Comparing the effects of age on amplitude modulation and frequency modulation detection

Nicolas Wallaert[a)]
UMR CNRS LSP 8248, Institut d'Etude de la Cognition, Ecole normale supérieure, Paris Sciences et Lettres, 29 rue d'Ulm, 75005 Paris, France

Brian C. J. Moore
Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, United Kingdom

Christian Lorenzi
UMR CNRS LSP 8248, Institut d'Etude de la Cognition, Ecole normale supérieure, Paris Sciences et Lettres, 29 rue d'Ulm, 75005 Paris, France

(Received 26 August 2015; revised 30 March 2016; accepted 10 May 2016; published online 8 June 2016)

Frequency modulation (FM) and amplitude modulation (AM) detection thresholds were measured at 40 dB sensation level for young (22–28 yrs) and older (44–66 yrs) listeners with normal audiograms for a carrier frequency of 500 Hz and modulation rates of 2 and 20 Hz. The number of modulation cycles, *N*, varied between 2 and 9. For FM detection, uninformative AM at the same rate as the FM was superimposed to disrupt excitation-pattern cues. For both groups, AM and FM detection thresholds were lower for the 2-Hz than for the 20-Hz rate, and AM and FM detection thresholds decreased with increasing *N*. Thresholds were higher for older than for younger listeners, especially for FM detection at 2 Hz, possibly reflecting the effect of age on the use of temporal-fine-structure cues for 2-Hz FM detection. The effect of increasing *N* was similar across groups for both AM and FM. However, at 20 Hz, older listeners showed a greater effect of increasing *N* than younger listeners for both AM and FM. The results suggest that ageing reduces sensitivity to both excitation-pattern and temporal-fine-structure cues for modulation detection, but more so for the latter, while sparing temporal integration of these cues at low modulation rates.
 [http://dx.doi.org/10.1121/1.4953019]

[EAS] Pages: 3088–3096

I. INTRODUCTION

Information about spectro-temporal changes in sounds, including speech, is conveyed in the auditory system by two main types of cues: (1) excitation-pattern (place) cues, related to the distribution of excitation along the basilar membrane within the cochlea; (2) temporal-fine-structure (TFS) cues related to the waveform of the stimulus at each point on the basilar membrane. Place cues are conveyed in the auditory nerve by differences in firing rate of neurons with different characteristic frequencies whereas TFS cues are conveyed by the detailed timing of the action potentials in neurons with different characteristic frequencies.

There is evidence that sensitivity to TFS declines with increasing age (for a review, see Moore, 2014). However, most of the data supporting this idea were obtained using psychophysical tests whose outcome is affected both by the availability of TFS information and by "processing efficiency," i.e., the ability of the central auditory system to make use of available sensory information. One such test involves measurement of the threshold for detecting low-rate frequency modulation (FM); the rationale for this is described later. This paper presents a study in which thresholds for detecting both FM and amplitude modulation (AM) were measured for younger and older listeners with normal audiograms. It is generally assumed that AM detection does not depend on the use of TFS information, whereas detection of low-rate FM probably does (e.g., Moore and Sek, 1995). Hence, by comparing the effect of age on AM and FM detection in the same listeners, it should be possible to tease out the effects of changes in the use of TFS information and changes in processing efficiency. Modulation rates of 2 and 20 Hz were used, since it has been argued that FM detection for a 2-Hz rate depends on the use of TFS information (Moore and Sek, 1995; Sek and Moore; 1995; Ernst and Moore, 2010, 2012), while FM detection for a 20-Hz rate probably does not. Again, comparison of results at the two FM rates should allow us to tease out the effects of changes in the ability to use TFS information and changes in processing efficiency.

As a way of checking the role of TFS as opposed to excitation-pattern cues in the detection of FM, modulation detection was also assessed as a function of the number of modulation cycles, *N* (between 2 and 9). AM and FM detection both improve (i.e., thresholds decrease) with increasing *N* (Viemeister, 1979; Hartmann and Klein, 1980; Sheft and Yost, 1990; Dau *et al.*, 1997), an effect that probably reflects relatively central processes involving "multiple looks" (Viemeister and Wakefield, 1991) or a template-matching

[a)]Electronic mail: nicolas.wallaert@ens.fr

 0001-4966/2016/139(6)/3088/9/$30.00

process (Hartmann and Klein, 1980; Dau *et al.*, 1997). Here, we refer to this improvement as "temporal integration," not in the sense that energy is integrated over time, but in the sense that information is integrated over time. If AM and FM detection were both based solely on the detection of changes in excitation level, then one would expect that detection thresholds for AM and FM would improve in a similar way with increasing *N*. However, if low-rate FM detection is based on the use of TFS cues, then temporal integration might differ from that obtained for FM detection at a higher rate, and for AM detection. If such a difference in temporal integration were found, it would support the idea of two different mechanisms for FM detection. However, the lack of a difference in temporal integration would not disprove the idea that there are two mechanisms. We are not aware of any previous comparisons of temporal integration for AM and FM detection for a very low rate (2 Hz) and an intermediate rate (20 Hz).

A. Role of TFS cues in the detection of low-rate FM

We consider next evidence for the role of TFS in the detection of low-rate FM. Several studies have investigated whether the ability to detect, discriminate, and recognize FM patterns depends on the use of excitation-pattern (place) or TFS information. Changes in frequency may be perceived by monitoring changes in excitation level (that is, temporal-envelope cues) at one place or at multiple places on the excitation pattern (Zwicker, 1952, 1956; Moore and Sek, 1994; Zwislocki and Nguyen, 1999). TFS information about FM is conveyed by changes in the pattern of phase locking over time. For most mammals, the precision of phase locking is constant for frequencies up to about 600–2000 Hz and then declines, becoming very weak at 3500–6000 Hz (Kiang, 1965; Rose *et al.*, 1967; Johnson, 1980; Palmer and Russell, 1986), although the exact upper limit in humans is still debated (Heinz *et al.*, 2001; Moore and Sek, 2009; Verschooten and Joris, 2014). Several researchers have suggested that changes in the pattern of phase locking over time may be used to perceive FM, at least for low FM rates and for carrier frequencies of 4000 Hz and below (Demany and Semal, 1989; Moore and Glasberg, 1989; Moore and Sek, 1995, 1996; Sek and Moore, 1995; Moore and Skrodzka, 2002). It has been proposed that TFS cues are not used to detect FM with rates above about 10 Hz because the mechanism for "decoding" the TFS information is "sluggish" and cannot track rapid changes in frequency (Moore and Sek, 1995, 1996; Sek and Moore, 1995).

B. Role of excitation pattern cues in FM detection

To assess the role of excitation-pattern cues in FM detection, Moore and Sek (1996) measured FM detection thresholds for a wide range of combinations of carrier frequency, f_c, and modulation rate, f_m, with and without sinusoidal AM with a 6-dB peak-to-valley ratio applied to all stimuli in a forced-choice trial. The AM had the same modulation rate as the FM, and the starting phase of the AM was chosen at random for each stimulus. The AM was intended to disrupt excitation-pattern cues for FM detection by introducing large fluctuations in excitation level that were uninformative about the FM. The added AM adversely affected performance and, for f_c below 4000 Hz, the adverse effect increased with increasing f_m, consistent with the idea that excitation-pattern cues play a greater role for higher f_m. For $f_c = 6000$ Hz, the adverse effect of the added AM was similar for all f_m, consistent with the idea that, for very high f_c, excitation-pattern cues dominate for all f_m.

C. Effects of age on FM detection

As noted earlier, the results of several studies suggest that sensitivity to TFS cues declines with increasing age (Ross *et al.*, 2007; Grose and Mamo, 2010; Hopkins and Moore, 2011; Moore *et al.*, 2012a, 2012b; Füllgrabe, 2013; King *et al.*, 2014; Füllgrabe *et al.*, 2015). On the other hand, several studies indicate that frequency selectivity does not change with age provided that audiometric thresholds remain normal (Lutman, 1991; Peters and Moore, 1992; Hopkins and Moore, 2011), which suggests that the excitation patterns evoked by modulated signals should be comparable for younger and older listeners. Hence, if FM is detected solely using excitation-pattern cues, the change in FM detection thresholds with age should be similar for low and high rates. In contrast, if low-rate FM detection depends on the use of TFS cues, then FM detection thresholds for a low rate should change with age more than FM detection thresholds for a high rate. However, there is no reason to expect that the effect of age would be different for low- and high-rate AM detection.

We are not aware of any previous studies that have assessed both AM and FM detection as a function of age, using both low and high modulation rates. Takahashi and Bacon (1992) measured AM detection thresholds as a function of AM rate (i.e., temporal modulation transfer functions, TMTFs) using a noise carrier. The data showed a progressive increase of thresholds with increasing age, especially for the lowest rate used ($f_m = 2$ Hz), but a repeated-measures analysis of variance (ANOVA) showed that the effect of age was not significant. He *et al.* (2007) measured TMTFs for $f_c = 500$ Hz. Listeners were given extensive training for $f_m = 5$ Hz. They found higher AM detection thresholds for older than for younger listeners for all AM rates except the lowest used (5 Hz). He *et al.* (2008) showed that sensitivity to FM for $f_c = 500$ Hz declined with increasing age, but they used only a single modulation rate, 5 Hz. Schoof and Rosen (2014) measured TMTFs using a noise carrier and measured FM detection thresholds for $f_c = 1000$ Hz and a modulation rate of 2 Hz. Inconsistent with the above studies, they did not observe any significant effect of age on either AM or FM detection thresholds. Füllgrabe *et al.* (2015) measured TMTFs using a 4000-Hz sinusoidal carrier and found that AM detection thresholds were higher for older than for young listeners with matched normal audiograms. However, the shapes of the TMTFs were similar for the two groups, suggesting that increasing age is associated with reduced processing efficiency but not reduced temporal resolution for envelope changes.

In summary, the goal of this study was to assess whether the increase in low-rate FM detection thresholds with increasing age reflects a decrease in the availability of TFS information or whether it reflects a change in processing efficiency with age. To achieve this, both AM and FM detection thresholds were measured for two modulation rates and as a function of the number of modulation cycles, using younger and older listeners with normal audiograms. As a means of encouraging the use of TFS cues for FM detection, the thresholds for detecting FM were measured in the presence of added AM in all intervals of the forced-choice task (Moore and Sek, 1996). This was intended to disrupt the use of excitation-pattern cues. We hypothesized that age would have a greater effect on low-rate FM detection than on high-rate FM detection, but that the effect of age would be similar for low- and high-rate AM detection. We also hypothesized that temporal integration might differ for low-rate FM detection and for high-rate FM detection, or AM detection.

II. METHOD

A. Listeners

There were 15 young listeners (Young), aged between 22 and 28 yrs [mean = 24 yrs; standard deviation (SD) = 2 yrs] and 14 older listeners (Older), aged between 47 and 66 yrs (mean = 57 yrs; SD = 8 yrs). All listeners had audiometric thresholds less than 20 dB hearing level (HL) for the tested (right) ear for octave frequencies between 0.25 and 3 kHz (see Fig. 1). Some of the Older listeners ($n = 7$) had elevated audiometric thresholds above 3 kHz. The mean audiometric threshold at 0.5 kHz was 8.1 dB HL (SD = 3.1 dB) for the Young group and 8.9 dB HL (SD = 4.9 dB) for the Older group. A t-test conducted on audiometric thresholds at 0.5 kHz showed no significant difference between groups [$t(27) = -0.61$; $p = 0.54$]. All listeners were fully informed about the goal of the study and provided written consent before their participation. This study was approved by the local ethical committee of University Paris Descartes (CERES, N° IRB: 20143200001072).

B. Stimuli

All stimuli were generated digitally at a sampling rate of 44.1 kHz. They were presented at a mean sensation level of 40 dB using Sennheiser HD 280 pro headphones (Old Lyme, CT) and an external soundcard (ECHO Indigo DJ 1-2, Santa Barbara, CA; 16-bit resolution). Stimuli were presented only to the right ear. At 0.5 kHz, audiometric thresholds ranged between 5 and 15 dB HL for the Young listeners and between 0 and 15 dB HL for the Older listeners. Thus, presentation levels covered the same range for the two groups, i.e., 40–55 dB sound pressure level.

A two-interval forced-choice task was used. Each trial contained a target (modulated) and a standard (unmodulated) stimulus, in random order, with a silent interval of 600 ms between them. The root-mean-square level of the two stimuli was, on average, the same. However, to discourage the use of level cues, the levels of the standard and target were roved independently within the range ± 1.5 dB. For each AM and FM stimulus, raised-cosine ramps were applied at the onset and at the offset. The ramp durations were 250 and 25 ms for the modulation rates of 2 and 20 Hz, respectively. The duration of each signal was determined by the number of modulation cycles, N, and the modulation rate, f_m. N was set to 2, 3, 4, 5, or 9 cycles.

1. AM detection

The carrier was a sinusoid with $f_c = 500$ Hz. This was either unmodulated to produce the standard stimulus, or modulated sinusoidally in amplitude to produce the target stimulus. Equation (1) describes the target stimulus T(t):

$$\mathrm{T}(t) = [1 + m \sin(2\pi f_m t + 3\pi/2)] \sin(2\pi f_c t + \varphi), \qquad (1)$$

where f_m is the modulation rate (2 or 20 Hz), φ is the starting phase of the carrier, and t is time (expressed in s). The value of φ was randomly chosen for each stimulus. The starting phase of the modulator, $3\pi/2$ radians, resulted in a modulation minimum at the onset and offset of the stimulus. The modulation depth, m, was adaptively varied to determine the threshold.

2. FM detection

The carrier was a sinusoid with $f_c = 500$ Hz. The standard stimulus contained AM but not FM. The target stimulus

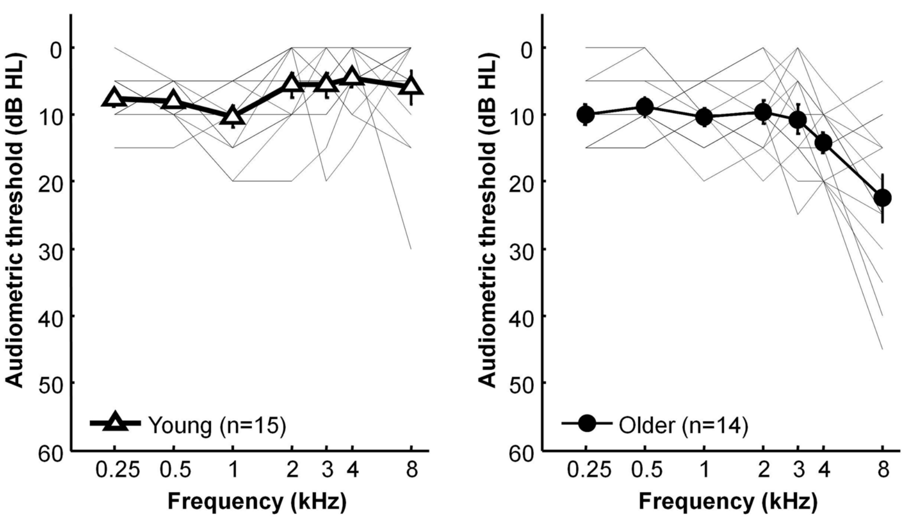

FIG. 1. Individual and mean audiometric thresholds for the younger (Young, left) and older (Older, right) listeners for the right ear. Error bars indicate ±1 standard error of the mean. They are omitted when they are smaller than the symbol used to plot the data.

contained both AM and FM. Equation (2) describes the target stimulus T(t)

$$T(t) = AM(t)\sin[(2\pi f_c t + \Phi) + \beta(\sin(2\pi f_m t + \varphi))],$$
$$\text{with } AM(t) = [1 + 0.33\sin(2\pi f_m t + 3\pi/2)]$$
$$\text{and } \beta = \Delta f/f_m, \quad (2)$$

where Δf is the frequency excursion in Hz, f_m is the modulation rate (2 or 20 Hz), φ is the starting phase of the FM, Φ is the starting phase of the carrier, and t is time in s. The values of φ and Φ were randomly and independently chosen for each stimulus. Although the starting phase of the AM was fixed, its phase relative to that of the FM was random (because φ was chosen randomly), so the AM should still have been effective in disrupting the use of excitation-pattern cues. For the standard stimulus, Δf was set to 0. The value of Δf for the target was adaptively varied to determine the threshold.

C. Procedure

Detection thresholds were measured using a two-interval forced-choice adaptive procedure estimating the 70.7% point on the psychometric function (Levitt, 1971). Each interval was marked by a light on the computer screen. Listeners were asked to indicate which interval contained the fluctuating sound for the AM detection task or the "extra" pitch fluctuation for the FM detection task. Visual feedback as to the correct response was provided after each response. The tracking variable was m for the AM detection task and Δf for the FM detection task. A run started with the tracking variable well above the estimated detection threshold. The step size was a factor of 1.58 until 2 reversals had occurred, and 1.26 thereafter. Fourteen reversals were obtained for each run, and the threshold estimate for that run was taken as the geometric mean of the tracking variable at the last six reversals. Two threshold estimates were obtained for each condition. The final estimate of the threshold was taken as the geometric mean of the two threshold estimates.

Thresholds were measured first for AM detection and then for FM detection. Within a block (AM or FM), the order of conditions (5 values of $N \times 2$ values of f_m) was chosen using a Latin-square design. This reduced the group effects of learning and fatigue. A test session was terminated when the listener reported fatigue or when the experimenter judged that the listener was becoming fatigued. No training was given before the beginning of the experiment. However, each listener was presented with some practice trials at the start of each block.

III. RESULTS

A. Effects of N and f_m

Figure 2 shows the mean modulation detection thresholds for each group plotted as a function of N, for $f_m = 2$ Hz (circles) and $f_m = 20$ Hz (triangles). The top and bottom panels show AM and FM detection thresholds, respectively. The thresholds for Young and Older listeners are shown by dashed and continuous lines, respectively. AM detection thresholds are expressed as $20\log_{10}m$.

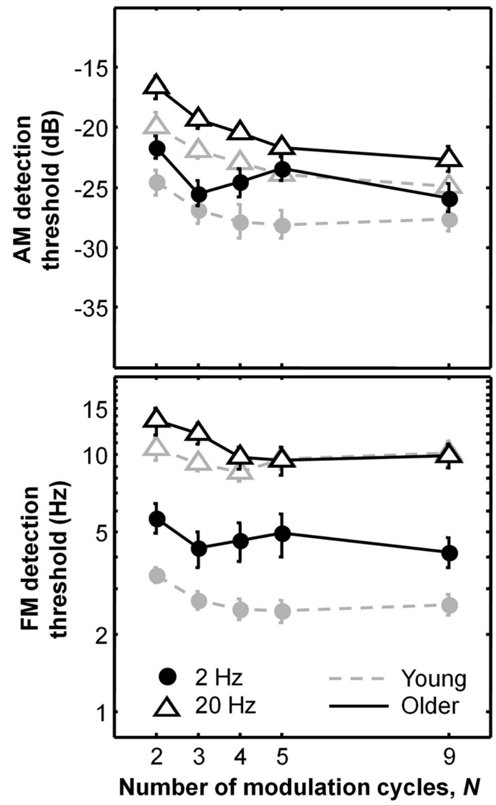

FIG. 2. Mean AM and FM detection thresholds for the Young listeners (dashed lines) and Older listeners (continuous lines), as a function of the number of modulation cycles, N, with modulation rate, f_m, as parameter (circles: 2 Hz; triangles: 20 Hz). The AM detection thresholds are expressed in dB as $20\log_{10}m$. The FM detection thresholds are expressed in Hz (log scale). Error bars indicate ± 1 standard error of the mean.

A repeated-measures ANOVA was conducted on the AM detection thresholds (expressed as $20\log_{10}m$) with between-subjects factor group (two levels) and within-subjects factors N (five levels) and modulation rate (two levels). The effect of group is discussed later. The effect of modulation rate was significant [$F(1, 27) = 37.8$, $p < 0.001$]. For both groups, AM detection thresholds were lower for $f_m = 2$ Hz than for $f_m = 20$ Hz for each value of N. For the Young listeners, the difference was about 5 dB for $N < 5$, and about 3 dB for $N = 9$. The thresholds for the Young listeners are broadly consistent with those found in previous studies of AM detection for normal-hearing listeners (Zwicker, 1952; Kohlrausch *et al.*, 2000; Moore and Glasberg, 2001), although information is lacking about AM detection for very low modulation rates (2 Hz) and low carrier frequencies (500 Hz).

The effect of N was significant [$F(4, 108) = 26.5$, $p < 0.001$]. For each modulation rate, AM detection thresholds for Young listeners decreased with increasing N. For Older listeners, at $f_m = 20$ Hz, AM detection thresholds also decreased with increasing N; at $f_m = 2$ Hz, the change in AM detection thresholds as a function of N was somewhat irregular, but thresholds were lower when $N = 9$ cycles than when $N = 2$ cycles. For the Young listeners, the decrease was 3–5 dB when N was increased from 2 to 9 cycles, but most of the effect of N occurred for $N \leq 5$. We are not aware of any previous study of temporal integration for AM detection using a sinusoidal carrier. The effect of N on AM detection is broadly consistent with the results of Sheft and Yost (1990) obtained with gated wideband noise carriers and normal-hearing listeners.

There was a significant interaction between N and f_m [$F(4, 108) = 3.8$, $p = 0.006$]. This may reflect the fact that the decrease in AM detection thresholds as N increased from 2 to 9 was greater for $f_m = 20$ Hz (5.4 dB) than for $f_m = 2$ Hz (3.3 dB). None of the other interactions were significant.

A linear regression analysis was conducted on the individual AM detection thresholds [log-transformed AM detection thresholds versus log(N)]. A repeated-measures ANOVA was conducted on the resulting slopes with between-subject factor group (two levels) and within- subjects factor f_m (two levels). The ANOVA showed a significant effect of f_m [$F(1, 27) = 9.0$, $p = 0.005$] but no significant effect of group [$F(1, 27) < 1$] and no significant interaction [$F(1, 27) < 1$]. These analyses confirm that temporal integration for AM detection is stronger at 20 Hz than at 2 Hz for both groups.

A repeated-measures ANOVA was conducted on the (log-transformed) FM detection thresholds with the same factors as described above. The effect of group is discussed later. The effect of modulation rate was significant [$F(1, 27) = 234.1$, $p < 0.001$], thresholds being lower for $f_m = 2$ Hz than for $f_m = 20$ Hz. The thresholds for the Young listeners are comparable to those reported by Moore and Sek (1996) and Moore and Skrodzka (2002). The effect of N was significant [$F(4, 108) = 10.0$, $p < 0.001$]. For each modulation rate and each group, FM detection thresholds decreased with increasing N up to 3 or 4, with no consistent change for greater N. The decrease for the Young listeners, corresponding to a factor of about 1.4 for $f_m = 2$ Hz and 1.1 for $f_m = 20$ Hz, is smaller than the factor of 1.8 found by Hartmann and Klein (1980) for $f_m = 4$ Hz and $f_c = 800$ Hz, possibly because we used interfering AM and they did not. The interaction between N and f_m was not significant [$F(4, 108) < 1$, $p > 0.05$], indicating that FM detection thresholds decreased similarly with increasing N for $f_m = 2$ Hz and $f_m = 20$ Hz.

B. Effects of group

For AM detection, the effect of group was significant [$F(1, 27) = 9.3$, $p = 0.005$]. For most conditions, the AM detection thresholds for the Older listeners were slightly higher (by about 2 dB) than those for the Young listeners. There were no interactions involving group, indicating that: (i) the pattern of results for AM detection did not differ significantly for the two groups and (ii) the Older group performed more poorly overall.

For FM detection, the effect of group was significant [$F(1, 27) = 8.6$, $p = 0.007$]. For most conditions, FM detection thresholds were higher for the Older than for the Young listeners, although this was not the case for $N = 5$ or 9 and $f_m = 20$ Hz. The interaction between group and f_m was significant [$F(1, 27) = 6.8$, $p = 0.014$], indicating that the effect of age was different for $f_m = 2$ Hz and $f_m = 20$ Hz. FM detection thresholds were higher for the Older than for the Young listeners by an average factor of about 1.7 for $f_m = 2$ Hz and 1.14 for $f_m = 20$ Hz. There was no significant interaction between group and N [$F(4, 108) < 1$, $p > 0.05$], indicating that the decrease in FM detection thresholds with increasing N was broadly similar for the Young and Older listeners. There was no significant interaction between group f_m and N.

C. Further analysis of the effect of *N*

To compare temporal integration effects across groups and modulation type (AM vs FM), the data were normalized for each listener and each f_m, by dividing each modulation threshold by the geometric mean detection threshold (expressed as m for AM detection, and in Hertz for FM detection) across N for that listener. Figure 3 shows the mean normalized detection thresholds plotted as a function of N.

A repeated-measures ANOVA was conducted on the normalized detection thresholds with between-subjects factor group (two levels) and within-subjects factors modulation type (two levels), N (five levels), and modulation rate (two levels). The main effect of N was significant [$F(4, 108) = 43.3$, $p < 0.001$]. None of the other main effects were significant. The interaction between N and modulation type was significant [$F(4, 108) = 4.9$, $p = 0.001$]. For each modulation rate and each group, thresholds decreased more with increasing N for AM than FM. The interaction between N and modulation rate was significant [$F(4, 108) = 3.0$, $p = 0.022$]. Thresholds decreased more with increasing N for $f_m = 20$ Hz than for $f_m = 2$ Hz. No other two-way interactions were significant.

The three-way interaction between N, modulation type, and modulation rate approached but did not reach significance [$F(4, 108) = 2.3$, $p = 0.068$]. AM and FM detection

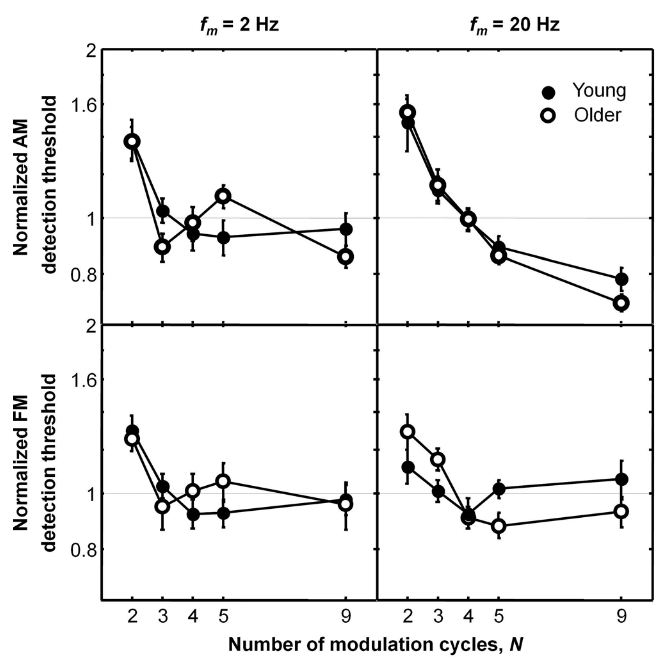

FIG. 3. Data replotted from Fig. 2, highlighting the effects of N. For each listener and each modulation rate, each modulation detection threshold was divided by the geometric mean detection threshold across N (expressed as m for AM detection, and in Hertz for FM detection). The arithmetic averages of the resulting normalized thresholds across listeners are plotted with error bars showing ±1 standard error.

thresholds tended to decrease similarly with increasing N for the two modulation rates, although there was a trend for AM detection thresholds to decrease more with increasing N for $f_m = 20$ Hz than for $f_m = 2$ Hz. There was no significant interaction between N and group [$F(4, 108) < 1$, $p > 0.05$] or between N, group, and modulation type [$F(4, 108) < 1$, $p > 0.05$]. There was a three-way interaction between N, group, and modulation rate [$F(4, 108) = 2.9$, $p = 0.025$], reflecting the observation that, for $f_m = 20$ Hz, AM and FM detection thresholds decreased slightly more with increasing N for the Older than for the Young listeners.

IV. DISCUSSION

A. Sluggishness and temporal integration for AM and FM detection

For both types of modulation (AM and FM), the modulation sensitivity of Young and Older listeners was poorer for the 20-Hz than for the 2-Hz modulation rate (see Fig. 2). However, this comparison was made with N equated across modulation rates, and, for a given N, the stimuli were a factor of 10 shorter in duration for the 20-Hz rate than for the 2-Hz rate. For stimuli with a fixed duration of a few hundred milliseconds, AM detection for rates close to 2 Hz tends to be *worse* than for rates close to 20 Hz (Sheft and Yost, 1990; Kohlrausch *et al.*, 2000; Ernst and Moore, 2012). In contrast, FM detection for similar durations and for low and medium carrier frequencies tends to be better for rates close to 2 Hz than for rates close to 20 Hz (Moore and Sek, 1995, 1996; Sek and Moore, 1995), especially when uninformative AM is present in all intervals of a forced-choice task (Moore and Sek, 1996; Ernst and Moore, 2010, 2012), as in the present experiment. This pattern of results is consistent with the idea that FM detection does not depend solely on the use of excitation-pattern cues (transformation of FM to AM), but rather that an extra cue is used for FM detection at low rates, probably based on the use of TFS information.

Temporal integration (defined here by the improvement in modulation detection thresholds with increasing N) was found for both types of modulation (see Fig. 3). For FM detection, temporal integration did not differ markedly for the two FM rates. This suggests that temporal integration is distinct from the "sluggishness" that has been proposed to apply to the use of TFS information to detect low-rate FM (Moore and Sek, 1995, 1996; Sek and Moore, 1995). According to the sluggishness hypothesis, the rate of change of instantaneous frequency within a single FM cycle needs to be sufficiently slow for the TFS information to be extracted, but this appears to be separate from the process of combining information across successive FM cycles (temporal integration).

For AM detection, temporal integration was greater for the 20-Hz than for the 2-Hz rate. This may reflect limitations in short-term auditory memory since for the 2-Hz rate, the stimuli were a factor of 10 longer in duration, and the duration reached 4.5 s when $N = 9$. This duration exceeds the assumed duration of echoic memory (Darwin *et al.*, 1972; Ardoint *et al.*, 2008).

Temporal integration was greater for AM than FM, mainly for the 20-Hz rate (see Fig. 3). This seems puzzling at first sight, since it is usually assumed that, for a 20-Hz rate, FM is detected via FM-to-AM conversion. The difference in temporal integration for AM and FM may be linked to the fact that the FM detection thresholds were obtained in the presence of uninformative AM. The presence of the AM meant that the FM could be detected via changes in excitation level only if the fluctuations in excitation level were compared for the lower and upper sides of the excitation pattern, since the AM made the fluctuations at any single point on the pattern an unreliable cue. This comparison process may have different temporal integration properties from the process involved in simple AM detection.

As noted earlier, the improvement in FM detection threshold with increasing N was smaller than that reported by Hartmann and Klein (1980) for normal-hearing listeners using $f_m = 4$ Hz and $f_c = 800$ Hz. This discrepancy may be linked to the presence of uninformative AM in the present study but not in the study of Hartmann and Klein (1980). To assess this possibility, FM detection thresholds were measured as a function of N (from 2 to 4) without interfering AM for 8 of the 15 Young listeners. The methods and procedures were identical to those described above. The data are shown in Fig. 4. FM detection thresholds collected with interfering AM for the same eight Young listeners are plotted for comparison. A within-subjects ANOVA was conducted on the (log-transformed) FM detection thresholds with factors presence/absence of interfering AM (two levels), N (three levels), and modulation rate (two levels). The main effect of interfering AM was significant [$F(1, 7) = 205.6$; $p < 0.001$], FM detection thresholds being better in the absence of interfering AM. The main effect of N was significant [$F(2, 14) = 30.5$; $p < 0.001$], FM detection thresholds decreased with increasing N. The main effect of modulation rate was significant [$F(1, 7) = 66.6$; $p < 0.001$], FM detection thresholds were better at $f_m = 2$ Hz than $f_m = 20$ Hz. The interaction between interfering AM and modulation rate was significant [$F(1, 7) = 22.4$; $p = 0.002$], the detrimental effect of the interfering AM being greater for $f_m = 20$ Hz than for $f_m = 2$ Hz. These findings are consistent with previous work (Moore and Sek, 1996; Ernest and Moore, 2010, 2012) and with the notion that excitation pattern cues play a greater role for $f_m = 20$ Hz than for $f_m = 2$ Hz.

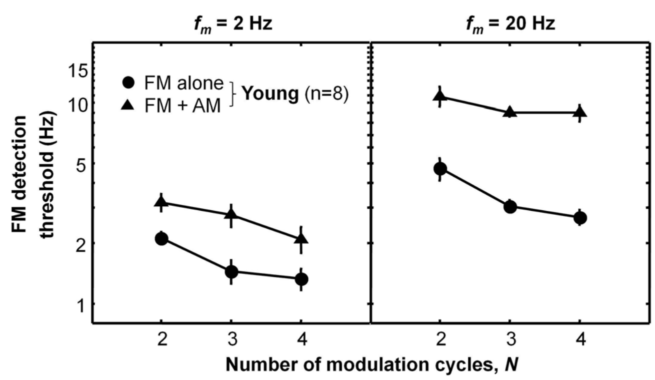

FIG. 4. Mean FM detection thresholds for eight Young listeners, as a function of N. The FM detection thresholds were measured with (filled triangles) and without (filled circles) interfering AM at the same rate as the FM.

The two-way interaction between interfering AM and N was not significant at the 0.05 level [$F(2, 14) = 3$; $p = 0.089$] but the three-way interaction between interfering AM, N, and modulation rate was marginally significant [$F(2, 14) = 3.5$; $p = 0.057$]. For the 2-Hz rate, the decrease in threshold with increasing N was the same in the absence (factor of 1.5) and in the presence (factor of 1.5) of interfering AM. For the 20-Hz rate, the decrease in threshold with increasing N was greater in the absence (factor of 1.8) than in the presence (factor of 1.2) of interfering AM. The decrease factor observed here in the absence of AM at both modulation rates is only slightly less than the factor of about 2 found by Hartmann and Klein (1980) for an FM rate of 4 Hz, consistent with the idea that the smaller temporal integration found in the main experiment was at least partly due to the presence of the added AM

B. Effects of age on AM and FM sensitivity

The modest but significant effect of age on AM detection observed in the present study (see Fig. 2, top panel) is consistent with most previous results obtained with older listeners than those used here (He *et al.*, 2008: mean age = 71 yrs; Füllgrabe *et al.*, 2015: mean age = 67 yrs; present study: Older group mean age = 57 yrs), although Schoof and Rosen (2014) reported no effect of age for detection of 20-Hz AM applied to a noise carrier.

The effect of age on FM detection for $f_m = 2$ Hz (mean thresholds a factor of 1.7 higher for the Older than for the Young listeners) is broadly consistent with the detrimental effects of age for a carrier frequency of 500 Hz reported by He *et al.* (2008) for $f_m = 5$ Hz (increase of FM detection threshold by a factor of about 2.5) and Grose and Mamo (2012) for $f_m = 2$ Hz (increase of FM detection threshold by a factor of about 1.8). However, Schoof and Rosen (2014) found no significant effect of age for detection of 2-Hz FM applied to a 1000-Hz carrier.

The small differences across studies that found an age effect are probably due to differences in the ages of the Older listeners, which were 47–66 yrs (mean = 57 yrs) for the present study, 65–77 yrs for the study of Grose and Mamo (2012), and a mean of 71 yrs for the study of He *et al.* (2008). The studies also varied in the extent to which they used stimulus manipulations to reduce the salience of excitation-pattern cues. The current study used interfering AM. Grose and Mamo (2012) roved the carrier frequency over a small range but this might not have been very effective at reducing the use of excitation-pattern cues. He *et al.* (2008) did not attempt to reduce the role of excitation-pattern cues. The added AM in our study would be expected to produce a greater reliance on TFS cues for the 2-Hz rate, thereby increasing the effect of any age-related decline in the ability to use TFS cues. Therefore, the smaller effect of age found here compared to the studies of Grose and Mamo (2012) and He *et al.* (2008) probably reflects the fact that the older listeners were not as old as for the earlier studies.

The detrimental effect of age on AM detection was similar for the two modulation rates (see Fig. 2, top panel); the interaction between group and modulation rate was not significant. This is consistent with the results of Füllgrabe *et al.* (2015). In contrast, the detrimental effect of age on FM detection thresholds was greater for $f_m = 2$ Hz than for $f_m = 20$ Hz (see Fig. 2, lower panel); the interaction between group and modulation rate was significant. This is consistent with the idea that low-rate FM detection depends on the use of TFS cues, and that sensitivity to TFS declines with age. However, the detrimental effect of age on FM detection for the 2-Hz rate was modest, perhaps because the mean age of the Older group was only 57 yrs. Also, there were large individual differences within the Older group. Figure 5 shows individual AM and FM detection thresholds averaged across N for each modulation rate (geometric mean). A detrimental effect of age on FM detection at $f_m = 2$ Hz occurred for 5 of the 14 Older listeners; the remainder had mean thresholds within the range found for the Young listeners. There was no significant correlation between age and (log-transformed) FM detection thresholds for $f_m = 2$ Hz for the Older group only (Pearson $r = -0.42$; $p = 0.13$). Hence, the poorest performers on the FM-detection task were not the oldest ones within the Older group. For the Older listeners only, there was no significant correlation between (log-transformed) FM detection thresholds at $f_m = 2$ Hz and absolute thresholds at 0.5 kHz (Pearson $r = -0.12$; $p = 0.68$) or mean absolute thresholds at 4 and 8 kHz (Pearson $r = -0.07$; $p = 0.82$). Further work is needed to understand the factors other than age that influence sensitivity to low-rate FM.

Age did not affect temporal integration for AM and FM detection for the 2-Hz modulation rate (see Fig. 3, left panels) and temporal integration for the 20-Hz rate was actually slightly greater for the older than for the younger listeners (see Fig. 3, right panels). For FM at least, the greater temporal integration for the Older listeners occurred because they

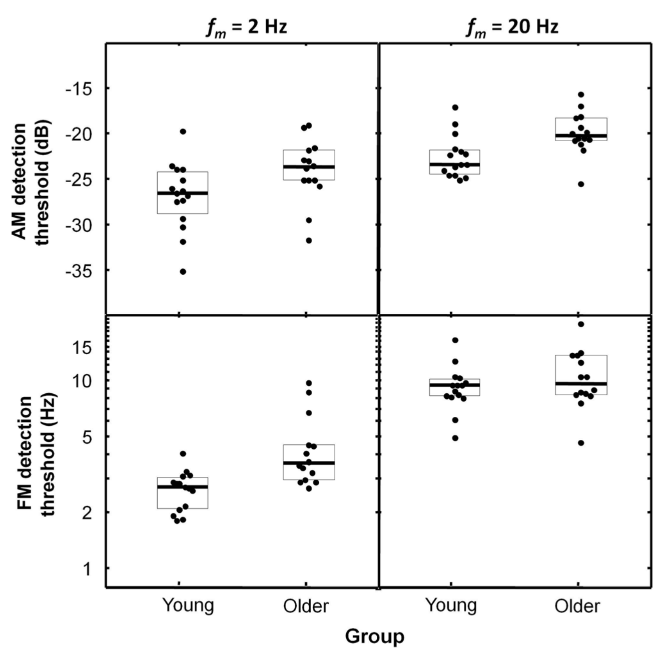

FIG. 5. The filled symbols show individual AM and FM detection thresholds averaged across N for each modulation rate. The bold lines show median values, and the lower and upper boundaries of the boxes show the first and third quartiles.

performed more poorly when the number of modulation cycles was small ($N = 2$ and 3). These findings indicate that ageing spares the processes underlying temporal integration such as multiple looks (Viemeister and Wakefield, 1991) or a template-matching process (Hartmann and Klein, 1980; Dau *et al.*, 1997) and support the notion that at least some aspects of processing efficiency do not decline with age. This is consistent with the finding that temporal integration for simple detection of pure tones in quiet does not vary significantly with age (Gehr and Sommers, 1999).

V. SUMMARY AND CONCLUSIONS

AM and FM detection thresholds were measured for a carrier frequency of 500 Hz and modulation rates of 2 and 20 Hz for Young and Older listeners with normal absolute thresholds below 3 kHz. FM detection thresholds were measured in the presence of uninformative AM in both intervals of a forced-choice trial, to disrupt the use of excitation-pattern cues. The number of modulation cycles, *N*, ranged from 2 to 9. The results show the following:

(1) For both groups and for each *N*, AM, and FM detection thresholds were lower for the 2-Hz than for the 20-Hz rate.
(2) For both groups, AM and FM detection thresholds decreased with increasing *N*, this effect being greater for AM than FM.
(3) Thresholds were higher for older than for younger listeners, especially for FM detection at 2 Hz. This is interpreted as reflecting a detrimental effect of age on the use of TFS cues for low-rate FM detection.
(4) The effect of increasing *N* was similar across groups for both AM and FM for the 2-Hz rate. For the 20-Hz rate, the older listeners showed a slightly greater effect of increasing *N* than the younger listeners for both AM and FM. These findings suggest that ageing spares temporal integration of the cues used to detect AM and FM.

ACKNOWLEDGMENTS

The authors wish to thank all the participants of this study. N.W. was supported by a grant from Neurelec Oticon Medical. C.L. was supported by two grants from ANR (HEARFIN and HEART projects). This work was also supported by ANR-11-0001-02 PSL* and ANR-10-LABX-0087. The authors wish to thank Nihaad Paraouty for comments and suggestions concerning this study and two anonymous reviewers for helpful comments.

Ardoint, M., Lorenzi, C., Pressnitzer, D., and Gorea, A. (**2008**). "Perceptual constancy in the temporal envelope domain," J. Acoust. Soc. Am. **123**, 1591–1601.

Darwin, C. J., Turvey, M. T., and Crowder, R. G. (**1972**). "An auditory analogue of the Sperling partial report procedure: Evidence for brief auditory storage," Cog. Psychol. **3**, 255–267.

Dau, T., Kollmeier, B., and Kohlrausch, A. (**1997**). "Modeling auditory processing of amplitude modulation. II. Spectral and temporal integration," J. Acoust. Soc. Am. **102**, 2906–2919.

Demany, L., and Semal, C. (**1989**). "Detection thresholds for sinusoidal frequency modulation," J. Acoust. Soc. Am. **85**, 1295–1301.

Ernst, S. M. A., and Moore, B. C. J. (**2010**). "Mechanisms underlying the detection of frequency modulation," J. Acoust. Soc. Am. **128**, 3642–3648.

Ernst, S. M. A., and Moore, B. C. J. (**2012**). "The role of time and place cues in the detection of frequency modulation by hearing-impaired listeners," J. Acoust. Soc. Am. **131**, 4722–4731.

Füllgrabe, C. (**2013**). "Age-dependent changes in temporal-fine-structure processing in the absence of peripheral hearing loss," Am. J. Audiol. **22**, 313–315.

Füllgrabe, C., Moore, B. C. J., and Stone, M. A. (**2015**). "Age-group differences in speech identification despite matched audiometrically normal hearing: Contributions from auditory temporal processing and cognition," Front. Aging Neurosci. **6**, 1–25.

Gehr, S. E., and Sommers, M. S. (**1999**). "The effects of age on temporal integration," J. Acoust. Soc. Am. **106**, 2208.

Grose, J. H., and Mamo, S. K. (**2010**). "Processing of temporal fine structure as a function of age," Ear Hear. **31**, 755–760.

Grose, J. H., and Mamo, S. K. (**2012**). "Frequency modulation detection as a measure of temporal processing: Age-related monaural and binaural effects," Hear. Res. **294**, 49–54.

Hartmann, W. M., and Klein, M. A. (**1980**). "Theory of frequency modulation detection for low modulation frequencies," J. Acoust. Soc. Am. **67**, 935–946.

He, N. J., Mills, J. H., Ahlstrom, J. B., and Dubno, J. R. (**2008**). "Age-related differences in the temporal modulation transfer function with pure-tone carriers," J. Acoust. Soc. Am. **124**, 3841–3849.

He, N. J., Mills, J. H., and Dubno, J. R. (**2007**). "Frequency modulation detection: Effects of age, psychophysical method, and modulation waveform," J. Acoust. Soc. Am. **122**, 467–477.

Heinz, M. G., Colburn, H. S., and Carney, L. H. (**2001**). "Evaluating auditory performance limits: I. One-parameter discrimination using a computational model for the auditory nerve," Neur. Comput. **13**, 2273–2316.

Hopkins, K., and Moore, B. C. J. (**2011**). "The effects of age and cochlear hearing loss on temporal fine structure sensitivity, frequency selectivity, and speech reception in noise," J. Acoust. Soc. Am. **130**, 334–349.

Johnson, D. H. (**1980**). "The relationship between spike rate and synchrony in responses of auditory-nerve fibers to single tones," J. Acoust. Soc. Am. **68**, 1115–1122.

Kiang, N. Y. S. (**1965**). "Stimulus coding in the auditory nerve and cochlear nucleus," Acta Otolaryngol. **59**, 186–200.

King, A., Hopkins, K., and Plack, C. J. (**2014**). "The effects of age and hearing loss on interaural phase difference discrimination," J. Acoust. Soc. Am. **135**, 342–351.

Kohlrausch, A., Fassel, R., and Dau, T. (**2000**). "The influence of carrier level and frequency on modulation and beat-detection thresholds for sinusoidal carriers," J. Acoust. Soc. Am. **108**, 723–734.

Levitt, H. (**1971**). "Transformed up-down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467–477.

Lutman, M. E. (**1991**). "Degradations in frequency and temporal resolution with age and their impact on speech identification," Acta Otolaryngol. **111**, 120–126.

Moore, B. C. J. (**2014**). *Auditory Processing of Temporal Fine Structure: Effects of Age and Hearing Loss* (World Scientific, Singapore), pp. 1–182.

Moore, B. C. J., and Glasberg, B. R. (**1989**). "Mechanisms underlying the frequency discrimination of pulsed tones and the detection of frequency modulation," J. Acoust. Soc. Am. **86**, 1722–1732.

Moore, B. C. J., and Glasberg, B. R. (**2001**). "Temporal modulation transfer functions obtained using sinusoidal carriers with normally hearing and hearing-impaired listeners," J. Acoust. Soc. Am. **110**, 1067–1073.

Moore, B. C. J., Glasberg, B. R., Stoev, M., Füllgrabe, C., and Hopkins, K. (**2012a**). "The influence of age and high-frequency hearing loss on sensitivity to temporal fine structure at low frequencies (L)," J. Acoust. Soc. Am. **131**, 1003–1006.

Moore, B. C. J., and Sek, A. (**1994**). "Effects of carrier frequency and background noise on the detection of mixed modulation," J. Acoust. Soc. Am. **96**, 741–751.

Moore, B. C. J., and Sek, A. (**1995**). "Effects of carrier frequency, modulation rate, and modulation waveform on the detection of modulation and the discrimination of modulation type (amplitude modulation versus frequency modulation)," J. Acoust. Soc. Am. **97**, 2468–2478.

Moore, B. C. J., and Sek, A. (**1996**). "Detection of frequency modulation at low modulation rates: Evidence for a mechanism based on phase locking," J. Acoust. Soc. Am. **100**, 2320–2331.

Moore, B. C. J., and Sęk, A. (**2009**). "Sensitivity of the human auditory system to temporal fine structure at high frequencies," J. Acoust. Soc. Am. **125**, 3186–3193.

Moore, B. C. J., and Skrodzka, E. (**2002**). "Detection of frequency modulation by hearing-impaired listeners: Effects of carrier frequency, modulation rate, and added amplitude modulation," J. Acoust. Soc. Am. **111**, 327–335.

Moore, B. C. J., Vickers, D. A., and Mehta, A. (**2012b**). "The effects of age on temporal fine structure sensitivity in monaural and binaural conditions," Int. J. Audiol. **51**, 715–721.

Palmer, A. R., and Russell, I. J. (**1986**). "Phase-locking in the cochlear nerve of the guinea-pig and its relation to the receptor potential of inner haircells," Hear. Res. **24**, 1–15.

Peters, R. W., and Moore, B. C. J. (**1992**). "Auditory filter shapes at low center frequencies in young and elderly hearing-impaired subjects," J. Acoust. Soc. Am. **91**, 256–266.

Rose, J. E., Brugge, J. F., Anderson, D. J., and Hind, J. E. (**1967**). "Phase-locked response to low-frequency tones in single auditory nerve fibers of the squirrel monkey," J. Neurophysiol. **30**, 769–793.

Ross, B., Fujioka, T., Tremblay, K. L., and Picton, T. W. (**2007**). "Aging in binaural hearing begins in mid-life: Evidence from cortical auditory evoked responses to changes in interaural phase," J. Neurosci. **27**, 11172–11178.

Schoof, T., and Rosen, S. (**2014**). "The role of auditory and cognitive factors in understanding speech in noise by normal-hearing older listeners," Front. Aging Neurosci. **6**, 1–14.

Sek, A., and Moore, B. C. J. (**1995**). "Frequency discrimination as a function of frequency, measured in several ways," J. Acoust. Soc. Am. **97**, 2479–2486.

Sheft, S., and Yost, W. A. (**1990**). "Temporal integration in amplitude modulation detection," J. Acoust. Soc. Am. **88**, 796–805.

Takahashi, G. A., and Bacon, S. P. (**1992**). "Modulation detection, modulation masking, and speech understanding in noise in the elderly," J. Speech Lang. Hear. Res. **35**, 1410–1421.

Verschooten, E., and Joris, P. X. (**2014**). "Estimation of neural phase locking from stimulus-evoked potentials," J. Assoc. Res. Otolaryngol. **15**, 767–787.

Viemeister, N. F. (**1979**). "Temporal modulation transfer functions based upon modulation thresholds," J. Acoust. Soc. Am. **66**, 1364–1380.

Viemeister, N. F., and Wakefield, G. H. (**1991**). "Temporal integration and multiple looks," J. Acoust. Soc. Am. **90**, 858–865.

Zwicker, E. (**1952**). "Die Grenzen der Hörbarkeit der Amplitudenmodulation und der Frequenz-modulation eines Tones" ("The limits of audibility of amplitude modulation and frequency modulation of a pure tone"), Acustica **2**, 125–133.

Zwicker, E. (**1956**). "Die elementaren Grundlagen zur Bestimmung der Informationskapazität des Gehörs" ("The foundations for determining the information capacity of the auditory system"), Acustica **6**, 356–381.

Zwislocki, J. J., and Nguyen, M. (**1999**). "Place code for pitch: A necessary revision," Acta Oto-laryngol. **119**, 140–145.