing synthesized vowels for 3 conditions: unprocessed synthesized vowels (UNP), envelope-vocoded synthesized vowels that simulated a cochlear implant (VOC), and synthesized vowels processed to simulate electroacoustic stimulation (EAS) hearing. Tasks included (a) *multiplicity*, which required listeners to identify whether a stimulus contained 1 or 2 sounds and (b) *double-vowel identification*, which required listeners to attach phonemic labels to the competing synthesized vowels.

Results—Multiplicity perception was facilitated by ΔF_0 in UNP and EAS but not in VOC, with no age-related deficits evident. Double-vowel identification was facilitated by ΔF_0 , with ΔF_0 benefit largest in UNP, reduced in EAS, and absent in VOC. Age adversely affected overall identification and ΔF_0 benefit on the double-vowel task.

Conclusions—Some but not all older listeners derived ΔF_0 benefit in EAS hearing. This variability may partly be due to how listeners are able to draw on higher-level processing resources in extracting and integrating cues in EAS hearing.

Keywords

aging; competing speech perception; electroacoustic hearing; envelope and fine structure perception

In *Older Americans 2008*, the Federal Interagency Forum on Aging-Related Statistics (2008) reported that approximately 37 million people (12% of the U.S. population) were 65 or older in 2006. By 2030, approximately 71.5 million people (20% of the U.S. population) are projected to be 65 or older. This same publication reported that hearing loss occurs in

approximately 32% of adults who are 65–74 years of age, 46% of adults who are 75–84 years of age, and more than 60% of adults over 85 years of age. Taken together, these statistics suggest that the number of older adults with hearing loss will increase substantially in the next 2 decades. Many of these older adults will be candidates for hearing aids, for cochlear implants, and for hearing systems that combine hearing aids (acoustic stimulation) and cochlear implants (electrical stimulus). In the present research, we focused on older adults' ability to benefit from combined electro-acoustic stimulation (EAS). Compared with listeners who have traditional cochlear implants, listeners with combined EAS hearing purportedly receive improved representation of fundamental frequency (F_0) information. In this study, we sought to learn whether older listeners are at a disadvantage in using F_0 information in the perception of competing talkers when using EAS hearing.

Role of F_0 Differences in Normal Hearing

The F_0 of a talker's voice plays a role in speech perception. For speech presented in quiet, F_0 contributes to the identification of talker gender (Gelfer & Mikos, 2005; Hillenbrand & Clark 2009; Whiteside, 1998), to the perception of lexical information in tonal languages (Kuo, Rosen, & Faulkner, 2008), and to the perception of prosody (Bachorowski, 1999). F_0 also helps with concurrent speech perception. For example, two talkers are easier to understand when their voice pitches are different. In younger listeners with normal hearing, recognition of competing sentences (Bird & Darwin, 1998; Brokx & Nooteboom, 1982) as well as competing vowels (Assmann & Summerfield, 1990; Culling & Darwin, 1993; de Cheveigné, Kawahara, Tsuzaki, & Aikawa, 1997; Meddis & Hewitt, 1992; Scheffers, 1983; Arehart, King, & McLean-Mudgett, 1997) improves as F_0 differences are increased. Discerning whether one or two vowels is present in a double-vowel stimulus also improves as F_0 differences increase (Arehart, Rossi-Katz, & Swensson-Prutsman, 2005; Assmann & Paschall, 1998; de Cheveigné et al., 1997).

For complex tones presented in quiet, temporal fine structure of resolved lower-frequency harmonics provides a more robust cue for pitch perception than the high-rate temporal envelope fluctuations caused by the interaction of higher-frequency unresolved harmonics. The dominance of low-frequency resolved harmonics is supported by F_0 discrimination studies, which showed that F_0 difference limens were smaller for stimuli containing only low-frequency resolved harmonics than for stimuli containing only unresolved high-frequency harmonics (e.g., Arehart, 1994; Bernstein & Oxenham, 2003; Houtsma & Smurzynski, 1990). Despite its reduced salience, the temporal envelope cues produced by the interactions of higher-order unresolved harmonics are sufficient to convey melodic pitch information (Houtsma & Smurzynski, 1990). F_0 information from low-frequency resolved harmonics has also been shown to be most important in mediating the use of small F_0 differences in the perception of competing vowels (Culling & Darwin, 1993; Rossi-Katz & Arehart, 2005) and in the perception of competing sentences (Bird & Darwin, 1998), with information from higher-frequency regions also contributing to the use of F_0 cues at larger F_0 differences.

Role of F_0 Differences in Cochlear Implant Hearing

Processing strategies for cochlear implants typically band pass filter the incoming speech. The envelopes within each band are extracted, low-pass filtered, compressed to fit the electrical dynamic range, and then used to modulate trains of electrical pulses. Such processing schemes provide listeners with temporal envelope (periodicity) cues but not fine structure cues because the spectral detail is too sparse to provide the user with information about the frequencies of individual harmonics (Wilson & Dorman, 2008).

Even without the availability of fine structure cues, individuals with cochlear implants have been shown to achieve some degree of voice pitch perception when listening in quiet. For example, cochlear implant users are able to discriminate male and female voices (Dorman, Gifford, Spahr, & McKarns, 2008; Fu, Chinchilla, Nogaki, & Galvin, 2005). Another line of evidence has shown that cochlear implant listeners are able to recognize Mandarin tones at above-chance levels, with best performers achieving approximately 70% correct on tone recognition tasks (e.g., Wei, Cao, & Zeng, 2004). Cochlear implant users are also able to discriminate rising versus falling contours, albeit not as well as listeners with normal hearing (Chatterjee & Peng, 2008). In contrast, cochlear implant users do not benefit in their ability to understand speech when F_0 differences are introduced between competing talkers. For example, the individuals with cochlear implants in Stickney, Assman, Chang, and Zeng (2007) were presented with competing sentences that had average F_0 s that ranged from 0 semitones (no difference) to 15 semitones (more than an octave difference). The word identification scores of the individuals with cochlear implants did not change as the average F_0 difference between the competing talkers increased. Cullington and Zeng (2008) also reported that cochlear implant recipients had difficulty identifying the number and gender of competing talkers, even when the competing talkers, who were of different genders (male and female), had disparate F_0 s.

Listeners who were presented with simulations of cochlear implants showed a similar difficulty in benefiting from F_0 differences between competing talkers (Carroll & Zeng, 2007; Cullington & Zeng, 2008; Qin & Oxenham, 2005; Stickney, Zeng, Litovsky, & Assmann, 2004; Stickney et al., 2007). In these studies, individuals with normal hearing listened to speech subjected to speech processing that is analogous to the speech processing in cochlear implants: An envelope vocoder divides the incoming signal into several contiguous frequency channels, extracts the temporal envelope from each of the channels, and then applies each channel's envelope modulation to a sine wave or white-noise carrier filtered to have the same bandwidth (e.g., Rosen, Faulkner, & Wilkinson, 1999; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995; Souza & Rosen, 2009; Stickney et al., 2007). Because only the envelope modulation is preserved within each channel, this type of processing limits resolution of individual harmonics and, for a noise carrier, removes temporal fine structure cues. Listeners with normal hearing who were presented with competing vowels (Qin & Oxenham, 2005) and with competing sentences (Carroll & Zeng, 2007; Cullington & Zeng, 2008; Stickney et al., 2004, 2007) processed through an envelope vocoder showed no benefit from F_0 differences. In addition, subjects with normal hearing who were presented with cochlear implant simulations had difficulty identifying the number of competing talkers in stimuli with relatively large F_0 differences (Cullington & Zeng, 2008). Thus, cues that are based on F_0 differences in envelope-vocoded stimuli are insufficient for young adults with normal hearing to accurately identify both the number and the content of competing speech sounds.

Role of F_0 Differences in EAS

Combined electric and acoustic stimulation (EAS) is one recent development in cochlear implant design and technology that may allow individuals to have improved representation and access to F_0 information (Wilson & Dorman, 2008). EAS allows listeners to combine residual hearing in the low frequencies with electrical hearing provided either by a short electrode in the same ear (Gantz et al., 2009) or by a traditional cochlear implant in the opposite ear (Dorman et al., 2008). Several studies have shown that subjects with short-electrode EAS hearing systems have better speech recognition in backgrounds with competing talkers than do patients who are fit with traditional cochlear implants (Turner, Gantz, Vidal, Behrens, & Henry, 2004; Turner, Gantz, & Reiss, 2008).

One line of experimental evidence suggests that EAS benefit (defined here as the improvement in perceptual tasks obtained with EAS hearing configurations compared to traditional cochlear implant configurations) may be due, in part, to better perception of F_0 cues in EAS hearing compared with cochlear implant hearing. Kong, Stickney, and Zeng (2005) showed that EAS benefit in a group of cochlear implant users with electrical hearing in one ear and residual low-frequency hearing in the opposite ear was greater when the target and masker voices were of different gender (and, thus, had greater differences in their F_0 s) than when the target and masker voices were of the same gender. In addition, Brown and Bacon (2009a) recently reported that listeners with EAS hearing had nearly as much EAS benefit when the acoustic portion of the target speech was replaced by a tone that tracked both the F_0 and amplitude envelope of the target talker. A subset of the listeners in the Brown and Bacon report also showed substantial EAS benefit when they were tested with a pure tone that tracked only the F_0 of the target talker. Zhang, Dorman, and Spahr (2010) measured sentence recognition in babble noise in nine listeners with a cochlear implant in one ear and low-frequency residual hearing in the opposite ear. The subjects showed significant EAS benefit, with the majority of the benefit coming from the frequency region of the F_0 .

Results of several studies using cochlear implant simulations also support the idea that the ability to use F_0 differences contributes to EAS benefit (Brown & Bacon, 2009b; Chang, Bai, & Zeng, 2006; Qin & Oxenham, 2006). For example, Qin and Oxenham (2006) showed that when an unprocessed low-frequency sound (<600 Hz; which provides information about the temporal fine structure of low-frequency harmonics) was combined with higher-frequency (>600 Hz) acoustic simulations of cochlear implant-processed speech, listeners with normal hearing showed significant benefit from F_0 for both competing-sentence and competing-vowel tasks.

Another set of recent studies has called into question whether F_0 plays a primary role in EAS benefit (e.g., Kong & Carlyon, 2007; Li & Loizou, 2007). For example, Kong and Carlyon (2007) used simulations to study the role of various cues in EAS benefit. They reported that the significant EAS benefit observed with the addition of a low-frequency acoustic signal was absent when the low-frequency signal was replaced by a complex tone that followed the F_0 contour. Furthermore, an EAS benefit was observed in one condition in which the F_0 contours were removed from the signal. Li and Loizou (2008) proposed that glimpsing of the target talker plays a major role in EAS benefit—that is, the low-frequency acoustic portion of the EAS stimulus provides listeners with time-frequency regions in which they are able to detect the target speech, and these glimpses then provide the listener with the opportunity to latch onto and integrate multiple cues (e.g., F_0 , first formant, voicing and onset cues) from the target speech.

In summary, listeners with real and simulated EAS hearing have been shown to benefit from F_0 differences in the perception of competing talkers, a benefit that is not evident in real or simulated cochlear implant hearing. In addition, F_0 information may not be necessary for EAS benefit. Finally, when F_0 cues contribute to EAS benefit, their use may be mediated by a glimpsing mechanism.

Role of F_0 Differences in Hearing by Older Adults

Aging can adversely affect neural encoding of the temporal properties of sounds in both lower and higher levels of the auditory system (e.g., Frisina et al., 2000; Hellstrom & Schmiedt, 1990; Walton, Simon, & Frisina, 2002). Such age-related deficits in temporal processing might impact the ability of older listeners to process temporal fine structure (e.g., Gordon-Salant & Fitzgibbons, 1993; Strouse, Ashmead, Ohde, & Grantham, 1998) and

periodicity cues (e.g., Souza & Boike, 2006) and, hence, may impact the ability of older listeners to utilize F_0 differences. In support of this conjecture, older adults with (near) normal hearing have been shown to have more difficulty processing F_0 information for sounds presented in quiet, as evidenced by F_0 difference limens that are significantly larger in older subjects than in younger subjects (Souza, Arehart, Miller, & Muralimanohar, 2010; Vongpaisal & Pichora-Fuller, 2007). Older adults also show increased difficulty using F_0 differences to perceive competing talkers (e.g., Rossi-Katz & Arehart, 2009; Snyder & Alain, 2005; Summers & Leek, 1998; Vongpaisal & Pichora-Fuller, 2007). For example, Summers and Leek (1998) reported that age negatively impacted the ability of listeners with hearing loss to benefit from F_0 differences in a double-vowel identification task. Although Vongpaisal and Pichora-Fuller (2007) and Snyder and Alain (2005) both reported that younger and older listeners in their studies showed comparable benefit in double-vowel identification due to F_0 differences, both studies also reported age-related deficits in the overall identification rates of double vowels. In addition, Vongpaisal and Pichora-Fuller (2007) reported age-related declines in the ability of listeners to utilize F_0 differences in the identification of stimuli containing two concurrent vowels with the same formants (and, thus, with the same phonemic label). The older adults in Snyder and Alain (2005) also showed longer reaction (processing) time for competing vowel tokens with small F_0 differences as well as age-related changes in an event-related potential (ERP) called *object-related negativity* (ORN), which is related to the auditory object segregation and the automatic processing of F_0 differences. Taken together, the results of these studies suggest age-related declines in the ability of older listeners to effectively utilize F_0 differences in double-vowel identification.

Finally, age may also adversely affect the ability of older listeners to effectively use F_0 differences to determine whether a double-vowel stimulus contains one or two sounds. Alain and MacDonald (2007) measured the effects of age on the ability of listeners to detect two sounds when a complex periodic tone had a single harmonic that was mistuned by 0%, 4%, or 16%. Compared with younger adults, older listeners once again showed reduced ORN responses and also had a greater likelihood of saying that two sounds were present with no mistuning and a lower likelihood of saying that two sounds were present when the harmonic was mistuned by 16%. Although the task in Alain and MacDonald (2007) was not specifically a double-vowel task, the authors noted that the mistuned harmonic of the complex tone might be perceived as being associated with a second F_0 and a second voice.

Aging and EAS Hearing

Recent clinical reports have suggested that older listeners may not derive as much benefit from EAS devices as do younger adults (Gantz et al., 2009; Luetje, Thedinger, Buckler, Dawson, & Lisbona, 2007). The present study focuses on older listeners' use of the various cues transmitted by EAS as well as traditional implants, with the goal of quantifying possible age-related deficits in EAS benefit. The observation that older adults may not benefit from EAS devices as much as younger adults, on the one hand, and the evidence (reviewed earlier in this article) that older adults have increased difficulty in processing F_0 differences between competing talkers, on the other hand, lead us to hypothesize that deficits in F_0 processing may contribute to age-related decrements in the ability of listeners to benefit from EAS hearing. The primary research question addressed in this study is as follows: How does age affect the ability of listeners to use F_0 differences in the perception of concurrent sounds in three different hearing configurations: (a) normal hearing, (b) EAS hearing, and (c) traditional cochlear implants?

Our experimental approach is to evaluate the effects of age on the ability of adults with (near) normal hearing to perceive double vowels using noise vocoder simulations of EAS

and cochlear implant hearing. The use of vocoder simulations allows us to separate the effects of age from other possibly confounding factors that may be present in older patients with actual EAS systems (e.g., age of implantation, duration of deafness, and co-morbid health issues). Vocoder simulations can be implemented with either noise or sine wave carriers. In the present research, we have chosen to use vocoder simulations with a noise carrier. Recent studies suggest that performance on tasks involving the use of F_0 cues by listeners with normal hearing who were presented with simulations using tonal carriers often exceeds performance on comparable tasks by cochlear implant users. In contrast, performance on speech perception tasks involving F_0 cues is more similar between cochlear implant users and listeners with normal hearing who were presented with simulations with noise carriers (Chatterjee & Peng, 2008; Souza & Rosen, 2009; Stone, Fullgrabe, & Moore, 2008). In addition, Souza and Rosen (2009) suggested that noise-vocoded speech represents a better model for perception of F_0 by cochlear implant wearers because the noise vocoder eliminates fine-structure cues, whereas sine-vocoded speech contains spectral detail not accessible in a traditional cochlear implant (Stone et al., 2008; Whitmal, Poissant, Freyman, & Helfer, 2007).

Alain, Reinke, He, Wang, and Lobaugh (2005) suggested that double-vowel identification involves the ability to (a) detect the presence of two sounds in the stimulus and (b) separate, categorize, and label the two vowels. In addition, the research previously discussed suggests that older adults may have difficulty not only in the identification of double vowels but also in the detection of how many sounds are in a double-vowel stimulus. Therefore, in this study, we included two experimental tasks using double-vowel stimuli. In the first task, referred to here as *multiplicity*, we assessed the ability of listeners to detect whether one or two sounds are present in a competing-vowel stimulus. In the second task, referred to here as *double-vowel identification*, we required listeners to identify the two vowels in the double-vowel stimulus.

The ability to detect two sound sources in a double-vowel stimulus has not been measured previously in simulations of EAS and cochlear implant hearing. However, Qin and Oxenham (2005) noted anecdotally that several of the participants in their cochlear implant simulation study reported hearing only one sound when listening to vocoded vowels with F_0 differences. Therefore, we predicted that both the older and younger listeners in our study would have difficulty detecting the presence of two sounds in simulated cochlear implant hearing but would be able to effectively utilize F_0 differences in the perception of multiplicity in both normal hearing and simulated EAS hearing.

As in previous studies (Qin & Oxenham, 2006), we expected listeners in this study to benefit from F_0 differences in double-vowel identification in both normal hearing and simulations of EAS hearing but not in simulations of cochlear implant hearing. Double-vowel identification involves integration of information from lower frequency regions (containing the F_0 and first formant) and higher frequency regions (containing the second and higher formants). The EAS stimulus combines a low-pass unprocessed stimulus with a high-pass vocoded stimulus; thus, it provides the listeners with undistorted signal information for the F_0 and the first formant but not for the second and higher formants. Because age-related deficits—including those related to F_0 processing—are more pronounced under more difficult and complex listening situations (Pilotti, Beyer, & Yasunami, 2001; Rossi-Katz & Arehart, 2009; Sommers, 1997), we predicted that the integration of information across frequency regions may be more difficult for older listeners in the simulation of EAS hearing than in normal hearing (due to less fidelity in the high-frequency portion of the signal), which, in turn, may cause older listeners to show poorer double-vowel identification rates and less benefit from F_0 differences in EAS hearing than in normal hearing.

Finally, we predicted that age-related deficits may be greater in the double-vowel task than in the multiplicity task, again, due to the premise that age deficits will be more pronounced for more difficult listening tasks. Although it is possible that listeners are able to reliably detect the number of sounds in the stimulus only after they are able categorize the vowels (Micheyl & Oxenham, 2009), we think that it is more likely that the detection of multiplicity is a lower-level process (and, thus, a simpler task) than the identification of the two competing vowels, which requires phonemic labeling. Such a view is consistent with the work of Alain and colleagues (see, e.g., Alain et al., 2005), which shows that neural activity associated with detecting the presence of two vowels occurs earlier than neural activity associated with identifying the competing vowels.

Method

Participants

Two groups of listeners participated in this study. One group consisted of 12 younger adults (10 female, two male), with an average age of 23.9 years and an age range of 18–32 years. Younger listeners had normal-hearing sensitivity, which is defined as audiometric thresholds of 20 dB HL (American National Standards Institute [ANSI], 2004) or better at octave frequencies from 250 Hz to 8000 Hz, inclusive. The average four-frequency pure-tone average (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz) of the younger group was 5.4 dB HL, with a range of 0–11.3 dB HL.

The second group consisted of 13 healthy older adults (11 female, two male), with an average age of 69.8 years and an age range of 65–82 years. All older listeners passed the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975)—which is a screening test of gross cognitive functioning—with a score of 26 or higher. The older adults had minimal or no hearing loss through 4000 Hz in the test ear (generally, thresholds of 25 dB HL or better). The average four-frequency pure-tone average of the older group was 14.5 dB HL, with a range of 6.3–21.3 dB HL.

Figure 1 shows the audiometric thresholds of the test ears for the two listener groups. To compensate for possible differences in audibility between the two groups, frequency shaping was applied to all stimuli (described in the next section). Participants in both groups had normal middle-ear function as determined by tympanometry testing (Wiley et al., 1996). All participants spoke English as their first or primary language. No participants had any prior hearing aid experience. All participants were paid for their participation. Approximately half of the listeners were tested at the University of Washington and half were tested at the University of Colorado, with the same test protocols and equipment used at both sites.

Stimuli

The stimuli in this study consisted of five synthesized vowels of American English (/ɑ/ as in *hod*, /ɛ/ as in *head*, /i/ as in *heed*, /ɜ/ as in *herd*, /u/ as in *who'd*). The vowel synthesis was based on Sensimetrics cascade formant software (Klatt, 1980) with a 20000-Hz sampling frequency and 16-bit quantization. The steady-state vowels had durations of 300 ms, with 20-ms rise–fall times. Formant frequencies of the individual vowels, based in part on those published in Peterson and Barney (1952), are listed in Table 1. Table 2 lists the possible values of F_0 of the individual vowels (100 Hz + ΔF_0 , with ΔF_0 ranging from 0 to 4 semitones (ST). Individual vowels were equated for root-mean-square (RMS) amplitude and then were combined with a second individual vowel to make three different types of stimuli.

The first type of stimuli is known as *same-vowel same- F_0 stimuli* (also called *single vowels*). The two individual vowels were the same and had the same F_0 , chosen from the following

five F_0 s: 100.0 Hz, 102.9 Hz, 105.9 Hz, 112.2 Hz, and 126.0 Hz. Presumably, these stimuli would be perceived as single vowels.

The second type of stimuli is known as *same-vowel different- F_0 stimuli*. The individual vowels were the same but had different F_0 s, chosen from four possible F_0 combinations: (a) 100.0 and 102.9 Hz, (b) 100.0 and 105.9 Hz, (c) 100.0 and 112.2 Hz, and (d) 100.0 and 126.0 Hz.

The third type of stimuli is known as *different-vowel stimuli* (also called *double vowels*). An individual vowel was paired together with each of the other four individual vowels (but not with itself), yielding 10 double-vowel combinations. One constituent vowel had an F_0 of 100 Hz, and the other constituent vowel had an F_0 of 100 Hz + ΔF_0 , with ΔF_0 ranging from 0 to 4 ST. Each double-vowel combination yielded two different double vowel pairs. For example, / α / and /i/ can be combined in two ways: (a) [/ α / 100.0 Hz; /i/ 100 Hz + ΔF_0] and (b) [/i/ 100.0 Hz; / α / 100 Hz + ΔF_0]. Double vowels were generated with values of $\Delta F_0 = 0, 1/2, 1, 2, \text{ or } 4$ ST.

Signal Processing

The three types of synthesized vowel stimuli described earlier were RMS equalized and then processed in three ways (see also Qin & Oxenham, 2006). The first processing condition, referred to here as UNP, consisted of synthesized vowels that were band-pass filtered between 80 Hz and 6 kHz using a 12th-order elliptical filter. This set was not subjected to any further processing.

The second condition, referred to here as VOC, simulated the electrical hearing provided by a fully inserted cochlear implant, using an eight-channel noise-excited vocoder. The processing is illustrated in the top panel of Figure 2. In this condition, the speech stimuli were first bandpass filtered into eight continuous channels using third-order Butterworth filters between 80 Hz and 6 kHz. The frequency range was partitioned using the Greenwood frequency place map (Greenwood, 1990). Table 3 contains the lower and upper cutoffs, as well as the center frequencies of the eight bandpass filters used. The envelopes of these band-limited signals were extracted by half-wave rectification followed by smoothing (low-pass filtering using a fourth-order Butterworth filter with a 300-Hz cutoff). The 300-Hz cutoff was chosen to retain the F_0 information. Each of the envelopes was modulated using an independent noise carrier. The resultant noise-excited signals were filtered using the same bandpass filter as that used in the first step of the processing. The individual channels were then added together, with the RMS level of each channel equalized to the level obtained from the initial bandpass filtering. The resulting signals were band-limited by low-pass filtering at 6 kHz using a 12th-order elliptical filter.

The bottom panel of Figure 2 illustrates the processing in the third condition, which simulates an “electric plus acoustic” stimulation and is referred to here as EAS. The input speech tokens were low-pass filtered using a 512-point Hamming-windowed linear-phase finite impulse response (FIR) filter. A cutoff of 661 Hz was chosen to avoid any gaps where possible cues might be lost and to maintain the original vocoder configuration. To meet the zero-phase criterion, the MATLAB “filtfilt” function was used. The normalized gain of the filter at cutoff was -6 dB. This low-pass section simulates any residual low-frequency hearing in cochlear implant users. This output was combined with a parallel section that consisted of only the fourth through eighth channels of the vocoder simulation, as discussed earlier. The low-pass acoustic stimulus and the high-pass vocoded channels were combined while maintaining RMS levels obtained from the initial filtering of the vocoder processing. The UNP, EAS, and VOC stimuli all had 20-ms rise–fall times shaped by a raised cosine function.

Stimulus Presentation

The signals were played out in the following way: Signals were sent from a custom MATLAB program to a Tucker–Davis Technologies (TDT; Alachua, FL) digital signal processor. Following digital-to-analog conversion, the signals were routed through a programmable attenuator before being delivered to the test ear of the listener with an ER2 insert earphone. Listeners were tested monaurally while seated in a sound-proof booth. The baseline level of presentation was 68 dB SPL.

Because of high-frequency threshold elevations of some of the older listeners, the 68 dB SPL stimuli were amplified using the National Acoustics Laboratories—Revised (NAL–R) linear prescriptive formula based on individual thresholds (Byrne & Dillon, 1986). The frequency-shaped amplification was implemented through linear-phase FIR digital filtering prior to the experiment. Stimuli were customized for each individual listener and were stored on a personal computer prior to being played out over the earphone. Listeners were able to register their responses with either a touchscreen monitor or a computer mouse.

Tasks and Procedures

Listeners were first tested on the perception of multiplicity (one vs. two sounds) and then were tested on the identification of double vowels. Listeners participated in 5 hr of testing, typically spread out over five 1-hr test sessions.

Training on single-vowel stimuli—At the beginning of each daily session, participants were familiarized with the single-vowel stimuli. The names of all five vowels were displayed on a computer screen. Participants used a mouse or touchscreen to select a particular vowel, and then that single vowel was played out to the listener. Listeners could repeat the presentation of individual vowels as many times as they wished. This familiarization was carried out for each of three processing conditions. Listeners then were tested on the identification of single vowels, in which the task was to listen to a single vowel and to identify which vowel it was. At the outset of each day of testing, listeners were presented with three blocks of vowels, with one block in each of the three processing conditions. Blocks of single vowels were 50 trials on the first day of testing and 25 trials on subsequent days of testing. Feedback was provided.

Multiplicity perception: Overview—The purpose of the multiplicity tasks was to assess the ability of listeners to discern whether one or two sound sources were present. Multiplicity was assessed with two different tasks, with each task involving approximately 1 hr of testing.¹

Multiplicity: One or two voices?—On each trial, listeners were presented with a stimulus and were asked to choose whether it contained one voice or two voices. Blocks were mixed in that they contained stimuli processed in all three processing conditions and contained both same-vowel–same- F_0 and same-vowel–different- F_0 stimuli. Of 405 total test trials in this task, 225 were same-vowel–same F_0 stimuli ($5 \text{ Vowels} \times 5 \text{ } F_0\text{s} \times 3 \text{ Processing Conditions} \times 3 \text{ Repetitions}$) and 180 were same-vowel–different- F_0 stimuli ($5 \text{ Vowels} \times 4 \Delta F_0 \text{ Combinations} \times 3 \text{ Processing Conditions} \times 3 \text{ Repetitions}$). The order of the 405 trials was randomized and then broken up into five blocks of 81 trials each. Feedback was provided such that “one voice” was indicated as correct on trials that contained same-vowel–

¹Prior to the implementation of our experimental protocol, we initially used just one set of instructions for the multiplicity task (“one or two sounds?”). However, for the same-vowel–different- F_0 s, listeners repeatedly asked for clarification as to whether they should respond on the basis of the number of voices or the number of vowels. Therefore, we refined our protocol to have two sets of instructions, including “one or two voices” and “one or two vowels.”

same- F_0 stimuli, and “two voices” was indicated as correct on trials that contained same-vowel–different- F_0 stimuli. To familiarize the listener with the task, listeners received one practice block of 81 trials prior to the 405 test trials.

Multiplicity: One or two vowels?—In the second multiplicity task, listeners were presented with a stimulus and were asked to choose whether it contained one vowel or two vowels. Blocks were mixed in that they contained stimuli processed in all three processing conditions and contained both same-vowel–same- F_0 stimuli (“single vowels”) and different-vowel stimuli (“double vowels”). Of 525 total test trials, 225 were single vowels ($5 \text{ Vowels} \times 5 \text{ } F_0 \text{ Conditions} \times 3 \text{ Processing Conditions} \times 3 \text{ Repetitions}$) and 300 were double vowels ($20 \text{ Double-Vowel Pairs} \times 5 \text{ } \Delta F_0 \text{ Conditions} \times 3 \text{ Processing Conditions}$). The order of the 525 trials was randomized and then broken up into seven blocks of 75 trials per block. Feedback was provided such that “one vowel” was indicated as correct on trials that contained single vowels, and “two vowels” was indicated as correct on trials that contained double vowels. To get familiar with the task, listeners received one practice block of 75 trials prior to the 525 test trials.

Double-vowel identification—The purpose of this task was to measure a listener’s ability to benefit from ΔF_0 in the identification of two competing vowels for the UNP, VOC, and EAS conditions. Listeners were presented with a double-vowel stimulus and were required to choose the two different vowels that were contained in the stimulus. Blocks of trials contained stimuli in a single processing condition. Listeners received 720 test trials, with 240 test trials presented in each of three 1-hr test sessions. Each of the three test sessions contained five separate blocks of trials, presented in random order. The UNP and EAS conditions each had a total of 100 test trials, broken up into two 50-trial blocks ($10 \text{ Double-Vowel Pairs} \times 2 \text{ } F_0 \text{ Combinations} \times 5 \text{ } \Delta F_0 \text{ Conditions}$). The VOC condition had 40 test trials presented in a single block ($10 \text{ Double-Vowel Pairs} \times 2 \text{ } F_0 \text{ Combinations} \times 2 \text{ } \Delta F_0 \text{ Conditions}$).² Consistent with previous studies of double-vowel identification (e.g., Culling & Darwin, 1993), feedback was not provided. Prior to the test trials in each session, listeners received practice blocks in each of the three processing conditions. Practice blocks were 25 trials for UNP and EAS, and 20 trials for VOC. The data reported for double-vowel identification are based on 60 test trials for each listener for each ΔF_0 in each of the three processing conditions.

Results

Single-Vowel Identification

Table 4 lists average identification rates of single vowels in the three processing conditions. Listeners in both groups achieved high average recognition rates of single vowels (>96%) in all three conditions. The identification rates were subjected first to an arcsine transformation (Studebaker, 1985) and then to a mixed-model analysis of variance (ANOVA).³ Shown in Table 5, this analysis showed a significant effect of processing condition but no significant differences between the older and younger groups. Post hoc comparisons with Bonferroni adjustments showed that single-vowel identification was significantly better in UNP than it was in either EAS or VOC ($p < .01$). The fact that single-vowel identification was high (>95%) in all three conditions indicates that the audibility of single-constituent vowels was sufficient for clear and consistent identification by listeners in both subject groups in all three conditions.

²Because previous studies have shown double-vowel perception to be poor across all ΔF_0 conditions for vocoded stimuli, we only tested ΔF_0 s of 0 ST and 4 ST in the VOC condition.

³In the ANOVA described in this study, we used Mauchley’s test to assess the assumption of sphericity. In the small number of cases in which the assumption of sphericity was violated, we used adjustments indicated by Greenhouse–Geisser.

Multiplicity (One or Two Voices?)

Figure 3 shows the proportion of trials in which listeners reported hearing “two voices” on trials that contained either same-vowel–same- F_0 stimuli ($\Delta F_0 = 0$ ST) or same-vowel–different- F_0 stimuli ($\Delta F_0 = 0.5, 1.0, 2.0$, or 4.0 ST). A mixed-model ANOVA was conducted on the arcsine-transformed proportion of trials on which “two voices” were reported in order to examine how multiplicity was affected by the within-subject factor of processing condition and ΔF_0 and the between-subjects factor of listener group. Summarized in Table 6, the results of this analysis indicated that the perception of voice multiplicity was significantly affected by the processing condition as well as by ΔF_0 but that multiplicity perception did not differ significantly between the younger and older groups.

The perception of multiplicity of voices was similar in UNP and EAS conditions but different in VOC, as indicated by post hoc comparisons with Bonferroni adjustments ($p < .01$). In addition, post hoc comparisons showed that perception of voice multiplicity at $\Delta F_0 = 0$ ST was significantly different from $\Delta F_0 = 0.5, 1.0, 2.0$, or 4.0 ST ($p < .01$). However, the effects of ΔF_0 on voice multiplicity perception were not the same in all three processing conditions, as indicated by the significant Processing $\times \Delta F_0$ interaction. In the UNP and EAS conditions, listeners reliably reported hearing only one voice when only one voice is present (same-vowel–same- F_0 stimuli; $\Delta F_0 = 0$ ST) and hearing two voices when the same vowel was presented on two different F_0 s ($\Delta F_0 > 0$ ST). In contrast, in the VOC condition, listeners were guessing “one voice” and “two voices” about equally, regardless of whether F_0 differed within the same-vowel stimulus. In summary, age did not interfere with listeners’ ability to use cues for the perception of multiplicity of voices derived from differences in F_0 in the UNP and EAS conditions, and, regardless of age, listeners were not able to derive ΔF_0 benefit in perception of multiple voices in the VOC condition.

Multiplicity (One or Two Vowels?)

Figure 4 shows the proportion of trials in which listeners reported hearing “two vowels” for both older listeners (left panel) and younger listeners (right panel) for the mixed blocks of trials containing both same vowel–same F_0 stimuli (“single vowels”) and different-vowel stimuli (“double vowels”). Each panel shows separately the average results for single vowels (SV) and for double vowels with $\Delta F_0 = 0, 0.5, 1.0, 2.0$, or 4.0 ST. Two mixed-model ANOVAs were conducted on the arcsine-transformed percent-correct scores to examine the within-subject effects of processing condition and ΔF_0 and the between-subjects effect of listener group on the perception of vowel multiplicity. The first ANOVA considered only the single-vowel trials, and the second ANOVA considered only the double-vowel trials.

Summarized in Table 7, the single-vowel analysis showed that the perception of vowel multiplicity was significantly affected by both listener group and processing condition. The ability of listeners to correctly perceive only a single vowel on single-vowel trials was indicated by how close single-vowel scores were to 0% “two vowels reported.” (0% “two-vowels reported” corresponds to 100% “one vowel reported.”) In both groups, unprocessed single vowels were identified as “two vowels” on only a very small proportion of trials (2.5% in the older group, 2.2% in the younger group). The perception of whether one or two sound sources was present for single-vowel trials was more ambiguous for EAS single vowels (22.2% in the older group, 10.7% in the younger group) and for the VOC single vowels (66.0% in the older group, 49.4% in the younger group). In the VOC condition, younger listeners appeared to be responding “one” or “two” vowels about equally for single-vowel trials. However, older listeners were responding “two vowels” on a greater percentage of trials than were younger listeners. This latter result suggested that listeners may sometimes have a bias toward responding “two vowels” for vocoded single vowels. This possible bias is discussed more in the paragraphs that follow.

The double-vowel analysis is summarized in Table 8. The lack of a significant main effect of group indicated that the overall perception of vowel multiplicity was not affected by age. Consistent with the significant main effect of processing, the perception of vowel multiplicity was different across processing conditions. Post hoc Bonferroni comparisons showed that EAS and UNP were similar to each other but that VOC was significantly different from both EAS and UNP ($p < .01$). Listeners also showed a statistically significant ΔF_0 benefit in vowel multiplicity, with post hoc Bonferroni comparisons indicating that vowel multiplicity at $\Delta F_0 = 0$ ST is significantly different from $\Delta F_0 = 0.5, 1.0, 2.0$, or 4.0 ST ($p < .01$). However, the $\Delta F_0 \times$ Processing interaction indicated that ΔF_0 benefit depends on the processing condition. The ΔF_0 benefit (defined as the difference in performance between 0 ST and 4 ST) was substantial for both UNP (90.4 and 67.5 percentage points for the older and younger groups, respectively) and EAS (65.0 and 55.0 percentage points for the older and younger groups, respectively). In contrast, multiplicity scores showed no systematic improvement as a function of ΔF_0 for VOC, with scores around 70% across all values of ΔF_0 .

In both the UNP and EAS conditions, the amount of ΔF_0 benefit was greater in the older group than in the younger group. Consistent with the higher-order interaction of $\Delta F_0 \times$ Processing $\times$ Group, this difference in benefit appeared to be due to differential scores between the groups at $\Delta F_0 = 0$ ST. For double-vowel stimuli with no F_0 difference, the older listeners reported hearing two vowels on 7.7% of trials for UNP and 33% of trials for EAS. In contrast, the “two-vowel” reports for younger listeners for double-vowel trials with $\Delta F_0 = 0$ ST is 32.5% for UNP and 43% for EAS.

Double-Vowel Identification

Figure 5 shows the average results for the group of older listeners (left panel) and the group of younger listeners (right panel). Percentage of trials in which both vowels of double-vowel pairs were correctly identified is shown as a function of ΔF_0 in semitones for each of the three processing conditions. In all three conditions, performance by both groups was well above chance (10%). The arcsine-transformed data for all three processing conditions were subjected to mixed-model ANOVA with a between-subject factor of group and within-subject factors of ΔF_0 and processing condition. Summarized in Table 9, this analysis included only data from $\Delta F_0 = 0$ and 4 ST, as double-vowel identification was not tested at $\Delta F_0 = 0.5, 1.0$, and 2.0 ST. The analysis showed significant main effects of processing condition, ΔF_0 , and group. Consistent with these main effects, average identification was best in the UNP condition and worst in the VOC condition, was better in the younger group than in the older group, and was better as ΔF_0 increased. In addition, the interactions of Processing $\times$ ΔF_0 , Processing $\times$ Group, and $\Delta F_0 \times$ Group were all significant. The three-way Processing $\times$ $\Delta F_0 \times$ Group interaction approached but did not reach statistical significance.

To clarify further the nature of these effects, separate ANOVAs were also performed for each of the three processing conditions. These analyses investigated (a) whether double-vowel identification differed between the listener groups in each specific processing condition and (b) if the listener groups showed different patterns of ΔF_0 benefit (reflected in the $\Delta F_0 \times$ Group interaction) in the different processing conditions. The analyses included data at $\Delta F_0 = 0, 0.5, 1.0, 2.0$, and 4.0 ST for the UNP and EAS conditions, and data at $\Delta F_0 = 0$ and 4 ST for the VOC condition. The results of the analyses are described in the paragraphs that follow and are summarized in Table 10.

UNP condition—As indicated by the significant effect of group in the UNP condition, the older group was significantly poorer at identifying the double vowels in the unprocessed condition. Listeners in both groups also benefited significantly as ΔF_0 increased, but—as

supported by the significant Group $\times$ ΔF_0 interaction—this ΔF_0 benefit was significantly less pronounced in the older group than in the younger group. In the UNP condition, both groups showed their poorest performance when ΔF_0 was 0 ST (mean identification accuracy was 51.5% in the younger group and 27.7% in the older group.) As ΔF_0 increased from 0 ST to 4 ST, double-vowel identification improved by 31.8 percentage points in the younger group (from 51.5% to 83.3%) and by 18.3 percentage points (from 27.7% to 46.0%) in the older group. In the UNP condition, ΔF_0 benefit in the younger group began to asymptote when ΔF_0 was 1 ST or greater. In contrast, in the older group, listeners continued to show slight improvements in double-vowel identification through 4 ST.

EAS condition—The effects of group and ΔF_0 were again significant for the EAS condition, supporting the finding that overall double-vowel identification was significantly poorer in the older group and that listeners' ability to identify both vowels correctly improved as ΔF_0 increased. Both groups showed poorest performance when ΔF_0 was 0 ST (mean identification accuracy was 40.6% in the younger group and 24.1% in the older group). As ΔF_0 increased from 0 ST to 4 ST, double-vowel identification improved by 17.6 percentage points in the younger group (from 40.6% to 58.2%) and by 11.4 percentage points in the older group (from 24.1% to 35.5%). The larger benefit shown by the younger group in the EAS condition was not statistically significant, as indicated by a lack of Group $\times$ ΔF_0 interaction.

VOC condition—The effects of group were significant in the VOC condition, such that overall double-vowel identification was poorer in the older group. However, neither group demonstrated significant ΔF_0 benefit. In the VOC condition, performance for the younger group was 43.3% at 0 ST and 45.4% at 4 ST, and performance for the older group was 29.7% at 0 ST and 24.2% at 4 ST. The finding that the average double-vowel identification of the older group actually decreased as ΔF_0 increased is consistent with the significant Group $\times$ ΔF_0 interaction.

Individual Variability

Variability among listeners was higher (a) in the double-vowel identification task compared with the multiplicity tasks, (b) in the older group compared with the younger group, and (c) in the EAS and VOC conditions compared with the UNP condition. Figures 6, 7, and 8 illustrate the individual variability in the double-vowel identification task for the three processing conditions. Figure 6 shows double-vowel identification as a function of ΔF_0 for individual listeners, and Figure 7 shows the amount of benefit ([proportion double-vowel correct at 4 ST] – [proportion double-vowel correct at 0 ST]), ordered on the basis of benefit in the UNP condition) for each of the three processing conditions for individual listeners in the older group (left panel) and younger group (right panel).

Several noteworthy trends emerged. First, in the UNP condition, the participants in the younger group all showed a benefit of at least 10 percentage points as ΔF_0 increased from 0 ST to 4 ST (range = 11.7 to 51.7 percentage points). In contrast, just over half (seven of 13) of the listeners in the older group showed a benefit that equals or exceeds 10 percentage points (range = –1.7 to 55.0 percentage points). The ΔF_0 benefit in the EAS processing condition varied substantially across subjects in both groups. In the younger group, ΔF_0 benefit ranged from 3.3 to 33.3 percentage points, with four of the 12 younger subjects showing a benefit of fewer than 10 percentage points.

In the older group, the benefit in EAS ranged from –3.3 to 30.0 percentage points, with seven of the 13 older subjects showing ΔF_0 benefit that was fewer than 10 percentage points. In the VOC condition, only one of the 13 older subjects showed a positive benefit (3.3

percentage points), whereas 6 of 12 younger subjects showed a positive benefit (range = 3.3 to 16.7 percentage points).

Figure 8 shows a scatterplot of benefit from ΔF_0 differences in the EAS condition plotted against the ΔF_0 benefit in the UNP condition. In the older group, there was a significant correlation between benefits in UNP and EAS conditions (Pearson's correlation coefficient: $r = .904, p < .001$). Older listeners tended to fall into one of two subgroups: (a) those who showed good ΔF_0 benefit in both the UNP and EAS conditions (e.g., o9, o10, o11) and (b) those who tended to show small ΔF_0 benefit in both conditions. In contrast, the correlation between benefits in the UNP and EAS conditions was much lower in the younger group (Pearson's correlation coefficient: $r = .457, p = .135$), such that several younger listeners (e.g., y5, y9, y12; cf. Figure 7) who showed large ΔF_0 benefit in the UNP condition showed small benefit (< 10 percentage points) in the EAS condition.

Discussion

The primary goal of this study was to compare how older and younger listeners use F_0 differences to determine (a) the number of sound sources (one vs. two) in a double-vowel stimulus and (b) the phonemic identity of two competing vowels. Of interest was how advanced age affects the amount to which listeners benefit from F_0 differences in three different hearing configurations: normal hearing (UNP), electroacoustic stimulation (EAS), and cochlear implant hearing (VOC). The results can be summarized as follows. The perception of multiplicity was facilitated by F_0 differences for the UNP and EAS conditions but not for the VOC conditions. Furthermore, the improvement in multiplicity perception provided by F_0 differences was immune to age effects. Double-vowel identification was also facilitated by F_0 differences, with ΔF_0 benefit largest in the UNP condition, significantly reduced in the EAS condition, and absent in the VOC condition. Furthermore, in contrast to multiplicity, age adversely affected performance on the double-vowel task in terms of amount of benefit and overall identification rates on the double-vowel task. Finally, substantial intersubject variability was observed among both older and younger listeners in their ability to benefit from F_0 differences, especially in the EAS condition.

Multiplicity

The finding that F_0 differences facilitate good multiplicity perception in UNP in younger listeners with normal hearing is consistent with other published data (Arehart et al., 2005; Assmann & Paschall, 1998; de Cheveigné et al., 1997). Although other studies have discussed potential effects of age (Vongpaisal & Pichora-Fuller, 2007) and vocoding (Qin & Oxenham, 2005) on the ability of listeners to detect the presence of one or two sounds in a double-vowel stimulus, the present study is—to our knowledge—the first to systematically look at the role of F_0 differences in multiplicity perception by older and younger listeners in EAS and VOC conditions.

The lack of improvement in the detection of two vowels or two voices in the VOC condition suggests that the high-rate envelope cues in the VOC stimulus are insufficient to convey benefits for multiplicity perception provided by F_0 differences. In contrast, the cues that are provided in the UNP and EAS conditions facilitate significant benefit from F_0 differences in multiplicity perception. Present models of double-vowel perception suggest two possible ways in which listeners could derive multiplicity cues on the basis of F_0 differences. First, listeners may rely on a process of F_0 -guided segregation, whereby a vowel would be separated from its competitor by grouping together the components that share a common F_0 (e.g., Assmann & Summerfield, 1990; de Cheveigné, 1999; Meddis & Hewitt, 1992). F_0 -guided segregation may help parse the composite formant peak (e.g., first formant) in the combined spectral envelope of the double vowel into the formant peaks of the constituent

vowels (Culling & Darwin, 1993). Second, waveform interactions or beating between adjacent low-frequency components may mediate perception of double vowels for F_0 differences less than 1 ST (Assmann & Summerfield, 1994; Culling & Darwin, 1994). The fluctuations caused by beating may result in evidence of each vowel being more readily discerned during various points in the stimulus waveform. Both F_0 -guided segregation and beating cues would be most perceptible from the outputs of the low-frequency auditory filters (and, hence, available in both the UNP and EAS conditions) because of the frequency spacing of harmonics relative to the auditory filter bandwidths (Assmann & Summerfield, 1994; de Cheveigné, 1999).

Although F_0 differences facilitate the perception of multiplicity in the EAS and UNP conditions, they may not be required. Results from this study (see Figure 5) as well as from other studies (e.g., Assmann & Summerfield, 1990; Culling & Darwin, 1993) demonstrate that listeners with normal hearing are able to identify double vowels well above chance, even when the F_0 s of the vowels are the same. This ability has been attributed, in part, to spectral peaks and shoulders of excitation patterns (Assmann & Summerfield, 1989). The ability to access these non- F_0 cues may be age dependent. For example, whereas the younger listeners in our study reported hearing two vowels (when two vowels were actually presented) in the UNP condition at $\Delta F_0 = 0$ ST on approximately one third of the trials, older listeners rarely did. However, this line of reasoning cannot be used to explain all of the data at $\Delta F_0 = 0$ ST. For example, in the vowel multiplicity task at $\Delta F_0 = 0$ ST, listeners were actually more likely to report hearing two vowels (when two vowels were actually presented) in the VOC condition. This result was unexpected, as non- F_0 cues (e.g., spectral representations) regarding the number of competing vowels available at $\Delta F_0 = 0$ ST would be expected to be less salient in the VOC condition due to loss of spectral detail.

In the vowel multiplicity task in the VOC condition, listeners also showed a tendency toward saying that they heard two vowels when only one vowel was actually presented. A recent analysis by Micheyl and Oxenham (2009) lends a possible interpretation for this “two-vowel” response tendency in the VOC condition. The authors suggested that listeners might use “perceived fusion” as the basis for judging whether pairs of simultaneous complex tones (presented in different frequency regions) have the same F_0 or different F_0 s—that is, the perceptual sensation evoked by stimuli containing simultaneous complex tones with the same F_0 would be characterized by greater fusion and less roughness than simultaneous complex tones with different F_0 s. This same “perceived fusion” explanation might be applied to the current multiplicity results. Without other salient cues to utilize (e.g., F_0 differences, spectral representations), listeners may base their multiplicity judgments on their expectations that a single vowel should evoke a percept of fusion on the basis of a clean harmonic spectrum. As such, for vowels subjected to vocoding with a noise carrier (which would include inherent noise fluctuations superimposed on the envelope), listeners may tend to respond “two” because the sound lacks the fused percept expected for a single sound.

In summary, results from the multiplicity tasks indicate that listeners are able to use F_0 cues effectively in the detection of two voices or two vowels. Older listeners benefit as much, and sometimes more, from F_0 differences in multiplicity judgments in the UNP and EAS conditions and may show a reduced ability to use non- F_0 cues when competing sounds have no F_0 differences. Finally, it is important to acknowledge that the perception of multiple sound sources and how that perception is affected by aging may depend on the specific nature of the task and stimuli that are used. For example, the use of F_0 cues might differ if listeners were instructed to report one pitch or two pitches, since listeners have been shown to require a 4-ST difference in F_0 in order to perceive two distinct pitches for double vowels (Assmann & Paschall, 1998). In addition, our tasks revealed no age deficit in the perception

of multiplicity, whereas older adults did show deficits in the ability to discern the presence of one or two sound sources in the mistuned harmonic task used by Alain and McDonald (2007).

Double-Vowel Identification

The double-vowel identification results in the UNP condition for the group of younger listeners corroborate the results from other published reports in that they show large ΔF_0 benefit, with performance reaching asymptote for $\Delta F_0 \sim 1$ ST (Arehart et al., 1997; Assmann & Summerfield, 1990; Culling & Darwin, 1993; de Cheveigné et al., 1997; Meddis & Hewitt, 1992; Scheffers, 1983). The results from the younger group also provide a partial replication of the results of Qin and Oxenham (2005, 2006), with younger listeners showing no systematic ΔF_0 benefit in the VOC condition and modest ΔF_0 benefit in the EAS condition.

The reduced overall double-vowel identification results shown by our older listeners in the UNP condition is consistent with the reduced double-vowel identification shown by the older adults in other studies (Snyder & Alain, 2005; Vongpaisal & Pichora-Fuller, 2007). The present results add to a literature that is mixed in terms of the apparent effects of age on ΔF_0 benefit in double-vowel identification (e.g., Snyder & Alain, 2005; Summers & Leek, 1998; Vongpaisal & Pichora-Fuller, 2007). Our largest age-related deficit was for ΔF_0 benefit in the UNP condition. Summers and Leek (1998) also reported that age significantly impacted ΔF_0 benefit on double-vowel identification by listeners with hearing loss. Snyder and Alain (2005) reported no age-related deficit in ΔF_0 benefit, and Vongpaisal and Pichora-Fuller (2007) reported age-related deficits in ΔF_0 benefit only for competing vowels that had the same formants (similar to the same-vowel-different- F_0 stimuli used in our voice multiplicity task). The reasons for these differences across studies are not clear, but they may be due, in part, to differences in specific groups of older listeners included in the different studies.

The types of processing involved in using F_0 differences in double-vowel identification may vary in younger and older listeners. For example, Alain and colleagues (Alain, Dyson, & Snyder, 2006; Alain, McDonald, Ostroff, & Schneider, 2004) have hypothesized that older adults may rely on more higher-level controlled processes or schema in perceptual organization to compensate for lower-level deficits in F_0 processing. Electrophysiological evidence reported by Snyder and Alain (2005) supports the idea that perceptual organization of competing vowels in younger listeners appears to be guided by automatic primitive processing of physical grouping cues (e.g., F_0). In contrast, older listeners appear to rely more on higher-level controlled processes in the identification of double vowels to compensate (at least, in part) for deficits in the automatic processing of physical grouping cues. The ability of older listeners to compensate for the degraded peripheral representations may be even more pronounced in conditions such as EAS, in which the stimuli have been reduced in terms of the amount of information that they provide.

As with multiplicity, the poor performance by both subject groups in the VOC condition suggests that the envelope-based cues in the VOC stimulus are insufficient to facilitate ΔF_0 benefit in double-vowel identification. The EAS stimulus provides significant ΔF_0 benefit in double-vowel identification, but this benefit is reduced compared with the UNP condition. Qin and Oxenham (2006) showed that younger listeners who were presented with double vowels that were low-pass filtered (<600 Hz) had poor double-vowel identification (~20%) and no ΔF_0 benefit for double vowels that were low-pass filtered (<600 Hz). The results for this low-frequency-only condition differ remarkably from the EAS results shown both in Qin and Oxenham (2006) and in our study, suggesting that listeners use and integrate cues both from the low-frequency acoustic portion and the higher-frequency vocoded portions of

the EAS double vowels. This integration of cues across frequency regions is consistent with the findings of other studies showing that listeners utilize both within- and across-formant grouping mechanisms in the perception of double vowels (Culling & Darwin, 1993; Rossi-Katz & Arehart, 2005).

Task Complexity

The ability to take advantage of ΔF_0 cues appears to be related to task complexity. Whereas older listeners were able to make use of F_0 differences as well as younger adults did in the multiplicity task, older adults showed reduced identification and reduced benefit from F_0 differences in the double-vowel identification task. Identifying two competing vowels was conceived as being operationally harder than detecting whether one or two sound sources was contained in the stimulus. Thus, the present results are consistent with the *age complexity effect* (Salthouse, 1991). This effect postulates that age-related deficits will be more pronounced as task complexity increases, due to increased demands that are placed on a finite—and potentially depleted—store of processing resources (e.g., Cerella, 1990; Craik & Byrd, 1982). In competing speech perception tasks, the performance of older listeners may decrease due to listeners reallocating a limited store of processing resources to recover degraded information at the auditory periphery (e.g., McCoy et al., 2005; Murphy, Craik, Li, & Schneider, 2000; Pichora-Fuller, Schneider, & Daneman, 1995; Rossi-Katz & Arehart, 2009; Schneider, Daneman, Murphy, & Kwong See, 2000; Wingfield & Tun, 2007). The costs associated with this reallocation of processing resources may be more apparent in the more difficult double-vowel identification task.

The idea that benefit from F_0 differences depends on processing resources and task complexity can also be helpful in understanding the finding that several younger listeners who showed large ΔF_0 benefit in the UNP condition showed small benefit (<10 percentage points) in the EAS condition. Processing the EAS stimulus involves extracting and integrating cues from both the low-frequency acoustic and higher-frequency vocoded portions of the stimulus (Li & Loizou, 2008). This integration process may be less “automatic” for double vowels in the EAS condition compared with the UNP condition. In the EAS condition, listeners may be confronted with a requirement for more controlled processes in perceptual organization due to the loss of automaticity in the processing of physical grouping cues. This requirement for more controlled processes might lead to more difficulty in processing ΔF_0 cues in the EAS condition compared with the UNP condition.

Although there was a general trend for ΔF_0 benefit to decrease as task complexity increased, there was also substantial variability among both the older and younger groups of listeners. Individual listeners may vary in how they allocate the resources that are required for controlled processing. This variability might, in turn, contribute to the variability in listeners benefiting from ΔF_0 cues in the more complex listening tasks.

Limitations and Implications

Due to the inherent limitations of simulation studies, the present results cannot be directly applied to older adults with actual EAS hearing. The results are also limited in that they are based on synthesized vowels rather than on natural full-length speech. However, the findings provide insight into issues that will be important to consider in clinical studies of EAS benefit. Older adults are able to derive benefit from F_0 differences in (simulated) EAS hearing in the perception of competing talkers. In addition, the amount of benefit depends on task complexity and varies substantially across individuals. Finally, the present findings suggest that it will be important to consider the higher-level processing resources that are required for extracting and integrating cues in EAS hearing—and how this processing may vary among individual listeners.

Summary

The primary goal of this study was to investigate the effects of age on listeners' ability to utilize F_0 differences of vowel sounds to determine (a) the number of sound sources (one or two) in a stimulus and (b) the phonemic identity of competing vowels. Of interest was how advanced age affected the amount by which listeners benefited from F_0 differences in simulations of different hearing configurations. The perception of multiplicity was facilitated by F_0 differences for sounds containing resolved low-frequency harmonics (UNP and EAS) but not for the stimulus that lacked low-frequency fine structure information (VOC). Furthermore, the multiplicity benefit provided by F_0 differences was immune to age effects. Double-vowel identification was also facilitated by F_0 differences, with ΔF_0 benefit largest in UNP, significantly reduced in EAS, and absent in VOC. Furthermore, in contrast to multiplicity, age adversely affected performance on the double-vowel task in terms of both amount of benefit and overall identification rates on the double-vowel identification task. Finally, substantial intersubject variability was observed among both older and younger listeners in their ability to benefit from F_0 differences, especially in the EAS condition.

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Appendix. Listener instructions

The instructions given to each listener for each task are included here.

Multiplicity: How Many Voices?

Each sound you hear contains either one voice or two voices. Your task is to choose whether you hear one or two voices in the sound. Please respond by choosing “ONE” or “TWO.” If you are not sure whether there are one or two voices, please make your best guess.

Multiplicity: How Many Vowels?

Each sound you hear contains either one vowel or two vowels. Your task is to choose whether you hear one vowel or two vowels in the sound. Please respond by choosing “ONE” or “TWO.” If you are not sure whether there are one or two vowels, please make your best guess.

Double-Vowel Identification

Each sound you hear contains two different vowel sounds. Your task is to choose two different vowels that you think are contained in the sound. Please respond by choosing two

different vowels. If you are not sure which two vowels are in the sound, please make your best guess.

Figure 1.
Audiograms of younger group and older group of listeners.

Figure 2. Processing for the VOC condition (top panel) and the EAS (bottom panel) condition. VOC = envelope-vocoded synthesized vowels that simulated a cochlear implant; EAS = synthesized vowels processed to simulate electroacoustic (EAS) hearing.

Figure 3.

Proportion of trials in which listeners reported hearing two voices for blocks of trials containing both same-vowel-same- F_0 and same-vowel-different- F_0 stimuli. Average results are shown for the younger and older groups of listeners in the UNP, EAS, and VOC conditions. Error bars represent the standard error. Chance performance (guessing) would correspond to 0.5 instances of “two voices” reported.

Figure 4.

Proportion of trials in which listeners reported hearing two vowels for trials actually containing two different vowels (double vowels). Average results are shown for the younger and older groups of listeners in the UNP, EAS, and VOC conditions. Chance performance (guessing) would correspond to 0.5 instances of “two vowels” reported. Results are also shown for single-vowel trials (SV). Error bars represent the standard error.

Figure 5.

Proportion of trials in which listeners correctly identify both vowels contained in a double-vowel stimulus. Average results are shown for the younger and older groups of listeners in the UNP, EAS, and VOC conditions. Error bars represent the standard error. Chance performance is 10%.

Figure 6.

Proportion of trials in which listeners correctly identify both vowels contained in a double-vowel stimulus. Results are shown for individual listeners in the UNP, EAS, and VOC conditions. Chance performance is 10%.

Figure 7.

ΔF_0 benefit (defined as proportion of double-vowel correct at 4 ST minus proportion of double-vowel correct at 0 ST) for individual listeners in the older group (left panel) and in the younger group (right panel) for the UNP, EAS, and VOC conditions. Subjects are ordered based on the amount of ΔF_0 benefit in the UNP condition.

Figure 8. Scatterplot of ΔF_0 benefit in the EAS condition plotted against the ΔF_0 benefit in the UNP condition.

Table 1

Formant frequencies (Hz) for vowels.

Formant frequency	/ɑ/	/e/	/ɛ/	/i/	/u/
F ₁ (90)	730	530	490	270	250
F ₂ (110)	1090	1840	1350	2290	850
F ₃ (170)	2440	2480	1690	3010	2240
F ₄ (250)	3350	3350	3350	3350	3350
F ₅ (300)	3850	3850	3850	3850	3850

Note. Values in parentheses represent formant bandwidths (in Hz).

Table 2

Differences in fundamental frequency (F_0) between individual vowels.

F_0 (in Hz)	ΔF_0 (in ST re: 100 Hz)
100.0	0
102.9	1/2
105.9	1
112.2	2
126.0	4

Note. Hz = Hertz; ST = semitone.

Table 3

Filter specifications for the VOC and EAS conditions.

Channel	Cochlear implant (VOC) simulation			EAS simulation		
	Lower cutoff (Hz)	Center frequency (Hz)	Upper cutoff (Hz)	Lower cutoff (Hz)	Center frequency (Hz)	Upper cutoff (Hz)
1	80	135	202	[Low-pass filtered cutoff 661 Hz]		
2	202	284	384			
3	384	507	657			
4	657	840	1065		657	840
5	1065	1339	1675		1065	1339
6	1675	2086	2589		1675	2086
7	2589	3203	3955		2589	3203
8	3955	4875	6000		3955	4875

Note. VOC = envelope-vocoded synthesized vowels that simulated a cochlear implant; EAS = synthesized vowels processed to simulate electroacoustic (EAS) hearing.

Table 4

Average proportion correct for single-vowel identification for the groups of older and younger listeners in each of three processing conditions.

Processing	Older group	Younger group
UNP	1.000 (.000)	.998 (.001)
EAS	.986 (.008)	.964 (.012)
VOC	.976 (.009)	.969 (.012)

Note. Standard error is indicated in parentheses.

Table 5

Summary of mixed-model analysis of variance (ANOVA) for arcsine-transformed percent correct scores for single-vowel identification.

Effect	<i>df</i>	<i>F</i>	<i>p</i>	Partial η^2
Proc	2, 46	11.6	< .000	.334
Proc $\times$ Group	2, 46	0.9	.381	.041

Note. Proc = processing.

Table 6

Summary of mixed-model ANOVA for arcsine-transformed percent correct scores for the perception of multiplicity (one vs. two voices) for trials containing two same-vowel tokens that have either the same F_0 or different F_0 s.

Effect	<i>df</i>	<i>F</i>	<i>p</i>	Partial η^2
Proc	2, 46	67.2	< .000	.745
ΔF_0	4, 92	581.8	< .000	.962
Group	1, 23	0.0	.893	.001
Proc $\times$ ΔF_0	8, 184	185.9	.000	.890
Proc $\times$ Group	2, 46	0.3	.647	.012
$\Delta F_0 \times$ Group	4, 92	1.4	.243	.059
Proc $\times$ $\Delta F_0 \times$ Group	8, 184	0.9	.456	.039

Table 7

Summary of mixed-model ANOVA for arcsine-transformed percent correct scores for the perception of multiplicity (one vs. two vowels) for trials containing only single vowels.

Effect	<i>df</i>	<i>F</i>	<i>p</i>	Partial η^2
Proc	2, 46	172.5	< .000	.882
Group	1, 23	5.6	.026	.197
Proc $\times$ Group	2, 46	2.7	.080	.104

Table 8

Summary of mixed-model ANOVA for arcsine-transformed percent correct scores for the perception of multiplicity (one vs. two vowels) for trials containing double vowels.

Effect	<i>df</i>	<i>F</i>	<i>p</i>	Partial η^2
Proc	2, 46	36.2	< .000	.612
ΔF_0	4, 92	175.0	< .000	.884
Group	1, 23	2.9	.104	.111
Proc $\times$ ΔF_0	8, 184	102.7	< .000	.817
Proc $\times$ Group	2, 46	1.7	.206	.068
$\Delta F_0 \times$ Group	4, 92	1.5	.233	.062
Proc $\times$ $\Delta F_0 \times$ Group	8, 184	2.6	.040	.100

Table 9

Summary of mixed-model ANOVAs for arcsine-transformed percent correct scores for the correct identification of two competing vowels for double-vowel trials.

Effect	<i>df</i>	<i>F</i>	<i>p</i>	Partial η^2
Proc	2, 46	60.1	< .001	.723
ΔF_0	1, 23	47.0	< .001	.671
Group	1, 23	30.5	< .001	.570
Proc $\times$ ΔF_0	2, 46	51.7	< .001	.692
Proc $\times$ Group	2, 46	11.8	< .001	.339
$\Delta F_0 \times$ Group	1, 23	7.2	.013	.239
Proc $\times$ $\Delta F_0 \times$ Group	2, 46	2.7	.078	.105

Table 10

Summary of mixed-model ANOVAs for UNP, EAS, and VOC conditions for arcsine-transformed percent correct scores for the correct identification of two competing vowels for double-vowel trials.

Condition	Effect	df	F	p	Partial η^2
UNP	Group	1, 23	55.7	< .001	.708
	ΔF_0	4, 92	49.7	< .001	.684
	Group $\times \Delta F_0$	4, 92	7.6	0.001	.249
EAS	Group	1, 23	25.0	< .001	.521
	ΔF_0	4, 92	17.8	< .001	.436
	Group $\times \Delta F_0$	4, 92	1.6	.209	.066
VOC	Group	1, 23	14.7	.001	.309
	ΔF_0	1, 23	2.1	.163	.083
	Group $\times \Delta F_0$	1, 23	7.8	.011	.252

Note. Separate analyses were done for each of the three processing conditions (UNP, EAS, and VOC).