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Research Article

Gap Detection and Temporal Modulation Transfer Function as Behavioral Estimates of Auditory Temporal Acuity Using Band-Limited Stimuli in Young and Older Adults

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Purpose: Gap detection and the temporal modulation transfer function (TMTF) are 2 common methods to obtain behavioral estimates of auditory temporal acuity. However, the agreement between the 2 measures is not clear. This study compares results from these 2 methods and their dependencies on listener age and hearing status.

Method: Gap detection thresholds and the parameters that describe the TMTF (sensitivity and cutoff frequency) were estimated for young and older listeners who were naive to the experimental tasks. Stimuli were 800-Hz-wide noises with upper frequency limits of 2400 Hz, presented at 85 dB SPL. A 2-track procedure (Shen & Richards, 2013) was used for the efficient estimation of the TMTF.

Results: No significant correlation was found between gap detection threshold and the sensitivity or the cutoff frequency of the TMTF. No significant effect of age and hearing loss on either the gap detection threshold or the TMTF cutoff frequency was found, while the TMTF sensitivity improved with increasing hearing threshold and worsened with increasing age.

Conclusion: Estimates of temporal acuity using gap detection and TMTF paradigms do not seem to provide a consistent description of the effects of listener age and hearing status on temporal envelope processing.

Encoding the information contained in the temporal envelopes of acoustic stimuli is a fundamental ability of the auditory system. An excellent temporal acuity eases the detection of a target sound in masker sounds with temporally fluctuating envelopes, sound localization, and the understanding of speech. It has been demonstrated that a listener's temporal-processing capability is predictive of his or her performance on speech recognition, especially in noisy and complex environments (e.g., George, Festen, & Houtgast, 2006; George et al., 2007; Jin & Nelson, 2006; Snell, Mapes, Hickman, & Frisina, 2002). Therefore, behavioral techniques to estimate auditory temporal acuity have been an important topic in psychoacoustics, and efforts have been made to implement these techniques into clinical practice (e.g., Florentine, Buus, & Geng, 2000; Musiek et al., 2005). Among the techniques that have been developed to estimate auditory temporal acuity, gap detection and temporal modulation transfer function (TMTF) are commonly adopted in clinical research and arguably are the most well studied. Although both gap detection and TMTF are believed to probe temporal processing, there is a lack of data directly comparing the results obtained from the two methods. The current study compared temporal acuity estimated using both gap detection and TMTF approaches for young and older listeners. Consistency in the effects of listener age and hearing status on these two measures of temporal acuity was also investigated.

In a gap detection experiment, listeners detect the presence of a silent gap in a carrier sound. The gap detection threshold corresponds to the shortest gap duration needed for the gap to be detectable. Both pure-tone and noise carriers have been used in gap detection experiments previously. When a noise carrier is used, the gap detection threshold decreases as the carrier bandwidth and stimulus level increases (Eddins, Hall, & Grose, 1992). When broadband noise carriers are used, listeners with hearing impairment usually exhibit higher gap detection thresholds

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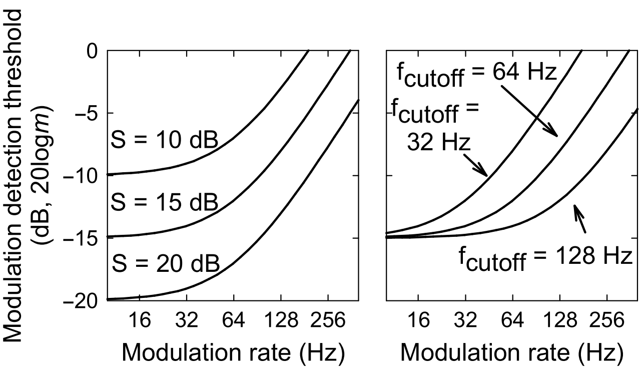
compared with those with normal hearing (e.g., Fitzgibbons & Wightman, 1982; Florentine & Buus, 1984; Irwin, Hinchcliff, & Kemp, 1981; Irwin & McAuley, 1987; Tyler, Summerfield, Wood, & Fernandes, 1982). For narrowband carriers, the gap detection thresholds are much worse for listeners with hearing impairment than for those with normal hearing, which has been explained by the loss of cochlear nonlinearity among those listeners with hearing impairment (Glasberg, Moore, & Bacon, 1987; Moore & Glasberg, 1988). Additionally, a number of previous studies have found that the gap detection thresholds measured from older listeners are higher than those of young listeners, even when the age-related hearing loss is controlled for (Fitzgibbons & Gordon-Salant, 1994; Grose, Hall, & Buss, 2001; He, Horwitz, Dubno, & Mills, 1999; Lister, Besing, & Koehnke, 2002; Lister, Koehnke, & Besing, 2000; Snell, 1997). Moreover, when the gap detection task is made cognitively demanding (e.g., by randomizing the temporal location of the gap within the carrier duration on a trial-by-trial basis), older adults show an increased age-related deficit in gap detection (Harris, Eckert, Ahlstrom, & Dubno, 2010; He et al., 1999).

Besides gap detection, another approach to estimate temporal acuity is to measure the TMTF (Viemeister, 1979). For a TMTF experiment, listeners detect the presence of sinusoidal amplitude modulation imposed on a carrier sound. A TMTF is typically a function relating the modulation detection threshold to the modulation rate. For broadband noise carriers, modulation detection thresholds are low and constant for low modulation rates. As the modulation rate exceeds approximately 60 Hz, the thresholds increase with increasing modulation rate at about 3–4 dB per octave (e.g., Viemeister, 1979). The shape of the TMTF resembles a first-order low-pass filter (or equivalently a leaky integrator in the time domain), and it can be described by two parameters: the sensitivity (*S*), which corresponds to the plateau performance at low modulation rates, and the cutoff frequency (f_{cutoff}) of the low-pass shape, which is thought to reflect the sluggishness of the auditory system. Figure 1 illustrates the shape of the TMTF as the *S* or f_{cutoff} parameter varies. As the value of *S* increases, the modulation detection threshold improves, and the entire TMTF shifts to a lower vertical position (left panel). Conversely, as the value of f_{cutoff} increases, the TMTF shifts horizontally toward higher modulation rates (right panel). Therefore, the modulation detection thresholds at low modulation rates are mainly determined by the sensitivity parameter *S*, while the thresholds at high modulation rates depend on both *S* and f_{cutoff}.

Besides broadband stimuli, the TMTFs could also be measured using narrowband stimuli, although difficulties might arise because of the potential confound of spectral cues (Kohlrausch, Fassel, & Dau, 2000; Strickland & Viemeister, 1997). Imposing amplitude modulation to a narrowband carrier creates spectral side bands. When this spectral change is comparable with the spectral resolution of the auditory periphery, listeners can use the spectral cue in performing the modulation detection task, leading to results that do not reflect temporal processing. One solution to this problem is to maintain the spectrum of the stimulus and manipulate the phase relationship among the spectral components to vary the modulation depth (Eddins, 1999; Strickland, 2000; Strickland & Viemeister, 1997; Tabuchi, Borucki, & Berg, 2012). This approach was adopted in the current study and will be described in detail in the Method section.

Figure 1. Illustrations of the effects of the sensitivity (*S*) and cutoff frequency (f_{cutoff}) parameters on the shape of the temporal modulation transfer function (TMTF). Left: three simulated TMTFs using a fixed f_{cutoff} value of 64 Hz and three different *S* values (10, 15, and 20 dB). Right: three simulated TMTFs using a fixed *S* value of 15 dB and three different f_{cutoff} values (32, 64, and 128 Hz).



Listeners with hearing impairment and those with normal hearing typically demonstrate a similar shape for their TMTFs, although both increased and decreased TMTF sensitivity has been reported for listeners with hearing impairment compared with those with normal hearing (Bacon & Gleitman, 1992; Bacon & Viemeister, 1985; Grant, Summers, & Leek, 1998). Using young and older adults with normal hearing, He, Mills, Ahlstrom, and Dubno (2008) studied the effect of age on the TMTF at low (500 Hz) and high (4000 Hz) frequency regions. In this study, a pure-tone carrier was used. At 4000 Hz, where the TMTF was less influenced by spectral cues, elevated thresholds in the TMTF were found for older listeners compared with younger listeners, which suggests an adverse effect of age on the TMTF sensitivity.

Because both gap detection and TMTF paradigms are thought to probe temporal-processing abilities, results from the two methods, in principle, should relate to each other, and the effects of listener age and hearing loss on these two measures of temporal acuity should be consistent. However, only a few studies have measured the gap detection threshold and TMTF from the same listeners and directly compared the results from the two paradigms. Forrest and Green (1987) measured both the TMTF and gap detection threshold for three listeners with normal hearing. In their gap detection measurements, the detection threshold for a partially filled gap as a function of the amount of decrement in root-mean-square amplitude during the gap relative to the carrier was measured. As the amplitude decrement increased, shorter gap durations were required to detect the presence of the gap, which approximately followed an exponential function. The authors demonstrated that the shapes of both the TMTF and the exponential trade-off function between amplitude decrement and gap detection threshold could be captured by a leaky integrator model (Viemeister, 1979). Given the small number of listeners included in the study by Forrest and Green (1987), it is not clear whether the individual differences in the TMTF could be explained by the gap detection results. However, if the leaky integrator model provides a valid framework to unify the TMTF and gap detection findings, it would predict that when temporal resolution is poor, the envelopes of the stimuli are passed through a leaky integrator with a long time constant (or equivalently a low-pass filter with a low cutoff frequency). Consequently, the cutoff frequency of the TMTF would be low while the gap detection threshold would be high.

This predicted negative correlation between the gap detection threshold and TMTF cutoff frequency has not been confirmed. Formby and Muir (1988) measured the gap detection threshold and the TMTF from six young female listeners using noise carriers with various bandwidths. For each listener, manipulating the carrier bandwidth affected both the gap detection and TMTF results. Unlike the prediction by the temporal integrator model, however, no correlation was found between the gap detection threshold and the TMTF cutoff frequency. Rather, a negative correlation was found between the gap detection threshold and the TMTF sensitivity, suggesting the gap detection threshold may be associated with the processing of low-rate amplitude modulation. In a recent study, Shen and Richards (2013) measured the gap detection threshold and TMTF from a relatively large number of young listeners with normal hearing by using broadband noise carriers. All listeners were naive to both gap detection and modulation detection tasks. Negative correlations were found between the gap detection threshold and the TMTF sensitivity across various experimental manipulations. Moreover, the gap detection threshold and the TMTF cutoff frequency were found to be either uncorrelated or positively correlated. Shen and Richards (2013) further showed that the relationship between the gap detection threshold and the TMTF cutoff frequency observed in their experiment could not be captured by the temporal integrator model proposed by Forrest and Green (1987). Potentially, the lack of a negative correlation between the gap detection threshold and TMTF cutoff frequency reflects the fact that the gap detection threshold is influenced not only by temporal acuity but also by the intensity resolution of the auditory system (Strickland & Viemeister, 1997).

The primary goal of the current study was to determine whether the gap detection threshold and TMTF parameters provide consistent descriptions of temporal acuity as listener age and hearing status vary. Listeners who are naive to psychoacoustical experimentation were tested, which simulates test scenarios in clinical settings. The experimental methods have been carefully designed to ensure satisfactory reliability in the measures of temporal acuity from naive listeners. Results from the current experiment would contribute to the development of clinical tools that assess auditory temporal acuity in restricted frequency regions.

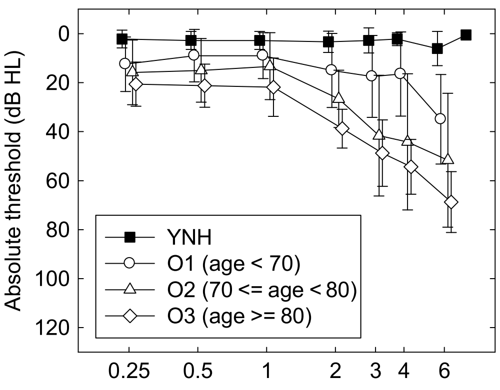
Method

Subjects

Nine young listeners with normal hearing (two male and seven female) and 24 older listeners (eight male and 16 female) participated in the current experiment. None of the listeners had previous experience in psychoacoustic experiments. Naive listeners were tested because the experiments aimed to resemble results obtained in a clinical setting. A number of experimental techniques were implemented to ensure the learnability of the experimental tasks and the reliability of the results. These techniques will be discussed in detail in the *Procedure* section.

All young listeners with normal hearing (YNH) were between 19 and 21 years of age and had audiometric thresholds equal or better than 15 dB HL between 250 and 8000 Hz in both ears. The left ears of the young listeners were tested. The older listeners were not selected based on hearing status and ranged between 55 and 88 years of age. These listeners exhibited various degrees of hearing loss, and the listeners with hearing loss all had bilateral sensorineural hearing losses with a steep-sloping configuration. The ear with lower pure-tone average (PTA) threshold (mean of the hearing level at 1, 2, and 4 kHz) was tested. Figure 2 plots the average audiometric thresholds for the older listeners together with the average audiometric threshold for the YNH. In the figure, the results from

Figure 2. Mean pure-tone thresholds for the ears tested in the current experiment. Results are shown separately for the young listeners with normal hearing (YNH) and for older listeners divided into three age groups (O1, O2, and O3). Error bars indicate ±1 *SD*. For older listeners, pure-tone thresholds at 8 kHz are not reported because many older listeners exhibited a high degree of hearing loss and could not detect the pure-tone signal at the maximum output of the audiometer.



the older listeners are divided into three subgroups. Subgroup 1 (O1: 10 listeners) includes listeners with ages below 70 years, Subgroup 2 (O2: six listeners) includes listeners with ages between 70 and 79 years, and Subgroup 3 (O3: eight listeners) includes listeners with ages equal to or greater than 80 years. All subjects provided written informed consent prior to their participation, which was approved by the institutional review board of the University of California, Irvine.

Stimuli

Both modulation discrimination and gap detection tasks were measured in the current experiment. For the modulation discrimination task, each experimental trial consisted of four sound intervals. The intervals were 500 ms in duration and separated by interstimulus intervals of 500 ms. Each interval contained a band-limited noise. The bandwidth of the noise was 800 Hz, with the upper frequency limit fixed at 2400 Hz. The noise was gated on and off using 10-ms raised-cosine ramps. In either the second or the third interval, determined at random for each trial, the band-limited noise was amplitude modulated (AM), while in the remaining three intervals in that trial, the band-limited noise was quasi-frequency modulated (QFM). The listener was instructed to select whether the second or the third interval sounded different from the other three intervals, that is, to discriminate the AM from the QFM noise.

The generation of the AM and QFM stimuli followed the procedures described in a previous study by Strickland and Viemeister (1997) exactly. Briefly, for each frequency component in the Fourier spectrum of the carrier, a new frequency component was introduced on either side of the center component. The distance from the side components to the center component was specified by the modulation rate, and the magnitudes of the side components relative to that of the center component were determined by the modulation depth. The difference between AM and QFM stimuli was in the phase configurations of the introduced side components. For the AM stimuli, the lower side component led the center component by π, while the upper side component lagged the center component by π. For the QFM stimuli, the two side components had the same initial phase, which led the initial phase of the center component by $\pi/2$. Because of this phase relationship, the resulting QFM stimulus would have an identical magnitude spectrum to the corresponding AM stimulus with the same modulation rate and depth, but the QFM stimulus would exhibit a relatively flat temporal envelope. Therefore, the purpose of implementing an AM-QFM discrimination instead of a modulation detection task was to limit the use of the spectral cues by the listeners so that their performance would reflect only temporal processing. Note that the QFM stimulus exhibited periodic sweeping of its instantaneous frequencies; however, these frequency sweeps were unlikely to dominate AM-QFM discrimination because the QFM noises were hardly discriminable from random noise for modulation frequencies tested in the current study (Strickland & Viemeister, 1997).

Prior to each presentation, the stimulus in each interval was adjusted to an overall sound pressure (root-mean-square) level of 85 dB SPL regardless of the stimulus type (AM or QFM), modulation rate, and modulation depth. In addition to the AM or QFM stimuli, two additional masking noises were presented in each interval (following Strickland, 2000). One masking noise ranged between 100 and 600 Hz, which prevented cues from combination tones. The other masking noise had a frequency range between 2450 and 3250 Hz, which was used to reduce the spread of excitation from the stimulus. These two masking noises were presented at a spectrum level of 30 dB SPL and were gated on and off with the AM or QFM stimulus using 10-ms raised-cosine ramps.

For the gap detection task, each experimental trial also contained four sound intervals separated by interstimulus intervals of 500 ms. Each interval contained a 500-ms band-limited Gaussian noise ranging from 1600 to 2400 Hz. In either the second or the third interval, a silent gap was introduced at the temporal center of the noise. The listener was instructed to indicate whether the second or the third interval contained the gap. The gap was generated using the following procedure: First, the stimulus amplitude within the gap duration was set to zero. Then, the resulting stimulus was passed through a sixth-order Butterworth filter with a pass band between 1600 and 2400 Hz. The band-pass filtering stage reduced the spectral splatter caused by imposing the temporal gap; at the same time, it smoothed the onset and offset edges of the gap with a time constant of approximately 0.2 ms (procedure adapted from Eddins et al., 1992). In the intervals where the gap was not present, the band-limited noise was passed through the same band-pass filter. Before each presentation, the stimulus in each interval was adjusted to an overall sound pressure (root-mean-square) level of 85 dB SPL and was gated on and off using 10-ms raised-cosine ramps. As with the AM-QFM discrimination task, two additional masking noises were presented with the stimulus in each interval. The two masking noises were configured as specified for the AM-QFM discrimination task.

In summary, the stimuli used for the modulation detection and gap detection tasks were chosen to probe temporal processing within the same frequency region (i.e., between 1600 and 2400 Hz) using the same sound intensity (i.e., 85 dB SPL). A relatively high sound intensity was used to ensure the audibility of the stimuli for listeners with hearing impairment.

All stimuli were generated digitally at a sampling frequency of 44100 Hz and were presented monaurally to the test ear via a 24-bit sound card (Envy24 PCI audio controller, VIA Technologies, Fremont, CA), a power amplifier (D-75, Crown International, Elkhart, IN), a programmable attenuator (PA4, Tucker-Davis Technologies, Alachua, FL), a headphone amplifier (HB6, Tucker-Davis Technologies), and a Sennheiser HD410 SL headphone (Sennheiser Electronic, Old Lyme, CT). During the experiment, listeners were seated in a double-wall, sound-attenuated booth.

Procedure

Gap detection thresholds and TMTFs were measured from YNH listeners as well as older adults (including all three subgroups, O1, O2, and O3). TMTFs were estimated using a two-track procedure, developed previously by Shen and Richards (2013). Each track of the two-track procedure consisted of 50 trials. In the first track (the low-rate track), the modulation rate of the stimulus was fixed at 16 Hz, and the modulation depth was manipulated using a two-down, one-up procedure (Levitt, 1971). That is, the modulation depth was reduced after two consecutive correct responses and increased after a single incorrect response. Combined with the four-interval, two-alternative forced-choice design, this procedure adaptively altered the modulation depth to maintain a percentage correct of approximately 70.7%. At the beginning of the track, the initial modulation depth was 0 dB (20log$m$, where m is the modulation depth). The step size for changing the modulation depth was initially 5 dB and was reduced to 2 dB after the fourth reversal of the track. For the second track of the two-track procedure (the high-rate track), the modulation depth was fixed at −5 dB, and the modulation rate was adaptively varied using a two-up, one-down procedure. In this case, the initial modulation rate was 32 Hz. The modulation rate was initially altered using a factor of 2.5. After the second reversal, this factor was reduced to 1.8, which was further reduced to 1.25 after the fourth reversal. The stimulus parameters (i.e., the modulation rate and depth) and the listener's responses from all trials across the high-rate and low-rate tracks were used to derive the TMTF sensitivity (S) and cutoff frequency (f_{cutoff}).

The two-track procedure was adopted to enable the efficient estimation of the TMTFs. This procedure was initially tested by Shen and Richards (2013) in listeners with normal hearing using broadband stimuli. Their results showed that the TMTF parameters (S and f_{cutoff}) estimated using the two-track procedure predicted well the TMTFs estimated using the traditional procedure while reducing testing time significantly. However, the authors also noted that when naive listeners were tested, the estimated parameter values, especially for f_{cutoff}, could sometimes be quite variable. To ensure the two-track procedure would provide reliable estimates of the TMTF parameters in the current experiment, a control experiment was conducted, in which the TMTFs were estimated with the identical stimuli as in the main experiment, using both the traditional and two-track procedures. Details on the control experiment are given in the Appendix. The results showed that the two-track procedure (two repetitions, 100 trials each) and the traditional procedure (900 trials) provided comparable estimates of the TMTFs.

Each estimate of the gap detection threshold was obtained using an experimental track of 50 trials. During the track, the gap duration was manipulated according to a two-down, one-up procedure. The initial gap duration was 50 ms. The gap duration was initially manipulated using a factor of 2.5, which was reduced to 1.8 after the first two reversals and further reduced to 1.25 after the first four reversals. If the total number of reversals in the track was even, the final threshold estimate was obtained by averaging the modulation depth at all except the first four reversals. If the total number of reversals was odd, the final threshold estimate was based on the average of the modulation depth at all except the first five reversals.

Half of the listeners (five young listeners and 13 older listeners), drawn at random, began with the estimation of the TMTF. After the two-track procedure, an estimate of the gap detection threshold was obtained. Finally, the data collection process, including the estimation of both the TMTF and gap detection threshold, was repeated. For the remaining half of the listeners, the gap detection threshold was measured before the TMTF, and then the process was repeated. The reported gap detection threshold for each listener was based on the average of the two individual estimates, and the reported S and f_{cutoff} estimates were derived from the pooled data from the two runs of the two-track procedure, using the maximum-likelihood algorithm described by Shen and Richards (2013). Data collection took approximately 1 hr, including the initial audiometric test.

The current experiment implemented a number of experimental techniques to improve the reliability of the results. This is important because naive listeners were tested. To make the tasks easy to follow, a four-interval, two-alternative, forced-choice task design (e.g., Shen & Richards, 2013; Shub, Durlach, & Colburn, 2008; Trahiotis, 1992) was implemented. The first and last intervals served the purpose of cueing the beginning and the end of each trial. Moreover, because they contained the same type of stimulus as in the nonsignal interval (the QFM stimulus for the modulation discrimination task and the no-gap stimulus for the gap detection task), the presence of the first and last intervals reduced the difficulty of following the tasks. That is, listeners could simply indicate whether the second or the third interval sounded different from the other three intervals.

In addition to the four-interval task design, a number of additional experimental techniques were used to ensure the reliability of the data. First, detailed oral instructions were provided before the experiment began. Second, written instructions were displayed to the listeners on a computer screen prior to each block of data collection. Third, trial-by-trial feedback was provided after each response regarding the correctness. Finally, listeners' responses were collected adaptively using the transformed up-down procedure (Levitt, 1971) for both the TMTF and gap detection measurements. The transform up-down procedure has been shown to provide reliable estimation of gap detection thresholds from naive listeners. Florentine et al. (2000) measured gap detection thresholds from YNH using band-limited stimuli and similar experimental procedures comparable to the current experiment. These authors found that the difference in gap detection thresholds between trained and naive listeners was small. In summary, it is expected that the procedure adopted in the current experiment was adequate for testing naive listeners. A further safeguard of the current procedure was provided by the control experiment (see Appendix).

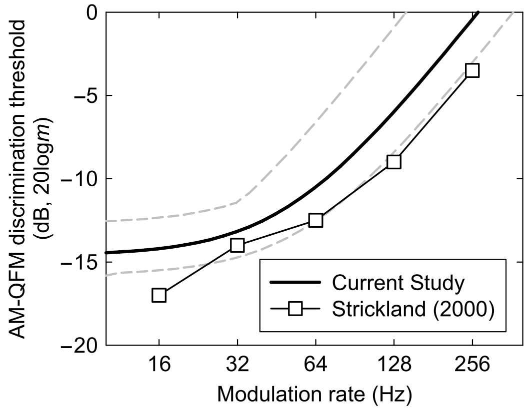
Results

AM-QFM Discrimination and Gap Detection Thresholds Among YNH

For the listeners with normal hearing, the estimated S had a mean of 14.6 dB and a standard deviation of 1.3 dB; the estimated f_{cutoff} had a mean of 51.0 Hz and a standard deviation of 17.3 Hz. Figure 3 plots the TMTF derived from the average S and f_{cutoff} estimates (thick curve) together with the range for the TMTFs across individual listeners (dashed curves). These TMTFs could be interpreted as the functions that relate the AM-QFM discrimination threshold and the modulation rate. As the modulation rate increased, the predicted AM-QFM discrimination threshold also increased, following the shape of a first-order, low-pass function.

Strickland (2000) measured the TMTF using the AM-QFM discrimination paradigm from well-trained listeners. In that study, one of the conditions used 800-Hz-wide noise stimuli with an upper frequency limit of 2400 Hz, which was identical to the stimuli used in the current experiment. The average AM-QFM discrimination thresholds from that study are plotted in Figure 3 as unfilled squares. The TMTF derived from the mean S and f_{cutoff} estimates (thick curve) was higher than the result of Strickland's by 2–3 dB. An inspection on the S and f_{cutoff} estimates reported by Strickland (2000, Figure 9) revealed that the difference between the TMTFs from the two studies was due to the higher S estimates in the current study, while the f_{cutoff} estimates were similar across studies. Both S and f_{cutoff} estimates obtained from the current studies exhibited a similar degree of individual differences compared with those reported by Strickland (2000, error bars in Figure 9). The overall higher S estimates from the current study compared with the reported values in the literature might have reflected the fact that naive listeners were tested in the current study (e.g., experienced listeners were tested in the study of Strickland). However, the inclusion of naive listeners did not seem to cause greater variability in the estimates of the TMTF parameters compared with previous studies.

Figure 3. The AM-QFM discrimination thresholds as a function of modulation rate derived from the averaged estimates for S and f_{cutoff} across nine young listeners with normal hearing (thick solid curve). The range for the TMTFs derived for individual listeners are marked using light dashed curves. Results from Strickland (2000) in a similar condition are plotted for comparison (dotted lines and squares). AM = amplitude-modulated; QFM = quasi-frequency modulated.



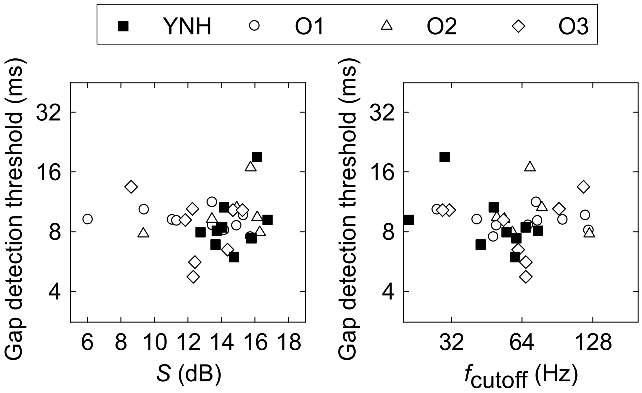
The gap detection threshold obtained for the same nine listeners with normal hearing ranged from 6 ms to 11 ms, except for one listener who had a gap detection threshold of 19 ms. The geometric mean of the thresholds across listeners was 8.8 ms. The average gap detection threshold was comparable to those measured in previous studies, and the variability in the gap detection threshold was also comparable to that reported previously for well-trained listeners. For example, Eddins et al. (1992, Figure 1) reported that the gap detection threshold was between 5 and 10 ms for a 800-Hz-wide noise stimulus with an upper frequency limit of 2200 Hz (the closest condition to the current experiment).

In summary, although naive listeners were tested in the current experiment, the observed means and individual differences in all three measures of temporal acuity (gap detection threshold, S, and f_{cutoff}) were comparable to those reported in previous studies for well-trained listeners.

Comparing the TMTF Parameters and the Gap Detection Thresholds

Figure 4 plots the gap detection thresholds as functions of the S and f_{cutoff} estimates from both the young

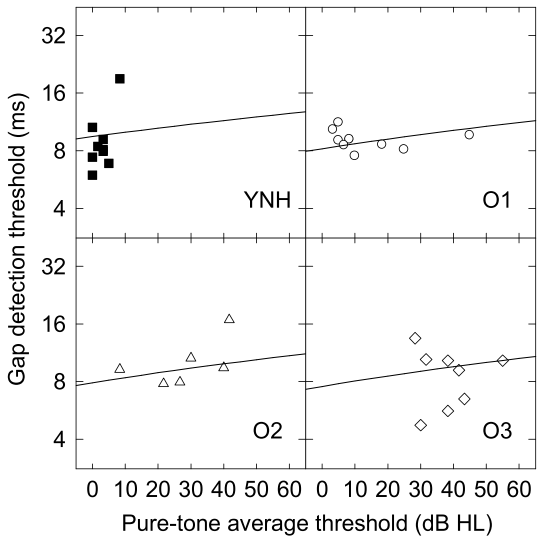
Figure 4. The comparisons between the gap detection threshold and the TMTF sensitivity (left panel) and between the gap detection threshold and the TMTF cutoff frequency (right panel). In each panel, different symbols indicate results from different listener groups.



(filled symbols) and older (unfilled symbols; different symbols indicate different age groups as defined in Figure 2) listener groups. Like the young listener group, the older listener groups exhibited individual differences in all three measures of temporal acuity (gap detection threshold, S, and f_{cutoff}). For the older listeners, the estimated S had a mean of 13.0 dB and a standard deviation of 2.7 dB; the estimated f_{cutoff} had a mean of 69.7 Hz and a standard deviation of 29.1 Hz; and the estimated gap detection threshold had a geometric mean of 9.0 ms and ranged between 4.7 and 16.8 ms. The variability in the estimates of the TMTF parameters was slightly greater for the older than the young listeners, while the variability of the gap detection threshold was similar for the young and older listeners.

The correlation between the gap detection threshold and S was not significant for young (r = .42, p = .26) or older (r = .01, p = .98) listeners, and it was not significant when the two groups of listeners were pooled together (r = .06, p = .75). Moreover, the correlation between the gap detection threshold and f_{cutoff} was not significant for young (r = −.51, p = .16) or older (r = .01, p = .96) listeners, and it was not significant when the two groups of listeners were pooled together (r = −.12, p = .49). Therefore, the current experiment failed to detect a systematic relationship between the gap detection threshold and the TMTF parameters.

Figure 5. Gap detection thresholds as functions of pure-tone average threshold (dB HL, averaged across thresholds at 1, 2, and 4 kHz). Results for the four listener groups are arranged in separate panels. Solid lines indicate the prediction from a general linear model, which uses listener age and pure-tone average threshold as the two independent variables. In each panel, the model prediction evaluated for the mean age of the listeners in that panel is shown.



Effects of Age and Hearing Loss

Listeners tested in the current experiments had wide ranges of age and degree of hearing loss. Both of these two factors can contribute to individual differences in temporal acuity measures. Because gap detection threshold, S, and f_{cutoff} did not covary with one another, the effects of listener age and hearing loss were studied separately for these three dependent variables. For each of the dependent variables, estimates from all 33 listeners (nine YNH and 24 older listeners) were used to fit a general linear model, which used the listener age and PTA threshold as the two independent variables. The PTA was calculated based on the absolute thresholds at 1, 2, and 4 kHz; these frequencies covered a wide frequency range geometrically centered at the spectral center of the stimuli. The regression model also allowed a flexible intercept, leading to 30 degrees of freedom for the error term.

The fitted general linear models were not significant for the gap detection threshold, $F(2, 30) = 0.60$, p = .55, or for the f_{cutoff}, $F(2, 30) = 1.34$, p = .28, accounting for only 3.9% and 8.2% of the total variance, respectively. Conversely, the fitted general linear model was significant for S, $F(2, 30) = 6.25$, $p < .01$, accounting for 29.4% of the total variance. Figures 5–7 plot the gap detection thresholds, the S estimates, and the f_{cutoff} estimates as functions of the PTA threshold, respectively. To improve visualization, listeners were grouped in the same manner as in Figure 2. The solid line in each panel indicates the predictions of the fitted general linear model as a function of PTA, evaluated for the mean age of the listeners in the corresponding panel. For the gap detection threshold and f_{cutoff} (Figures 5 and 7, respectively), the regression lines are relatively flat in all panels, and the intercept of these lines changes only

Figure 6. Estimates of the TMTF sensitivity as functions of pure-tone average threshold (dB HL, averaged across thresholds at 1, 2, and 4 kHz). Results for the four listener groups are arranged in separate panels. Solid lines indicate the prediction from a general linear model, which uses listener age and pure-tone average threshold as the two independent variables. In each panel, the model prediction evaluated for the mean age of the listeners in that panel is shown.

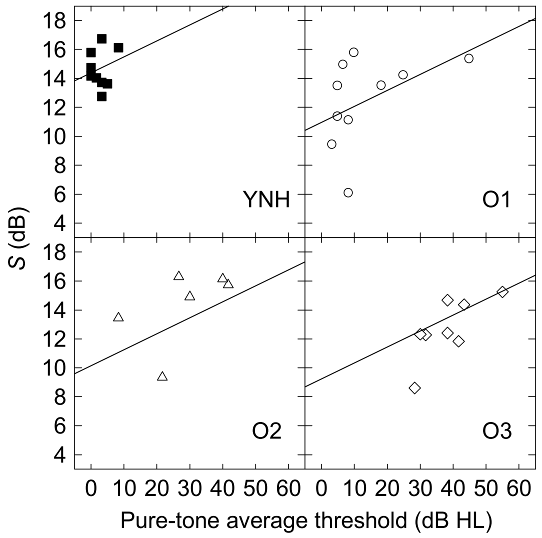
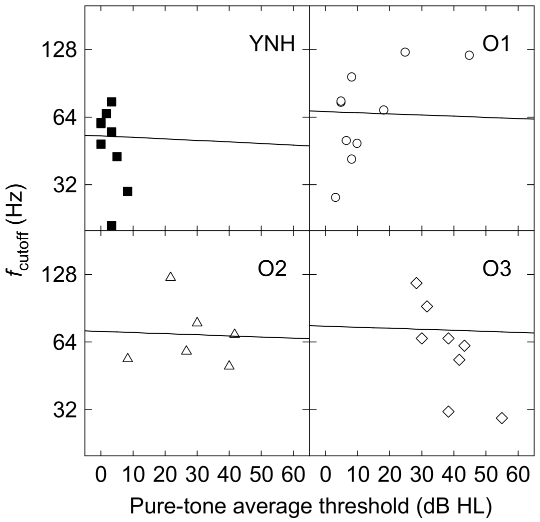


Figure 7. Estimates of the TMTF cutoff frequency as functions of pure-tone average threshold (dB HL, averaged across thresholds at 1, 2, and 4 kHz). Results for the four listener groups are arranged in separate panels. Solid lines indicate the prediction from a general linear model, which uses listener age and pure-tone average threshold as the two independent variables. In each panel, the model prediction evaluated for the mean age of the listeners in that panel is shown.



slightly across panels. For *S*, the regression line in each panel exhibits a positive slope, predicting increasing sensitivity to low-rate amplitude modulation with a greater degree of hearing loss. The intercept of the regression lines decreases as the listener mean age increases across the four panels (20.2, 63.2, 73.5, and 84.9 years for listener groups YNH, O1, O2, O3, respectively), predicting that the low-rate amplitude modulation processing degrades with increasing age.

To investigate the significance of the effects of listener age and hearing status on the *S* estimate, one or the other of the independent variables was removed from the original general linear model. If the restricted model with an independent variable removed showed a significantly poorer fit (evaluated via an *F* test) than the full model, it would provide evidence for a significant effect of the removed independent variable. Removing either age or PTA led to a significantly worse fit compared with the full model, $F(1, 30) = 11.84$, $p < .01$, for the restricted model with PTA removed; $F(1, 30) = 9.96$, $p < .01$, for the restricted model with listener age removed. This suggests that the sensitivity parameter of the TMTF, which reflects the listener's capability of processing low-rate amplitude modulation, increases with increasing degree of hearing loss and decreases with increasing age (Figure 6). This finding is inconsistent with many previous studies that did not find a significant effect of hearing loss on the TMTF (e.g., Moore, Shailer, & Schooneveldt, 1992). This will be discussed in greater detail below.

To investigate the potential effect of age alone on gap detection threshold, *S*, and f_{cutoff} without the potential influence from hearing loss, eight older listeners with PTA equal or less than 10 dB were selected to form a new group of older listeners with norming hearing (ONH). The ONH group had ages between 55 and 70 years with a mean age of 63.3 years, whereas the YNH group had ages between 19 and 21 years with a mean age of 20.3 years. A multivariate analysis of variance was conducted, treating listener group (YNH and ONH) as the fixed factor and gap detection thresholds, *S*, and f_{cutoff} as the three dependent variables. Listener group was found to have a significant effect on *S*, $F(1, 15) = 5.51$, $p = .03$, but not on gap detection threshold, $F(1, 15) = 0.00$, $p = .99$, nor on f_{cutoff}, $F(1, 15) = 0.59$, $p = .45$. Therefore, in the current study, the effect of listener age on temporal processing was limited to the TMTF sensitivity.

Discussion

Gap Detection Versus the TMTF

In the current study, no between-subject correlation for the gap detection threshold and the TMTF parameters was found. In particular, I did not find an increase in gap detection threshold with decreasing TMTF cutoff frequency, as would be expected on the basis of the leaky-integrator model of temporal processing (Forrest & Green, 1987). This might be because both temporal and intensity acuity affect the gap detection threshold, whereas the form of the TMTF reflects only temporal processing (Strickland & Viemeister, 1997). Moreover, the data did not indicate a negative correlation between the gap detection threshold and the TMTF sensitivity previously reported for YNH and for broadband noise stimuli (e.g., Shen & Richards, 2013, Figure 3, upper panels). Therefore, at least for the band-limited stimuli adopted in the current study, the results from gap detection and TMTF experiments cannot be easily translated to one another.

The fact that a significant correlation was observed between the gap detection threshold and the TMTF sensitivity by Shen and Richards (2013) but not in the current study might reflect the difference in stimulus bandwidth between the two studies. The current study used band-limited stimuli instead of broadband stimuli, which was chosen to facilitate the estimation of temporal acuity in a restricted frequency region. One potential consequence of this stimulus design is that the listening bandwidth was set by the stimuli rather than individual listeners' auditory system. It is known that broader listening bandwidths lead to higher TMTF sensitivity and shorter gap detection thresholds (Bacon & Viemeister, 1985; Strickland, 2000). If individual difference in listening bandwidth is the origin of the correlation between the TMTF sensitivity and gap detection threshold found in the study of Shen and Richards (2013), it is reasonable to expect a diminished correlation when band-limited stimuli are tested.

Effect of Hearing Loss on Gap Detection Threshold

The effects of hearing loss on gap detection threshold have been investigated in various studies. Many studies have reported that hearing impairment is associated with longer gap detection thresholds (Fitzgibbons & Wightman, 1982; Florentine & Buus, 1984; Glasberg et al., 1987; Irwin et al., 1981; Irwin & McAuley, 1987; Moore & Glasberg, 1988; Tyler et al., 1982).

For example, Moore and Glasberg (1988) measured gap detection thresholds for normal-hearing and hearing-impaired ears of listeners with unilateral hearing loss. In one condition, the stimulus was an 84 dB SPL, band-limited noise spanning 1562 to 2562 Hz. It was found that the impaired ears had higher gap detection thresholds than the normal-hearing ears. Using band-limited noise stimuli very similar to those used by Moore and Glasberg, the current study did not find a significant effect of hearing loss on gap detection threshold. This lack of effect might be related to the fact that the listeners included in the current study typically had no more than moderate hearing loss (<55 dB HL) within the pass band of the stimulus (between 1600 and 2400 Hz). Most of the older listeners exhibited only a mild hearing loss at 2 kHz. In contrast, the impaired ears tested by Moore and Glasberg (1988) had moderate to moderately severe hearing loss at 2 kHz. Therefore, it is possible that the range of hearing loss for the listeners included in the current study was not sufficient to reveal the effect of hearing loss on gap detection.

Effect of Age on Gap Detection Threshold

Besides the effect of hearing loss, the current study also failed to identify a significant effect of listener age on gap detection threshold. Several studies have shown that older adults tend to have higher gap detection thresholds than young adults when age-related hearing loss is controlled (Fitzgibbons & Gordon-Salant, 1994; Grose et al., 2001; He et al., 1999; Lister et al., 2000, 2002; Snell, 1997), although young and older listeners could exhibit considerable overlap in gap detection thresholds (see Reed, Braida, & Zurek, 2009, for a comprehensive review). Moreover, differences in gap detection thresholds between young and older listeners are expected to be small or not detectable for an experimental task that is relatively simple (e.g., Bertoli, Smurzynski, & Probst, 2002). As the task complexity is increased by introducing spectral mismatch between the portions of the stimulus before and after the gap (Lister et al., 2000, 2002; Lister & Roberts, 2005), by using spectrally complex carriers (Lister & Tarver, 2004; Pichora-Fuller, Schneider, Benson, Hamstra, & Storzer, 2006), by randomizing the temporal location of the gap in the stimulus (He et al., 1999), or by using stimuli with short duration (Schneider, Speranza, & Pichora-Fuller, 1998), older listeners exhibit an increased deficit in gap detection. This is because older listeners usually find the gap detection task more mentally demanding than younger listeners do when the task complexity is high (e.g., Harris et al., 2010). Here, efforts were made to reduce the task complexity (see, e.g., the *Procedure* section). The purpose here was to probe auditory processing of temporal envelope relatively free from cognitive demands. Because the effect size to be detected might be small, no significant effect of age was observed for the current study.

Effect of Hearing Loss on the TMTF

In contrast to the gap detection threshold, the current experiment found that both hearing loss and age affected the estimated TMTF sensitivity. Previous studies of the effect of hearing impairment on TMTF have suggested that when broadband stimuli are used, listeners with sloping hearing losses usually show reduced sensitivity to amplitude modulation (Bacon & Viemeister, 1985). This reduction in sensitivity is thought to reflect the reduced listening bandwidth for these listeners. When listeners with flat losses are tested, performance in modulation detection is similar for listeners with hearing impairment and normal hearing at high sound pressure levels (Bacon & Gleitman, 1992). Using octave-wide noises, which restricts listening bandwidths, Moore et al. (1992) measured the TMTFs for both the normal-hearing and hearing-impaired ears of listeners with unilateral hearing losses. No significant difference was found between the TMTFs estimated for the two ears. In an additional study, Moore and Glasberg (2001) used AM sinusoids and measured the TMTFs for listeners with normal hearing and those with hearing impairment. At low modulation rates, where the TMTF was not affected by the presence of spectral cues, the listeners with hearing impairment showed similar sensitivity to amplitude modulation compared with the listeners with normal hearing at equal sound pressure level and better performance at similar sensation level. Therefore, previous studies did not provide direct support for an improvement of the TMTF sensitivity with increasing degrees of hearing loss.

One potential explanation for the dependency of S on hearing loss found in the current study might be that listeners with hearing impairment had abnormal intensity resolution because of loudness recruitment, which causes an amplification of amplitude modulation (e.g., Moore, Wojtczak, & Vickers, 1996). Supports for this argument can be found in physiological studies of envelope coding in the auditory system. Kale and Heinz (2010) investigated envelope coding in auditory nerve fibers using anesthetized chinchillas with either normal hearing or noise-induced hearing loss. These authors found that the noise-exposed fibers exhibited enhanced coding for amplitude modulation. However, an improvement of intensity resolution with hearing loss has not been demonstrated previously at equal sound pressure levels (e.g., Florentine, Reed, Rabinowitz, Braida, & Durlach, 1993; Turner, Zwislocki, & Filion, 1989). Therefore, the presently observed effect of hearing loss on S requires further validation.

Effect of Age on the TMTF

Aging is known to have an adverse effect on coding of amplitude modulation. Takahashi and Bacon (1992) measured the TMTFs from older listeners with normal hearing or mild sensorineural hearing loss. Broadband noise carriers were used in their study. At low modulation rates, a negative correlation was found between the sensitivity to amplitude modulation and age. He et al. (2008) estimated the TMTFs from older and younger listeners with comparable hearing using AM tones. Although the TMTFs did not exhibit clear low-pass shapes due to the presence of spectral cues, the modulation detection threshold tended to be lower (better sensitivity) for the young listener group. For a carrier frequency of 4000 Hz (the most similar condition compared with the current study), the age-related threshold difference was found at modulation frequencies between 40 and 200 Hz. Therefore, the effect of age on the TMTF sensitivity found in the current study is in general agreement with previous studies.

Conclusion

Gap detection thresholds and temporal modulation transfer functions were estimated using band-limited stimuli and naive listeners who exhibited a wide range of age and hearing status. Significant correlations between the gap detection threshold and the TMTF parameters (i.e., sensitivity and cutoff frequency) were not found. Listener age and hearing status influenced the TMTF sensitivity, which reflects the perception of low-rate amplitude modulation, but not the TMTF cutoff frequency, which reflects the perception of high-rate amplitude modulation, or the gap detection threshold. The TMTF sensitivity decreased with increasing age but improved as the degree of hearing loss increased.

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Appendix (p. 1 of 2)

Reliability of the Two-Track Procedure for the Estimation of the Temporal Modulation Transfer Function

Method

Seven young listeners with normal hearing (two male and five female) participated in this control experiment; none of these same listeners participated in the main experiment. Moreover, none of the listeners had previously participated in any experiments measuring either the temporal modulation transfer function (TMTF) or the gap detection threshold, although three of the listeners had experiences in other psychoacoustic experiments. These listeners were between 18 and 35 years of age and had audiometric thresholds equal or better than 15 dB HL between 250 and 8000 Hz in both ears. Given that comparable hearing thresholds between the ears were found for all listeners, the left ears were tested.

The TMTFs were estimated using both the two-track and traditional procedures. The stimuli were identical to those used in the main experiment. Each listener started with a run of the two-track procedure (100 trials), followed by the traditional procedure and then a second run of the two-track procedure. The two-track procedure was configured identically as in the main experiment. The traditional procedure involved estimating quasi-frequency modulated (QFM) discrimination thresholds at modulation rates of 16, 32, 64, 96, 128, and 256 Hz. The QFM discrimination threshold at each of these modulation rates was estimated using a two-down, one-up procedure, estimating the modulation depth that corresponded to the 70.7% correct place on the psychometric function (Levitt, 1971). Each track terminated after 50 trials. If the total number of reversals in the track was even, the final threshold estimate was obtained by averaging the modulation depth at all except the first four reversals. If the total number of reversals was odd, the final threshold estimate was based on the average of the modulation depth at all except the first five reversals. For each listener, the six modulation rates were tested in random order, and the process was repeated in the same order four additional times, leading to a total of five threshold estimates at each modulation rate. Among the five threshold estimates, three were drawn at random. These three threshold estimates were averaged and then used to fit a first-order low-pass function (Eddins, 1993; Formby & Muir, 1988), from which the TMTF sensitivity (*S*) and cutoff frequency (f_{cutoff}) were estimated. The remaining two threshold estimates were averaged and reserved for the purpose of data analysis (see below).

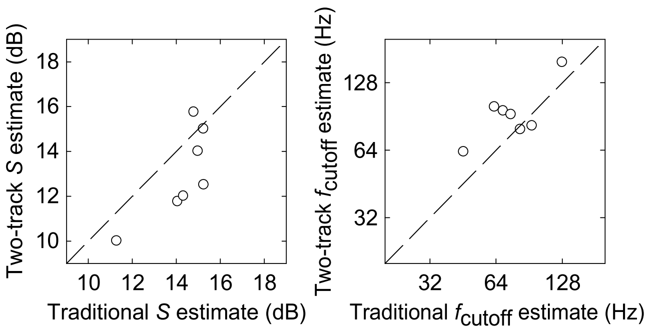
Results

The TMTFs were estimated using the traditional and two-track procedures; the major difference between the two procedures was efficiency (200 trials in the two-track procedure and 900 trials in the traditional procedure). The agreement between the traditional and the two-track procedures were investigated in two aspects: (a) the parameter values for *S* and f_{cutoff} and (b) the predictability of the TMTF estimated from a listener on an independent set of data for the same listener.

Figure A1 plots the estimates of *S* (left) and f_{cutoff} (right) from the two-track procedure as a function of those from the traditional procedure. The correlation between the parameter estimates was significant for both *S* ($r = .76$, $p = .05$) and f_{cutoff} ($r = .77$, $p = .04$). Moreover, two-tail, paired *t* tests suggested that the *S* estimates from the two-track procedure were consistently lower than those from the traditional procedure, $t(5) = -2.57$, $p = .04$, and the f_{cutoff} estimates from the two-track procedure were slightly higher than those from the traditional procedure, $t(5) = -2.42$, $p = .05$. On average, the two-track procedure produces an *S* estimate 1.28 dB lower and an f_{cutoff} estimate 0.28 octave higher than the traditional procedure. Although the parameter estimates from the two procedures have numerical differences, these differences do not change the rank order of the data from individual listeners, and the two procedures are similar in their abilities to code individual differences.

As can be observed from Figure A1, the individual differences in the *S* and f_{cutoff} estimates were comparable between the two-track and traditional procedures. For the two-track procedure, the standard deviations for the *S* and f_{cutoff} estimates were 2.0 dB and 30.1 Hz. Using the same two-track procedure with an equal number of trials for each TMTF estimate, Shen

Figure A1. The TMTF sensitivity (left panel) and cutoff frequency (right panel) estimated using two different experimental procedures as scatterplots. In each panel, the abscissa indicates estimates using the traditional procedure, while the ordinate indicates estimates using the two-track procedure. Each circle indicates data collected from an individual listener, and the dashed line marks the line of equivalence.



Appendix (p. 2 of 2)

Reliability of the Two-Track Procedure for the Estimation of the Temporal Modulation Transfer Function

and Richards (2013, Experiment IIIc) reported a standard deviation of 4.7 dB for S and a standard deviation of 283 Hz for f_{cutoff} for a group of 14 naive, young listeners with normal hearing. Therefore, compared with the study of Shen and Richards, the individual differences in the S and f_{cutoff} estimates from the current experiment were much reduced. Shen and Richards (2013) used broadband stimuli, whereas the current study used 800-Hz-wide stimuli, suggesting the reduction in individual differences between the studies might reflect the difference in stimulus bandwidths. For the traditional procedure, the standard deviations for the S and f_{cutoff} estimates were 1.4 dB and 26.2 Hz. Therefore, compared with the traditional procedure, the S and f_{cutoff} estimates from the two-track procedure were slightly more variable.

A validation analysis was performed to investigate how well the S and f_{cutoff} estimates obtained from a listener generalize to an independent data set for the same listener. Two of the five QFM discrimination thresholds during the traditional procedure (randomly drawn and independent for each listener) for each modulation rate were reserved and did not contribute to the estimation of the TMTF parameters. The parameter estimates from the traditional and the two-track procedure were used to generate predictions for the QFM discrimination thresholds at a percentage correct of 70.7% for modulation rates ranging from 16 to 256 Hz. For each procedure, the root-mean-square (RMS) deviation from the predicted thresholds to the six empirical thresholds (averaged across the two estimates) in the reserved data set was computed. Smaller RMS deviation indicates better predictability of the TMTF parameters. Both the traditional and two-track procedures provided close predictions to the reserved data. For the traditional procedure, the average RMS deviation was 1.65 dB with a standard deviation of 0.31 dB; for the two-track procedure, the average RMS deviation was 2.14 dB with a standard deviation of 0.65 dB. A paired t test failed to identify a significant difference between the RMS deviations derived using the two procedures, $t(5) = 2.19$, $p = .07$. This means that the TMTF parameters estimated using the two procedures exhibit comparable predictive power, despite that the parameter estimates from the two-track procedure are slightly more variable than the traditional procedure.

In summary, the two-track procedure with 200 experimental trials provided estimates of the TMTF parameters that correlated with those obtained using the traditional procedure (from 900 trials). The S and f_{cutoff} parameters estimated using the two procedures from a listener were comparable in their ability to estimate an independently derived set of QFM discrimination thresholds for the same listener. For the parameter estimates from the two-track procedure, the individual differences for a group of young, naive listeners were smaller compared with a previous study (Shen & Richards, 2013) using the two-track procedure with an identical total number of trials for each TMTF estimate. Overall, results from this control experiment demonstrated the satisfactory reliability of the two-track procedure when naive listeners were tested.