Temporal weighting of binaural cues revealed by detection of dynamic interaural differences in high-rate Gabor click trains

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Listeners detected interaural differences of time (ITDs) or level (ILDs) carried by single 4000-Hz Gabor clicks (Gaussian-windowed tone bursts) and trains of 16 such clicks repeating at an interclick interval (ICI) of 2, 5, or 10 ms. In separate conditions, target interaural differences favored the right ear by a constant amount for all clicks (condition *RR*), attained their peak value at onset and diminished linearly to 0 at offset (condition *R*0), or grew linearly from 0 at onset to a peak value at offset (condition 0*R*). Threshold ITDs and ILDs were determined adaptively in separate experiments for each of these conditions and for single clicks. ITD thresholds were found to be lower for 16-click trains than for single clicks at 10-ms ICI, regardless of stimulus condition. At 2-ms ICI, thresholds in *RR* and *R*0 conditions were similar to single click thresholds at 2-ms ICI; thresholds in the 0*R* condition were significantly worse than for single clicks at 2-ms ICI, consistent with strong rate-dependent onset dominance in listeners' temporal weighting of ITD. ILD thresholds, in contrast, were predominantly unaffected by ICI, suggesting little or no onset dominance for ILD of high-rate stimuli. © *2010 Acoustical Society of America.* [DOI: 10.1121/1.3377088]

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I. INTRODUCTION

A. Binaural adaptation for high-frequency, high-rate stimuli

The ability of human listeners to localize amplitude-modulated (AM) high-frequency sounds has been studied for several decades (David *et al.*, 1959; Harris, 1960; Yost *et al.*, 1971; Henning, 1974; Nuetzel and Hafter, 1976). Past studies have demonstrated a clear sensitivity to interaural time differences (ITDs) carried by the temporal envelopes of such sounds, suggesting that localization at high-frequencies is subserved by a combination of ITD and interaural-level-difference (ILD) processing, which otherwise dominates localization at high frequency (Strutt, 1907).

Although sensitivity to envelope ITD at high-frequencies can be comparable to sensitivity to ITD carried in the fine structure of low-frequency tones (Bernstein and Trahiotis, 2002), its utility appears to strongly depend on the modulation rate of the envelope. Numerous studies have demonstrated impaired ITD discrimination for high-frequency and certain broadband AM sounds presented at modulation rates above approximately 250 Hz or with correspondingly short delays between successive stimuli ($<\approx 4$ ms). Rate limitations of this sort have been described in studies of interaural discrimination (Nuetzel and Hafter, 1976; McFadden and Moffitt, 1977; Burns and Colburn, 1977; Freyman *et al.*, 1997; Bernstein and Trahiotis, 2002), binaural adaptation (Hafter and Dye, 1983; Hafter *et al.*, 1983, 1990; Hafter and Buell, 1990), and temporal weighting of sound-localization cues (Saberi, 1996; Stecker and Hafter, 2002). A markedly similar delay-dependent loss of sensitivity is observed in free-field and headphone-based studies of the precedence effect (Wallach *et al.*, 1949; Haas, 1972; Zurek, 1980; Litovsky *et al.*, 1999).

Although rate-limited interaural processing is apparent for a wide range of stimuli, it appears especially robust when tested with narrowband, high-carrier-frequency, AM signals conveying ITDs in their ongoing temporal envelopes. In one example, Bernstein and Trahiotis (2002) measured normal-hearing listeners' discrimination thresholds for ITD imposed on the envelopes of 4000-Hz amplitude-modulated tones. Using both sinusoidal and pulsatile ("transposed tones," van de Par and Kohlrausch, 1997) modulators, the authors found a majority of listeners to be capable of performing the task for modulation rates at or below 256 Hz, but not at 512 Hz. Similarly, Hafter and Dye (1983) found that ITD thresholds for 4000-Hz narrowband click trains improved with click-train duration only for interclick intervals (ICIs) greater than 2 ms (i.e., modulation rate <500 Hz). Shorter ICIs (i.e., faster modulation) produced discrimination performance that was similar to that for single clicks over a range of click-train durations, suggesting that listeners were unable to utilize the ongoing envelope ITD at high rates. Note that both studies also observed individual differences in the magnitude of threshold elevation and in the range of modulation frequencies that affected performance. For example, one subject tested by Bernstein and Trahiotis (2002) showed low thresholds for modulation rates as high as 512 Hz. Such differences suggest the possibility of multiple mechanisms or strategies for ITD-based localization, only some of which are subject to rate limitations.

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For stimuli carrying ITD via whole-waveform delay, three types of ITD cues are potentially available: first, the envelope ITD carried by the stimulus onset and offset; second, the ongoing envelope ITD available during the (more or less) steady-state middle epoch of the sound; and third, the fine-structure ITD indicated by interaural differences in the phase of the carrier signal at the two ears (McFadden and Pasanen, 1976).[1] When high carrier frequencies ($>\approx 2000$ Hz) are used, the utility of fine-structure cues is reduced or eliminated so that sensitivity to whole-waveform delay is uniquely subserved by envelope ITD. When onset, offset, and ongoing envelope delays are all available, rate limitation appears as a shift from a use of ongoing cues toward a greater dependence on onset cues (Hafter and Dye, 1983; Saberi and Perrott, 1995; Buell *et al.*, 2008). Slow and/or diotic onset and offset gating reduces the salience of onset/offset cues; for example, Bernstein and Trahiotis (2002) employed diotic 20-ms rise/fall ramps, and observed rate limitation as an inability to discriminate on the basis of the remaining ongoing envelope ITD cue.

Proposed mechanisms that potentially account for reduced sensitivity to ongoing envelope ITD at high rates include (1) binaural adaptation (Hafter and Dye, 1983), a nonstationary, rate-dependent reduction in the neural response among inputs to binaural comparison mechanisms in the brainstem, (2) 150-Hz lowpass filtering of envelope representations in high-frequency channels of the central auditory system (Kohlrausch *et al.*, 2000; Bernstein and Trahiotis, 2002), (3) down-weighting of binaural information contained in ambiguous or spectrally sparse ongoing sound (Freyman *et al.*, 1997), and (4) delay-dependent trading of ITD and ILD, as in the "plausibility hypothesis" of Rakerd and Hartmann (1985).[2]

B. ITD discrimination with bilateral cochlear implants

A question of growing interest is whether the rate-limited binaural processing observed in normal-hearing (NH) listeners also plays a major role in the limited sensitivity of bilaterally implanted cochlear implant (BiCI) users to binaural information. These patients receive auditory stimulation through electrical prostheses that bypass the normal cochleae and stimulate the spiral ganglion cells of the auditory nerve directly. By virtue of the placement of electrode contacts, the devices aim to stimulate spatially restricted groups of auditory nerve fibers corresponding to restricted excitation of a single cochlear place (i.e., fibers tuned to similar characteristic frequencies in a NH cochlea). In a typical implant, electrical stimulation consists of a series of electrical pulses delivered at a steady rate, with pulse amplitude modulated by the envelope of sound picked up by an external microphone.

A potential benefit of binaural versus monaural implantation is the availability of binaural cues, including ITD and ILD, for sound localization and segregation of multiple competing sound sources. In a number of studies to date, however, the ability of BiCI users to process ITD information has appeared to be significantly limited. For example, in their study of two BiCI users, van Hoesel and Clark (1997) found subjects unable to discriminate ITDs of less than 500 μs at low pulse rates, or less than 4000 μs at the highest tested rate of 300 pulses per second (pps). Such threshold ITDs are more than an order of magnitude poorer than thresholds of NH listeners engaged in a similar task (Bernstein and Trahiotis, 2002). van Hoesel and Clark (1997) also found poor performance in a binaural rate discrimination task, where listeners were required to discriminate a difference in pulse rates presented either diotically or dichotically. Although the authors noted an advantage for dichotic presentation consistent with sensitivity to the time-varying ITD cue (a form of "binaural beat;" McFadden and Pasanen, 1975), that advantage was not apparent at rates beyond 200 pps. That rate limitation does not appear related to listeners' overall thresholds, as van Hoesel (2007) found similar results among three BiCI listeners who demonstrated relatively good ITD sensitivity for static low-rate pulse trains (thresholds of 100–200 μs at 100 pps). Although thresholds in the later study improved with increasing stimulation duration, the amount of improvement was suboptimal at higher rates (e.g., 400 pps), consistent with strong binaural adaptation (Hafter and Dye, 1983). van Hoesel (2007) also tested a binaural-beat (dynamic ITD) detection task similar to that in van Hoesel and Clark, 1997; consistent with the prior study, none of the three listeners could perform the task at 300 pps. Similarly, Carlyon *et al.* (2008) tested four additional BiCI users on a comparable rate discrimination task, finding minimal benefit of binaural-beat over monaural presentation, and no benefit at the highest tested rate, 300 pps.

Thus, sensitivity to ITD appears limited in BiCI users, particularly at stimulation rates around 300 pps or higher. Many BiCI users are able to localize sound, however, and recent evidence indicates that BiCI users' sensitivity to ILD using clinical processors may be near that of NH listeners. Grantham *et al.* (2008) tested ITD and ILD thresholds for 11 BiCI listeners with 200-ms Gaussian noise bursts bandpass filtered from 100 to 4000 Hz. In that study, stimuli were presented through standard CI processors which were not synchronized between the ears; thus, subjects did not have access to fine-timing cues available in the studies described above. Consistent with that limitation, as well as with previous reports, average ITD thresholds were poor (typically >1000 μs, with the best subject at 400 μs); ILD thresholds, however, were close to normal, averaging 1.9 dB with device compression disabled. Note, however, that direct comparison to "normal" ILD threshold is complicated by the mapping of acoustic to electric intensity within the two CI processors. A subsequent analysis of the same subjects' free-field localization performance suggested that localization was primarily mediated by ILD sensitivity. That result is mirrored in a recent study measuring temporal weighting functions for ITD and ILD in BiCI users (van Hoesel, 2008). Consistent with results for NH listeners (Saberi, 1996; Stecker and Hafter, 2002; Brown and Stecker, 2009), the results of that study revealed a strong onset dominance for ITD at pulse rates of 300 and 600 pps, but not at 100 pps. The degree of onset dominance was substantially reduced for ILD, suggesting reduced effects of rate limitation on processing of that cue by BiCI users.

The cause of rate limitation in BiCI ITD sensitivity remains unclear at present. Exacerbated neural refractoriness and synchronous activation of broad cochlear extent, both resulting from electrical stimulation, have been suggested as potential explanations (van Hoesel, 2007; van Hoesel *et al.*, 2009). The rate limitation for envelope ITD processing observed in NH listeners offers another. Studies of NH listeners (Hafter and Dye, 1983; Freyman *et al.*, 1997; Bernstein and Trahiotis, 2002; Goupell *et al.*, 2009) suggest that narrowband (i.e., place-limited within the cochlea) stimuli with temporally regular modulation may be especially sensitive to this limitation. Typical implant stimulation patterns share both the narrow bandwidth and temporal regularity of such stimuli (Carlyon and Deeks, 2002). Thus, it can reasonably be expected that listeners with otherwise-normal hearing would exhibit impaired ITD sensitivity for BiCI stimulation at high rates (beyond 200–300 pps).

In the current study, we employ an approach similar to one used previously in BiCI users (binaural-beat detection, van Hoesel and Clark, 1997) to study the effects of onset dominance on NH listeners' sensitivity to ITD and ILD cues across modulation rate. By comparing performance across a range of rates, we aimed to directly compare the rate limitation observed in BiCI studies with that occurring in the normal auditory system, and to determine if the failure of dichotic rate discrimination in BiCI users might be attributed to onset dominance. By measuring performance with both ITD and ILD, we aimed to evaluate whether the rate limitation is specific to ongoing envelope ITD (as suggested by preserved ILD processing in BiCI users), or whether rate limitations and onset dominance occur similarly for the two cues (Hafter *et al.*, 1983, 1990).

II. EXPERIMENT 1: DETECTION OF DYNAMIC ITD

In order to assess the sensitivity of normal-hearing listeners to dynamic ITD, we adapted the procedure used by van Hoesel and Clark (1997) in their study of BiCI users. Specifically, van Hoesel and Clark (1997) constructed binaural-beat stimuli by presenting slightly different electrical-pulse rates to the two ears. The resulting stimulus carries an ITD that, over time, increasingly favors the ear receiving the higher rate. Numerous studies have used binaural-beat or modulated-ITD stimuli to evaluate sensitivity to auditory motion (Grantham and Wightman, 1978; Grantham, 1984; Saberi *et al.*, 2003) and dichotic rate perception (van Hoesel and Clark, 1997; Carlyon and Deeks, 2002; van Hoesel, 2007; Carlyon *et al.*, 2008). In contrast to many of those studies, the current study focuses primarily on sensitivity to the displacement, or overall ITD, cue conveyed by different temporal portions of a sound, rather than to motion *per se* (cf. Grantham and Wightman, 1978).

In the current study, we presented NH listeners with bandpass-filtered impulse ("click") trains with acoustic energy restricted to a relatively narrow, high-frequency (4000-Hz) region of the spectrum, similar to the place-limited electrical excitation of (typically basal) regions of the cochlea in BiCI stimulation (Carlyon and Deeks, 2002). Such stimuli

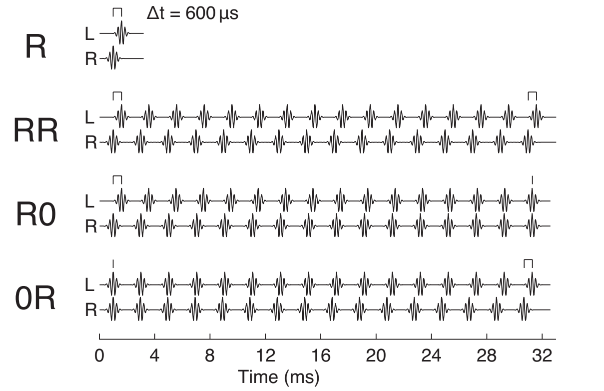

FIG. 1. Schematic illustrations of the stimuli used in experiment 1. From top to bottom, examples of left-ear (L) and right-ear (R) target-interval stimulus waveforms presented with 2-ms ICI in conditions R, RR, $R0$, and $0R$. For conditions R and RR, the target ITD Δt (for illustration, $\Delta t = 600\ \mu s$) was applied to each click. For condition $R0$, ITD decreased linearly from Δt at onset (click 1) to $0\ \mu s$ at offset (click 16). For condition $0R$, ITD increased from $0\ \mu s$ to Δt over the duration.

additionally allow variation of click rate independent of carrier frequency (as in BiCI stimulation), along with click-specific variation of the ITD and ILD cues.

The stimuli used by van Hoesel and Clark (1997) were impulse trains in which the initial pulse in each stimulus was temporally aligned at the two ears (i.e., zero ITD), thus eliminating onset ITD as a cue and requiring listeners' sensitivity to ongoing or offset ITD for good performance on the task. That arrangement is duplicated in the current experiment as condition $0R$ (0-μs ITD at onset growing linearly over the 16-click duration to a right-leading ITD at offset) and contrasted with performance in a temporally reversed condition $R0$ (right-leading onset ITD diminishing to zero offset ITD), a static-ITD condition RR, and a single click condition R. The stimulus conditions are illustrated in Fig. 1. Relative thresholds across these conditions can be predicted according to multiple-looks theory (Houtgast and Plomp, 1968; Hafter and Dye, 1983; Viemeister and Wakefield, 1991) subsequent to temporal weighting of individual clicks by the model of Hafter and Buell (1990) as follows:

$$w_j = (n_j)^k - (n_{j-1})^k. \tag{1}$$

Equation (1) describes the relative effectiveness, or weight, of each click j as a function of its numerical position n_j in the train. The exponent k controls the degree of onset dominance, and varies with ICI. Relative predictions of this model are plotted in Fig. 2. At short values of ICI, where sensitivity to ongoing ITD is limited and onset dominance is strong (i.e., $k \approx 0$), performance in condition $0R$ (which lacks onset cues) is expected to be very poor—ultimately limited to the listeners' sensitivity to monaural pitch cues present for large Δt. Thresholds in the other conditions should all be comparable to single-click performance. At longer values of ICI, sensitivity to ongoing ITD suggests that performance should be based on a *cue averaging* strategy (i.e., $k \approx 1$), with RR thresholds expected to improve beyond single-click by a factor of $\sqrt{16} = 4$ according to multiple-looks theory. For cue averaging, it would also be expected that thresholds for

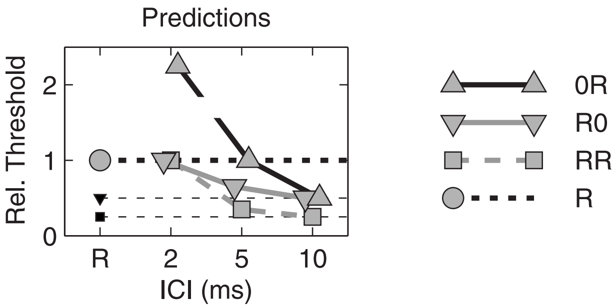

FIG. 2. Predictions for the experiment. The predicted ITD thresholds relative to single-click (gray symbols) are plotted against ICI for conditions *RR* (square symbols/dashed lines), *R*0 (downward-pointing triangles/solid gray lines), and 0*R* (upward-pointing triangles/solid black lines). The predicted single-click threshold (circle) is projected across ICI (dotted line) for comparison. Black symbols and fine dashed lines indicate theoretical improvement over single-click for an ideal observer weighting all clicks equally, resulting in $\sqrt{n}$ (i.e., fourfold) improvement in condition *RR* (black square/fine dashed line). Note that the thresholds for conditions *R*0 and 0*R* converge to twice the *RR* threshold (black triangle/fine dashed line).

conditions *R*0 and 0*R* at long ICI should be equal to one another and intermediate between *R* and *RR* thresholds.[3]

A. Methods

All procedures, including recruitment, consenting, and testing of human subjects, followed the guidelines of the University of Washington Human Subjects Division and were reviewed and approved by the cognizant Institutional Review Board.

1. Subjects

Seven subjects participated in this experiment. One (0501) was the first author, and one (0504) was an undergraduate research assistant working in the laboratory. The remainder (0601, 0602, 0603, 0605, and 0701) were paid subjects naive to the purpose of the experiment. Each subject participated in one or more of the testing conditions ("rove" and "no-rove," see below), but not all subjects participated in all conditions. All subjects reported normal hearing and demonstrated pure-tone detection thresholds <10 dB hearing level (HL) over the range 250–8000 Hz.

2. Stimuli

The stimuli consisted of Gabor clicks (Gaussian-windowed tone bursts) or trains of such clicks. Each click consisted of a 4-kHz cosine multiplied by a Gaussian temporal envelope with $\sigma=221$ μs. The resulting spectral bandwidth was also Gaussian, with $\sigma=750$ Hz, giving a half-maximal bandwidth of 1.8 kHz. Single-clicks or trains of 16 clicks were synthesized at 48.848 kHz (Tucker-Davis Technologies RP2.1, Alachua, FL) and presented via headphones (STAX 4070, Saitama, Japan) at approximately 65–74 dB sound pressure level (SPL), *A*-weighted. Click trains were presented with a peak-to-peak ICI equal to 2, 5, or 10 ms.

Four stimulus conditions were tested. In each case, "standard" intervals (see Sec. II A 3) presented diotic stimuli, while "target" intervals contained a right-leading ITD, Δt. Condition *R* presented a single click in each interval; target intervals featured ITD$=\Delta t$. Condition *RR* presented a train of 16 clicks with identical ITD, with target ITD set to Δt for all clicks. Condition *R*0 also presented a train of 16 clicks; in this case target intervals carried a dynamic ITD that decreased linearly from Δt at onset (click 1) to 0 μs at offset (click 16). Condition 0*R* was the temporal reverse of *R*0; the ITD of target intervals increased from 0 μs at onset to Δt at offset. In all cases, Δt was constrained to less than 1/2 ICI to avoid ambiguous lateralization caused by mismatching periods across the ears or multiple rotations of the binaural-beat stimulus.

Note that the stimuli used in conditions 0*R* and *R*0 carry both "static" cues related to the peak or overall interaural difference, as well as dynamic cues related to the changing interaural difference. These dynamic cues give rise to a motion whose velocity is correlated with both Δt and stimulus duration (which varies, in turn, with ICI). Previous research on sensitivity to this motion cue suggests a rather "sluggish" mechanism, requiring integration over fairly long durations of 150–300 ms (Grantham, 1986). As a result of the short durations used in the current study (31–151 ms), we presume limited sensitivity to motion *per se*. Thus, performance should be limited primarily by sensitivity to the overall ITD cue.

Two conditions of level and ICI roving were tested in separate runs. In the no-rove condition, ICI was fixed at 2, 5, or 10 ms and peak amplitude was fixed at 80 dB SPL throughout the run. The overall level measured at the entrance to the ear canal was approximately 65 dB SPL (*A*-weighted) for single-clicks and 71–74 dB SPL for 16-click trains (depending on ICI). In the rove condition, these values were supplemented with additional random variation added independently to each interval. The ICI was roved by $\pm 10\%$ (uniform sampling distribution) between intervals, while the level was roved by ± 5 dB (Bernstein, 2004). The purpose of the ICI rove was to reduce the informativeness of pitch cues caused by dynamic ITD in the *R*0 and 0*R* conditions. The level rove was incorporated to match the rove condition of Experiment 2, where it served to reduce monaural intensity cues introduced by manipulation of ILD. Not all listeners participated in both conditions.

3. Procedure

ITD discrimination was assessed using a four-interval two-alternative forced-choice (4I2AFC) procedure, with a single right-leading target stimulus (click or 16-click train) presented randomly in either the second or third interval on each trial. Other intervals presented a diotic standard stimulus. Intervals were separated by an interstimulus interval of 500 ms. Following presentation of the fourth interval, subjects indicated by button press which interval contained the right-leading target; feedback notification of the correct interval was provided by light emitting diode (LED) immediately thereafter.

Threshold values were obtained using a two-down one-up adaptive procedure tracking Δt at 71% correct (Levitt, 1971). Target ITD Δt was set to 400 μs at the start of each run, with the step size set to 30 μs for the initial 4 of 12 adaptive reversals, and 10 μs thereafter. Threshold was

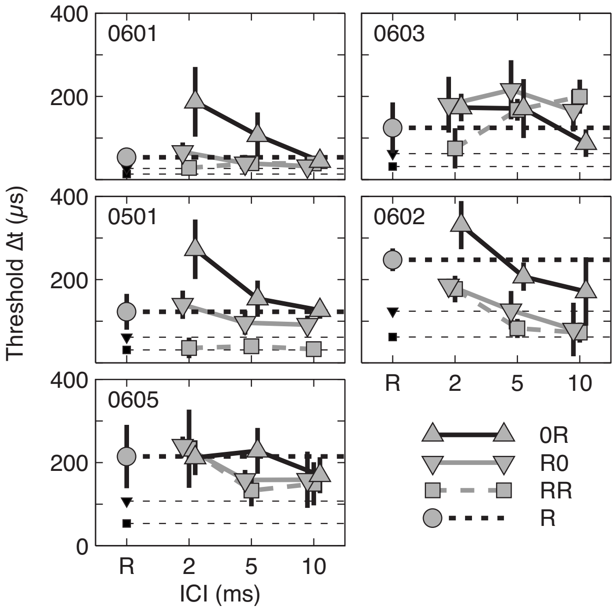

FIG. 3. Results of experiment 1, no-rove condition, for each listener. Plotted in each panel are mean ITD thresholds computed across runs for conditions *RR* (square symbols/dashed lines), *R*0 (downward-pointing triangles/solid gray lines), and 0*R* (upward-pointing triangles/solid black lines). Single-click thresholds (circles) are projected across ICI (dotted lines) for comparison. Error bars plot 95% confidence intervals. Black symbols and fine dashed lines plot 1/4 and 1/2 single-click thresholds as cue averaging predictions for static (square symbol, $\sqrt{n}$ improvement) and dynamic (triangle) trains (see Fig. 2).

estimated as the mean of the final eight reversals on each run. Occasional tracks which failed to converge were eliminated from subsequent analyses. Following practice consisting of at least three runs at each ICI in condition *RR* and condition *R*, subjects completed at least four test runs at each combination of ICI and condition (*R*, *RR*, *R*0, and 0*R*). Condition/ICI combinations were tested in random order for each subject to minimize sequential effects.

4. Analysis

Both individual-subject and across-subject mean thresholds were computed for display and analysis. Appropriate statistical confidence intervals were computed at $\alpha=0.05$ for each threshold and included in the plots. For individual subjects (e.g., Fig. 3), mean thresholds were computed across repeated runs for each combination of roving condition, stimulus condition, and ICI. 95% confidence intervals were computed across runs (i.e., not taking into account the number of reversals included in each threshold estimate). For group-level plotting and analysis (e.g., Fig. 5), mean thresholds were computed across subjects for each combination of roving, stimulus, and ICI. 95% confidence intervals were computed across individual mean thresholds in that case (i.e., not taking into account the number of runs contributing to each individual mean threshold). Statistical comparisons of individual values can be made on the basis of the plotted confidence intervals, and statements of significant differences between individual values reflect such comparisons. Reported statistical comparisons involving multiple threshold values (e.g., when comparing overall thresholds between rove and no-rove conditions) were conducted using explicit null-hypothesis significance tests [repeated-measures analysis of variance (ANOVA) and *t*-tests].

B. Results

Figure 3 plots threshold ITD across ICI and stimulus condition (symbols) for individual subjects (panels) in the no-rove condition. Circles and dotted lines plot single-click threshold ITD to which other values may be compared. Consistent with expectations, the majority of subjects recorded higher thresholds in the 0*R* condition than in either the *R*0 or *RR* conditions, and this difference was greatest at 2-ms ICI. In general, thresholds reduced with increasing ICI, particularly for condition 0*R*. Such improvement is consistent with subjects taking partial advantage of "multiple looks" at the ongoing ITD (Hafter and Dye, 1983; Viemeister and Wakefield, 1991) for longer values of ICI. Note, however, that in several cases, thresholds did not converge on the values predicted for an ideal observer in such circumstances (black symbols).

Results obtained in this condition were submitted to a two-way repeated-measures ANOVA to test the statistical significance of effects across subjects. The main effects of stimulus condition [*RR* vs *R*0 vs 0*R*, $F_{(2,8\ df)}=5.4,\ p<0.05$ and ICI $F_{(2,8\ df)}=6.0,\ p<0.05$] were both statistically significant, as was the condition-by-ICI interaction [$F_{(4,16\ df)}=3.4,\ p<0.05$], consistent with a relatively greater dependence of threshold on ICI in condition 0*R* [paired t-test comparing 0*R* thresholds at 10- and 2-ms ICI: $t_{(4\ df)}=5.2,\ p<0.05$] than in the temporally reversed condition *R*0 [$t_{(4\ df)}=3.5,\ p<0.05$] or in static condition *RR* [$t_{(4\ df)}=0.3,\ p>0.05$].

Although all subjects showed a threshold improvement with ICI in condition 0*R*, clear individual differences are present in the magnitude of that improvement and in the pattern of threshold ITD across the other conditions. The reasons for such differences are not entirely clear; they do not closely follow listeners' overall sensitivity (note the differences between 0602 and 0605 despite similarly poor single-click threshold ITD). One possibility is that attention to extraneous (non-ITD) cues limited some subjects' ability to focus on the ITD cue. These include the non-informative 0-dB ILD which was present at all times, and a monaural rate cue present for the 0*R* and *R*0 conditions, which featured dynamic changes in ITD. Essentially a pitch cue, that difference could support discrimination at very large values of Δt (van Hoesel and Clark, 1997) and thus prevent listeners who focus on pitch differences from achieving lower, binaurally mediated thresholds. To counter that possibility, a second (rove) condition was tested, in which ICI varied ±10% between intervals. Stimulus intensity was additionally roved ±5 dB for consistency with experiment 2. Figure 4 plots threshold ITD across ICI and stimulus condition for individual subjects in this condition. Aside from the different subjects tested, the format is identical to Fig. 3. Note that inter-subject differences are less apparent than in the no-rove condition; this may reflect the reduced utility of non-ITD cues or a simple difference in the subjects recruited in each

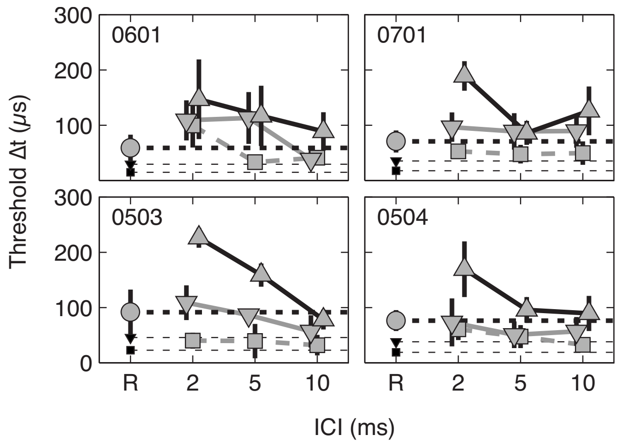

FIG. 4. Results of experiment 1, rove condition. The format is identical to Fig. 3.

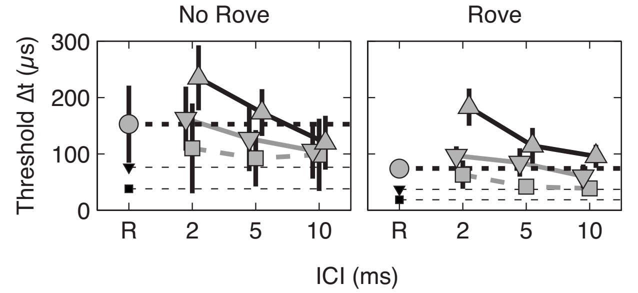

FIG. 5. Results of experiment 1, plotting across-subject means for the rove condition (left panel) and the no-rove condition (right panel). Symbols plot mean threshold ITD, and error bars indicate 95% confidence intervals, computed across subjects. The format is otherwise identical to Fig. 3.

case. Indeed, mean thresholds were lower overall than in Fig. 3 [matched-samples t-test across condition and ICI, $t_{(9\ df)}=10.2$, $p<0.05$], consistent with a more-sensitive cohort of listeners in this condition. There was no significant difference between rove and no-rove when tested using only the two subjects that were tested in both conditions [$t_{(9\ df)}=-0.13$, $p>0.05$], suggesting that roving did not directly affect threshold ITDs. Overall thresholds of the two groups notwithstanding, key features of the data appear to replicate across conditions. Namely, in a majority of subjects tested at 2-ms ICI, threshold ITDs were significantly higher for condition 0*R* than condition *R*0, for which thresholds were similar to similar to those for single-clicks. Consistent with that observation, threshold ITDs reduced with ICI most dramatically with increasing ICI in condition 0*R*, suggesting a shift from onset dominance at short values of ICI to cue averaging at long values of ICI. As in the no-rove condition, in many cases overall improvements failed to converge with expectations based on cue averaging by an ideal observer (black symbols), even at an ICI of 10 ms.

As for the no-rove condition, results obtained in the rove condition were submitted to a two-way repeated-measures ANOVA to test the statistical significance of effects across subjects. Consistent with no-rove results, the main effects of stimulus condition [*RR* vs *R*0 vs 0*R*, $F_{(2,6\ df)}=36.5$, $p<0.05$ and ICI $F_{(2,6\ df)}=14.7$, $p<0.05$] were statistically significant; the condition-by-ICI interaction, in contrast, was not [$F_{(4,12\ df)}=2.8$, $p>0.05$]. Paired *t*-tests comparing thresholds at 10- and 2-ms ICI, however, revealed significant differences for conditions 0*R* [paired t-test comparing thresholds at 10- and 2-ms ICI: $t_{(3\ df)}=4.2$, $p<0.05$] and *R*0 [$t_{(3\ df)}=2.4$, $p<0.05$], but not *RR* [$t_{(3\ df)}=2.0$, $p>0.05$], consistent with the differences observed in the no-rove condition.

Across-subject mean threshold ITDs are plotted in Fig. 5 for both no-rove (left panel) and rove conditions (right panel). The patterns of average data appear similar between these conditions, and reiterate the pattern of results seen in the majority of individual data. Most importantly, threshold ITDs in condition 0*R* at 2-ms ICI were significantly higher than single-click (*R*) thresholds [paired t-test: $t_{(4\ df)}=3.0$ (no-rove), $t_{(3\ df)}=9.9$ (rove), both $p<0.05$]. In contrast, *RR* and *R*0 thresholds at 2-ms ICI did not differ significantly from single-click thresholds [$t_{(4\ df)}=-2.3$ (*RR*, no-rove), $t_{(4\ df)}=1.2$ (*R*0, no-rove), $t_{(3\ df)}=-0.6$ (*RR*, rove), and $t_{(3\ df)}=2.0$ (*R*0, rove), all $p>0.05$]. Taken together, these results are consistent with strong onset dominance at 2-ms ICI, producing poor performance in the absence of informative onset cues (condition 0*R*). Thresholds tended toward convergence at an ICI of 10 ms, consistent with averaging of cues over the full duration of low-rate stimuli. At 10-ms ICI (where onset dominance was not found or expected), mean thresholds approached but did not consistently attain the theoretical maximum (e.g., $\sqrt{n}$ for *RR*) improvement over single-clicks. Threshold ITDs at 10-ms ICI remained consistently greater than $\sqrt{n}$ predictions in absolute terms, although the differences were not statistically significant for all stimulus conditions [paired t-tests for rove: $t_{(3\ df)}=3.8$, $p<0.05$ (*RR*), $t=2.2$, $p=0.06$ (*R*0), and $t=4.8$, $p<0.05$ (0*R*); no-rove: $t_{(4\ df)}=1.9$, $p=0.07$ (*RR*), $t=1.2$, $p=0.15$ (*R*0), and $t=4.6$, $p<0.05$ (0*R*)]. Overall, the pattern of improvements suggests a partial or suboptimal integration of ongoing ITD. For example, in many cases, 0*R* thresholds approached but did not surpass single-click performance, implying approximately one click's worth of usable binaural information carried by the entire train of 16 clicks.

III. EXPERIMENT 2: DETECTION OF DYNAMIC ILD

The results of experiment 1 demonstrated a clear effect of onset dominance on ITD for an ICI of 2 ms (i.e., a 500-Hz modulation rate), but not for longer values of ICI. The results were similar to those obtained in a study of BiCI users engaged in a nearly identical task (van Hoesel and Clark, 1997), and consistent with previous findings of rate-limited sensitivity to ongoing envelope ITD at high carrier frequency (Bernstein and Trahiotis, 2002) and consequent dependence on onset ITD at high rates (Hafter and Dye, 1983). As discussed in the Introduction, there exist multiple competing accounts of this rate limitation, some suggesting a rather specific effect on ITD processing at high carrier frequency (Bernstein and Trahiotis, 2002), and others a more general evaluation of available cues (e.g., Rakerd and Hartmann, 1985). Probably the most extensive investigation of these effects has been conducted by Hafter and colleagues (Hafter and Dye, 1983; Hafter *et al.*, 1983, 1988; Hafter and Richards, 1988; Hafter *et al.*, 1990; Hafter and Buell, 1990; Hafter, 1997), and one key conclusion of those studies has been that binaural adaptation affects both ITD and ILD in similar ways (Hafter and Dye, 1983; Hafter *et al.*, 1983). Furthermore, the two cues adapt together in an integrated manner (Hafter *et al.*, 1990). On the basis of these results, Hafter and colleagues argued that binaural adaptation acts upon a neural representation common to both cues (Hafter *et al.*, 1990; Hafter, 1997). If so—and assuming that listeners' performance in the current study is limited primarily by binaural adaptation—one should expect the patterns of discrimination performance observed in Experiment 1 to be obtained using either cue interchangeably. Alternatively, if the rate limitation observed in Experiment 1 primarily reflects a consequence of lowpass filtering of envelope representations (Bernstein and Trahiotis, 2002), then the effect should be significantly reduced for ILD. Experiment 2 of the current study tests this hypothesis by repeating the experiment with ILD as the discriminated cue. As far as possible, other aspects of experiment 2 were identical to Experiment 1.

A. Methods

Methods of experiment 2 corresponded closely to those of experiment 1, with the substitution of ILD for ITD in the tested stimuli.

1. Subjects

Six subjects participated in this experiment. One (0501) was the first author, and two (0503 and 0504) were undergraduate research assistants working in the laboratory. The remainder (0601, 0602, and 0605) were paid subjects naive to the purpose of the Experiment. All but 0503 participated in Experiment 1 prior to testing in experiment 2. All subjects reported NH and demonstrated pure-tone detection thresholds <10 dB HL over the range 250–8000 Hz.

2. Stimuli

Stimuli consisted of Gabor clicks and click trains identical to those used in experiment 1, with one modification: Stimuli were presented with zero ITD, and targets were defined by a right-favoring ILD ΔL. Condition *RR* presented trains of 16 clicks sharing a fixed ILD. Conditions *R*0 and 0*R* presented trains of 16 clicks with a dynamic ILD that decreased linearly from ΔL at click 1 to 0 dB at click 16, or increased from 0 dB to ΔL, respectively. Single-clicks (condition *R*) were tested for comparison to other conditions. In all conditions, the ILD was implemented symmetrically by reducing the level in the left ear and increasing the level in the right ear by equal decibel amounts.

3. Procedure

Testing procedures were similar to Experiment 1. Threshold ΔL was measured using the two-down one-up adaptive procedure (Levitt, 1971) in a two-alternative forced-choice (2AFC) task. Adaptive tracks started with $\Delta L = 3.8$ dB and proceeded by steps of 0.6 dB for four reversals, followed by 0.1 dB steps for eight additional reversals. Thresholds were estimated as the mean of the final eight

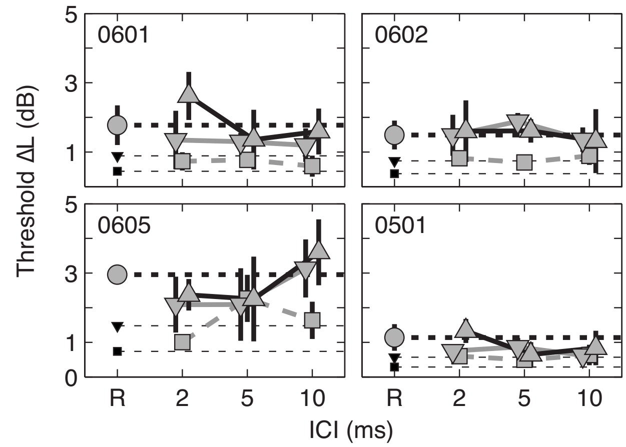

FIG. 6. Results of experiment 2, no-rove condition. In each panel, mean (across runs) threshold ILD is plotted against ICI for each condition. Individual panels represent individual subjects. The format is otherwise identical to Fig. 3.

reversals per run. The no-rove condition of Experiment 2 employed two-interval 2AFC to reduce the ability of subjects to make "odd-one-out" judgments on the basis of monaural intensity differences between standard and target intervals. The rove condition used the same 4I2AFC task as in experiment 1. In that case, roving parameters were configured identically to experiment 1, with monaural intensity cues obscured by the ± 5 dB intensity rove across intervals.

B. Results

Figures 6 and 7 plot individual-subject ILD thresholds measured in the no-rove and rove conditions, respectively. In contrast to the results of experiment 1, the majority of subjects' ILD thresholds did not vary systematically with ICI, suggesting a minimal or absent rate limitation in ILD processing. Moreover, thresholds were similar between conditions 0*R* and *R*0, which featured the absence and presence, respectively, of nonzero ILD at onset, suggesting no onset dominance for ILD in this task. One exception appears in the data of subject 0601 in the no-rove condition, whose 0*R* threshold at an ICI of 2 ms (2.6 dB) exceeded the equivalent *R*0 (1.3 dB) and single-click (*R*, 1.8 dB) thresholds (although

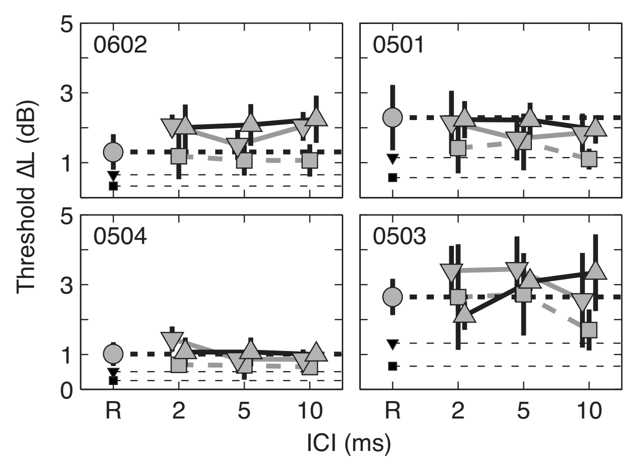

FIG. 7. Results of experiment 2, rove condition. The format is identical to Fig. 6.

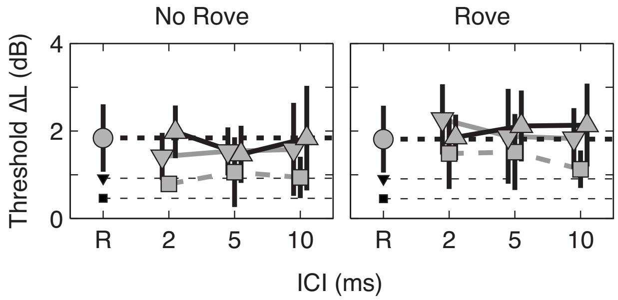

FIG. 8. Results of experiment 2, plotting across-subject means for the rove condition (left panel) and the no-rove condition (right panel). Symbols plot mean threshold ILD, and error bars indicate 95% confidence intervals, computed across subjects. The format is otherwise identical to Fig. 6.

by an apparently smaller factor than in experiment 1, where equivalent thresholds were 186, 66, and 53 μs, respectively; see Fig. 3).

As in Experiment 1, results were submitted to a two-way repeated-measures ANOVA to test the statistical significance of effects across subjects. In the no-rove conditions, and consistent with the pattern of individual data apparent in Fig. 6, the main effect of stimulus condition was statistically significant [$F_{(2,6\ df)}=14.8,\ p<0.05$]. The main effect of ICI, in contrast, was not statistically significant [$F_{(2,6\ df)}=0.1,\ p>0.05$], nor was the condition-by-ICI interaction [$F_{(4,12\ df)}=0.5,\ p>0.05$]. An identical pattern of results was obtained for the rove condition [significant main effect of stimulus condition: $F_{(2,6\ df)}=17.9,\ p<0.05$, no main effect of ICI: $F_{(2,6\ df)}=1.0,\ p>0.05$, or condition-by-ICI interaction: $F_{(4,12\ df)}=2.2,\ p>0.05$].

The two subjects who were tested in both rove and no-rove conditions (0501 and 0602) exhibited higher ILD thresholds with roving than without [matched-samples t-test across ICI and condition: $t_{(9\ df)}=10.5$ and 2.8, respectively, $p<0.05$], suggesting some interference between ILD and overall intensity variation across intervals (cf. Melara and Marks, 1990). That difference was also evident in the group-averaged thresholds [$t_{(9\ df)}=-3.6,\ p<0.05$], although the average difference across conditions and ICI was just 0.4 dB (see Fig. 8). Overall threshold differences notwithstanding, the pattern of data—specifically, the lack of ICI-dependence—did not appear to vary between roving conditions.

Figure 8 plots the mean thresholds across subjects for each combination of stimulus type, roving, and ICI. The average data support the differences described above, namely, that (1) ILD thresholds did not depend systematically on ICI, and (2) performance did not suffer from removal of onset cues in condition 0*R*. Consistent with expectations of cue averaging, the lowest thresholds ILDs were obtained in condition *RR*, averaging 1.0 dB across roving conditions at 10-ms ICI. As in experiment 1, these thresholds approached but did not consistently attain the theoretically optimum $\sqrt{N}$ improvement (black symbols in Fig. 8) compared to single-click thresholds, which averaged 1.8 dB across conditions. Rove-condition threshold ILDs at 10-ms ICI significantly exceeded predicted values for all stimulus conditions [paired *t*-test: $t_{(3\ df)}=4.7$ (*RR*), 3.9 (*R*0), 3.5 (0*R*), all $p<0.05$]. In the no-rove condition, 10-ms *RR* thresholds remained significantly above $\sqrt{N}$ predictions [$t_{(3\ df)}=3.0,\ p<0.05$], while thresholds for other stimuli exceeded predictions by statistically non-significant amounts [$t_{(3\ df)}=1.9,\ p=0.08$ (*R*0), $2.2, p=0.06$ (0*R*)]. A further expectation of cue averaging is that 0*R* and *R*0 thresholds should be equivalent and intermediate between single-click and *RR* thresholds. Although the mean *R*0 and 0*R* thresholds do appear similar to one another overall, neither was consistently better than single-click thresholds (note that 95% confidence intervals contain the mean single-click thresholds for all values of ICI). That is, neither the static (*RR*) nor dynamic (0*R* and *R*0) ILD thresholds are consistent with optimal averaging of ILD information over the train; rather, they suggest a suboptimal weighting of the ILD information across clicks. In direct contrast to the onset dominance evidenced for ITD in Experiment 1, however, listeners' sensitivity to ILD was evidently independent of its temporal placement within the click train (i.e., the data provided no indication of onset dominance for ILD).

IV. DISCUSSION

A. Summary of findings

1. Onset dominance for ITD at short ICI

Consistent with past studies of dichotic rate discrimination (van Hoesel and Clark, 1997; Carlyon and Deeks, 2002; van Hoesel, 2007; Carlyon *et al.*, 2008), the results of experiment 1 demonstrated a clear effect of onset dominance on ITD for an ICI of 2 ms (= 500-Hz modulation rate), but not for longer values of ICI. That is, when onset ITD cues were eliminated (in condition 0*R*), there was a marked increase in threshold for ITD carried by later portions of the stimulus. When the stimulus was reversed in time so that onset ITD was available (condition *R*0), thresholds at short ICI were similar to thresholds measured for single clicks. The necessity of onset cues for detection of ITD at high rates is consistent with rate-limited processing of ongoing envelope ITD at high carrier frequencies, as suggested previously by others (Hafter and Dye, 1983; Bernstein and Trahiotis, 2002).

2. Partial averaging of ongoing ITD at long ICI

Compared to the results at short values of ICI, threshold ITD consistently improved at longer (5–10 ms) ICI, especially for stimuli that lacked onset ITD cues (condition 0*R*). That pattern of results is consistent with increasing availability of information from ongoing ITD at low rates, and a consequent shift toward cue averaging. Thresholds generally failed to converge on the theoretical optima for multiple independently noisy "looks" at the ITD (Houtgast and Plomp, 1968; Hafter and Dye, 1983; Viemeister and Wakefield, 1991). That failure suggests a partial or suboptimal averaging of ITD over the stimulus duration even at rates below the putative rate limitation for ongoing envelope ITD.

3. Lack of onset dominance for ILD at short ICI

In contrast to the results of Experiment 1, Experiment 2 revealed no strong evidence for rate-limited or onset-dominated ILD processing. With a single exception, thresholds in condition $0R$ were similar to those measured in condition $R0$ at all values of ICI, suggesting that ILD had similar effects whether presented near the onset or offset of a stimulus. Moreover, ILD thresholds did not vary systematically with ICI for any stimulus condition, suggesting no rate limitation for ILD processing, at least over the tested range of ICI.[4]

4. Partial averaging of ILD over time

The similarity of ILD thresholds between conditions $R0$ and $0R$ suggests that sensitivity to ILD is maintained over the entire duration of a stimulus. It is reasonable, therefore, to expect ILD discrimination to take full advantage of averaging multiple looks at the stimulus (Viemeister and Wakefield, 1991). Thus a fourfold (i.e., $\sqrt{n}$) improvement in threshold was expected for static trains of 16 clicks (condition RR) and approximately half that benefit (i.e., a twofold improvement) for dynamic trains ($0R$ and $R0$). Contrary to expectations, but similar to the results of experiment 1, ILD thresholds did not achieve this theoretically optimum benefit of stimulus duration. Indeed, although RR thresholds were somewhat lower than single-click thresholds overall, threshold ILDs for dynamic trains were similar to, and in some cases worse than, single-click values. That is, the combination of binaural information across clicks was not optimal as defined by multiple-looks theory, suggesting uneven weighting of ILD over the stimulus duration.[5]

B. Importance of onset ITD at high rates in both normal hearing and BiCI use

Condition $0R$ of experiment 1 was modeled after previous work in BiCI users (van Hoesel and Clark, 1997; van Hoesel, 2007; Carlyon and Deeks, 2002). Consistent with the results of those studies, we found discrimination of dynamic ITD in the absence of onset ITD to be impaired at high rates (2-ms ICI or 500 pps). Given the similar results and the intentional similarity of the stimuli (place-limited pulsatile stimuli for BiCI users and narrowband pulsatile acoustic stimuli for normal-hearing listeners), we argue that the decreasing ITD sensitivity of BiCI users at pulse rates above 200 pps can at least partly be accounted for by the rate limitation of ongoing envelope ITD sensitivity observed in NH listeners. That is, gross differences in the abilities of NH and BiCI listeners to utilize ITD in natural stimuli can be accounted for by the differences in effective stimulation received by the two populations, as presenting NH listeners with high-rate, pulsatile, narrowband stimuli reveals similar limitations to those observed in BiCI users. In agreement with the conclusion of van Hoesel (2007), the current results suggest a critical role of normal rate limitation, rather than central auditory dysfunction or CI-specific failure of auditory peripheral encoding, in the limited abilities of BiCI users to process ITD.

Although the pattern of results is qualitatively in agreement with studies of BiCI users, quantitative differences between NH and BiCI listeners appear to remain. In examining the ability of BiCI users to discriminate static ITD, van Hoesel (2007) found thresholds to increase monotonically as pulse rate increased from 100 to 300 pps. When presented a dichotic rate discrimination task using a binaural-beat stimulus similar to that of the current condition $0R$ (but with potentially multiple rotations of the beat; see below), BiCI users' performance diminished more dramatically as pulse rate increased from 100 to 200 pps. Dichotic thresholds appeared similar to monotic rate thresholds at 300 pps. Carlyon *et al.* (2008) reported a similar pattern in their study of BiCI users' dichotic rate discrimination thresholds from 100 to 300 pps. Thus, studies of dynamic-ITD processing in BiCI users suggest a significant reduction in performance at 200 pps, and a near-total failure of ITD sensitivity at 300 pps. The current results with NH subjects suggest instead that rate limitations take hold somewhere in the range between 200 and 500 Hz, as threshold ITDs in the $0R$ condition were significantly elevated beyond single-click thresholds at 2-ms ICI, but not at 5 ms ICI. As in the earlier studies, we assume that $0R$ thresholds at the highest rates were likely subserved by detection of the monaural pitch cue available for large peak ITD, although we did not explicitly measure monaural performance. Thus, we interpret the failure of our subjects to discriminate ITD in condition $0R$ at 2-ms ICI similarly to the failure of BiCI users to discriminate dynamic ITD in absence of onset cues at 300 pps (van Hoesel, 2007; Carlyon *et al.*, 2008). Since the current study did not assess NH performance at 300 Hz (=3.3 ms ICI), however, the current results are not sufficient to determine whether the critical rate differs between NH and BiCI listeners.

A direct comparison of thresholds across studies is further complicated by two factors. First, both of the cited BiCI studies presented interaural differences in pulse rate large enough to allow multiple rotations of the ITD over the duration of a stimulus. When that occurs, listeners may not base their decision on the lateral position, or sidedness, of the image because the average ITD approaches zero. Second, those studies expressed discrimination performance as a function of differences in pulse rate between the ears, rather than the peak ITD. Because the peak, mean, and offset ITDs in such stimuli vary non-monotonically with interaural rate difference, it is not entirely clear which cues (e.g., lateral position versus apparent source width) listeners may have utilized, or whether the same cues were used in different conditions. A more direct comparison between BiCI and NH listeners was made by Carlyon *et al.* (2008). They found that most NH listeners could utilize binaural cues to perform the task at 300 pps, at least for relatively slow modulations of the ITD (interaural rate differences around 3.75 pps or less, corresponding to 1.25% of the underlying 300 pps rate), whereas BiCI users could not.

By comparison to additional experimental conditions beyond the $0R$-like conditions tested by van Hoesel and Clark (1997) and others, we are able to elucidate two key features of this result. First, we confirmed that poor ITD sensitivity in the $0R$ task [as in the experiment of van Hoesel and Clark (1997)] is attributable to the lack of an onset ITD cue, as no such deficit was observed in condition $R0$. We are not the first to propose that the availability or lack of onset ITD dramatically shapes detection at high rates; many studies of dynamic-ITD sensitivity have specifically avoided including onset cues. Carlyon *et al.* (2008), in particular, speculated that the absence of onset ITD might explain their normal-hearing subjects' insensitivity to dynamic ITD at high rates, but did not test equivalent conditions that included onset ITD. Grantham and Wightman (1978), in contrast, directly compared detection of ITD modulation in noises with diotic and left-lateralized onsets, speculating that "precedence effects" might explain the advantage of lateralized onsets for detection at low ITD-modulation rates (<5 Hz). Second, we found that the rate-limited processing of ITD found in experiment 1—and consequent impairment on the 0*R* tasks at high rates—did not extend to ILD discrimination in experiment 2. This result is consistent with numerous reports of good ILD sensitivity among BiCI users (Long *et al.*, 2003; Laback *et al.*, 2004; Grantham *et al.*, 2008; Litovsky *et al.*, 2010), and is in at least partial agreement with recent observer-weighting studies of ITD and ILD sensitivity in NH listeners (Brown and Stecker, 2009) and BiCI users (van Hoesel, 2008), which have suggested a relatively greater salience of onset ITD than onset ILD carried by high-rate click or electrical-pulse trains.

C. Binaural adaptation in ITD and ILD

Effective coding of ongoing envelope ITD by the brain requires sufficient modulation of the responses of auditory neurons by fluctuations in the sound envelope, as the ITD is carried by the temporal alignment of those fluctuations across the two ears. In contrast, it would appear that coding of ILD should have no such requirement, as binaural intensity comparison might as easily be carried out for a steady tone as for a modulated one. Thus, the envelope filtering hypothesis of Bernstein and Trahiotis (2002) predicts a significant rate limitation for ongoing envelope ITD (since low-pass filtering the envelope diminishes the representation of high-rate amplitude fluctuations), but not for ILD. The current results are therefore consistent with that hypothesis. They are inconsistent, however, with previous reports that binaural adaptation affects sensitivity to the two cues identically (Hafter and Dye, 1983; Hafter *et al.*, 1983, 1990). This is a significant discrepancy which we cannot adequately explain at this time. It may, however, be useful to consider the differences between stimuli and tasks employed in these studies. Hafter and colleagues presented 4000-Hz narrowband impulse trains with static ITD and/or ILD, similar to condition *RR* of the present study. They found ITD and ILD discrimination thresholds to improve systematically with increasing duration from 1 to 24 clicks, consistent with multiple-looks theory (Hafter and Dye, 1983; Viemeister and Wakefield, 1991). The slope of threshold improvement with duration, however, was optimal only for an ICI of 12 ms. As ICI decreased from that value, improvement was increasingly limited. At very short ICIs (<2 ms), the functions were effectively flat, with similar performance for single clicks or long-duration trains (cf. Saberi and Perrott, 1995). Across studies, the slopes, and their dependence on ICI, were nearly identical for ITD (Hafter and Dye, 1983), ILD (Hafter *et al.*, 1983), and combinations of ITD and ILD (Hafter *et al.*, 1990).

By comparing thresholds across stimuli of varying duration, Hafter and Buell (1990) modeled the relative effectiveness (or *weight*) of each click in a train under the assumption that clicks are processed sequentially (i.e., that later clicks do not alter the processing of earlier clicks, and therefore that increasing duration improves performance due to the contribution of clicks added at the end of the stimulus). Equation (1), adapted from that study, expresses the weight for each click j in a train. The set of weights for all clicks defines a temporal weighting function (TWF) for a click-train stimulus. The analysis of Hafter and Buell (1990) revealed TWFs that were flat (equal weight on all clicks) for long values of ICI and became increasingly dominated by the onset click at shorter values of ICI. More recently, Stecker and Hafter (2002, 2009) measured TWFs for click trains presented in the free field, using a more direct "observer-weighting" procedure (Berg, 1989).[6] Similar to Hafter and Buell (1990), Stecker and Hafter (2002) found onset-dominated TWFs at 3-ms ICI. They additionally reported an "upweighting" of clicks near the offset (Stecker and Hafter, 2009), a feature not anticipated by the prior work. They explained the discrepancy by pointing out that TWFs estimated by Hafter and Buell (1990) depend strongly on the sequential-processing assumption and are therefore constrained to be monotonically non-increasing. The somewhat "U-shaped" TWFs described by Stecker and Hafter (2002, 2009) are inconsistent with that assumption, and suggest a possible reinterpretation of the prior data. Specifically, the data of Hafter and Dye (1983) and others are potentially consistent with a range of assumption-violating TWFs, such as U-shaped functions with sensitivity to *both* the onset and offset and insensitivity to intermediate portions of the sound (cf. Zurek, 1980; Houtgast and Aoki, 1994; Grantham, 1997; Akeroyd and Bernstein, 2001). Thus, the equivalence of a 2-click stimulus and a 16-click stimulus (at short ICI) might not reflect a reduced contribution of clicks 3–16 but rather the similar contribution made by potent onset and offset clicks in each case.

The current data provide a compelling case for strong onset dominance in the processing of ITD at high rates, while arguing against onset dominance for ILD. Instead, the data suggest either (1) uniform weighting of ILD across all clicks, such that similar performance is obtained regardless of which clicks carry the most informative cues, or (2) non-uniform weighting that nevertheless treats *R*0 and 0*R* stimuli equivalently. An important prediction of the uniform-weighting alternative is that thresholds should improve optimally with increasing duration. That hypothesis was not borne out by the data, with *RR* thresholds consistently falling above the "optimal" value of 1/4 of the single-click threshold ILDs. Instead, the data are more consistent with non-uniform weighting of ILD, with comparable sensitivity at onset and offset but degraded sensitivity to intermediate cues (cf. Stecker and Hafter, 2002, 2009). Non-uniform U-shaped weighting of ILD would treat *RR* stimuli as approximately equal to two clicks' worth of information (i.e., the onset ILD and offset ILD), thus restricting the improvement gained by multiple looks, while $R0$ and $0R$ stimuli would each be treated as approximately equal to one click. Although we cannot thoroughly evaluate the possibility of U-shaped temporal weighting of ILD based on the present data alone, this account would be consistent with upweighting reported in TWFs for localization of free-field stimuli carrying both ITD and ILD (Stecker and Hafter, 2002, 2009). U-shaped TWFs are also suggested by studies that measured threshold ITD and ILD for brief noise "probes" embedded in longer diotic noise "fringes" (Zurek, 1980; Houtgast and Aoki, 1994; Akeroyd and Bernstein, 2001). Finally, it may also be consistent with the reported equivalence of threshold-versus-duration slopes for ITD and ILD (Hafter and Dye, 1983; Hafter *et al.*, 1983), although evaluating that possibility will require specific quantitative models for TWFs in ITD and ILD.

One final consideration with respect to differences between the current study and those of Hafter and colleagues is the possibility that the data might reflect differences in the population of listeners tested and/or their experience with the task. Of note is subject 0601 described in the current study, who showed elevated ILD thresholds at an ICI of 2 ms in condition $0R$ of experiment 2. That result is consistent with some degree of onset dominance for ILD, which was expected but not observed among the other subjects. This is an experienced subject with consistently low ITD thresholds across these and other experiments in the laboratory. Although other experienced listeners (e.g., 0501) did not show the same pattern, it is possible that 0601's listening experience and/or underlying sensitivity may be correlated with more similar processing of ITD and ILD, and that a subpopulation of listeners with similar characteristics might have contributed more significantly in the work of Hafter *et al.* (1983, 1990). Along similar lines, Hafter and Jeffress (1968) described listeners' sensitivity to two distinct auditory "images" in ITD/ILD trading studies: a "time" image dominated by ITD and an "intensity" image combining ITD and ILD. They suggested that listeners may vary in their ability or propensity to make use of one or the other, and that with sufficient training, listeners can be made aware of both images. It is possible that differences in the utilization of these images might underlie some of the individual variation seen in this and other studies (e.g., McFadden *et al.*, 1973).

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[1]It is important to distinguish our focus on the relative potency of ITD carried by the onsets, offsets, and ongoing portions of sound from that of studies addressing the relative potency of "gating" or "transient" delays independent of delays carried by the stimulus' internal content. In a recent study of that type, Buell *et al.* (2008) introduced gating delays (which they termed "onset/offset delays") by imposing an interaurally delayed temporal envelope upon a sinusoidal AM stimulus carrying a separate interaural delay (the "ongoing delay" in their terms). The resulting stimuli combined envelope ITD resulting from the delayed modulator waveform with dynamic ILD resulting from delays in the onset and offset ramps. For whole-waveform delays (as encountered in typical listening situations and employed in the current study), "gating" delays necessarily coincide with envelope delays at onset and offset. Following the argument outlined by McFadden and Pasanen (1976), we refer to cues carried by the first arriving sound (the "first wavefront" in terms of free-field stimulation) as "onset" cues, those carried by the ongoing steady-state portion of a sound as "ongoing" cues, and those carried by the last arriving sound as "offset" cues. Note that this is quite different from the usage of terms "onset/offset" and "ongoing" by Buell *et al.* (2008). Detailed discussions of this distinction have been made previously by McFadden and Pasanen (1976) and Zurek (1993).

[2]The plausibility hypothesis of Rakerd and Hartmann (1985) suggests that when one cue becomes unreliable (for example, when ongoing ITD becomes distorted by the presence of echoes), listeners depend more strongly on the remaining reliable cues rather than mis-localizing on the basis of the distorted cue. By reducing the reliability of ongoing ITD cues, high modulation rates might cause listeners to weight the ILD cue more strongly. Since ITD studies typically employ an ILD of 0 dB, such a strategy would act to dilute the ITD cue regardless of whether the ITD cue suffers explicitly from inhibition, adaptation, or envelope filtering.

[3]If performance were based on the simple arithmetic mean of ITD across clicks (i.e., ignoring any nonlinearity of the decision variable or nonstationarity of variance), a twofold improvement over single-click would be expected, as the mean ITD in conditions $R0$ and $0R$ was half the peak ITD. For the geometric mean, a 1.6-fold improvement would be expected.

[4]An alternative interpretation, that rate limitation occurs for ILD but with a critical rate outside the tested range, may be considered. A critical rate lower than 100 Hz, for example, would imply rate-limited performance across all multi-click ILD conditions tested in the current study. In that case, the lack of difference between $R0$ and $0R$ thresholds suggests that rate limitation is not accompanied by increased onset dominance as it is for ITD. That interpretation is appealing but inconsistent with the results of Hafter *et al.* (1983), who demonstrated binaural adaptation for ILD over the same range of ICI tested by Hafter and Dye (1983) in their study of ITD.

[5]The equivalence of $R0$ and $0R$ threshold ILD values is consistent with uneven weighting of ILD information only if that weighting is approximately symmetric in time. For example, U-shaped temporal weighting of ILD which treats onsets and offsets similarly would predict similar thresholds for $R0$ and $0R$, but would produce suboptimal improvement in thresholds with stimulus duration.

[6]By measuring listeners' sensitivity to perturbation of each click simultaneously, the observer-weighting approach avoids comparing performance across stimuli of different duration. Thus, it avoids the sequential-processing assumption of Hafter and Buell (1990) that later clicks do not alter the processing of earlier clicks.

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