Temporal weighting of interaural time and level differences in high-rate click trains

Andrew D. Brown and G. Christopher Stecker^{a)}

Department of Speech and Hearing Sciences, University of Washington, 1417 NE 42nd Street, Seattle, Washington 98105

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Temporal weighting functions (TWFs), quantifying sensitivity to interaural time differences (ITD) and interaural level differences (ILD) over the duration of brief stimuli, were measured in 6 normal hearing subjects using trains of 16 Gabor clicks centered at 4 kHz presented dichotically at 4 rates [inter-click intervals (ICI) of 10, 5, 2.5, and 1.25 ms]. Random ITD or ILD were imposed independently on each click in the train in separate conditions. The subject's task was to discriminate the lateral position of the click train ("left" or "right"). Receiver operating characteristic (ROC) analysis was then used to quantify the effectiveness or "weight" of each click according to individual click ITD or ILD. Although individual differences were evident, onset cues appeared to dominate at high rates. Onset dominance was apparent for both ITD and ILD at 1.25 ms ICI and for ITD at 2.5 ms ICI, but for neither cue at 5 or 10 ms ICI. Onset dominance was greater on average for ITD than ILD, although TWFs were qualitatively similar for the two cues. No evidence was found for "upweighting" of late-arriving ILD [Stecker, G. C., and Hafter, E. R. (2009), *J. Acoust. Soc. Am.* **125**, 3914–3924]. © 2010 Acoustical Society of America. [DOI: 10.1121/1.3436540]

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I. INTRODUCTION

An extensive body of psychophysical evidence and mounting physiological evidence indicates that listeners localize sound sources in echoic environments by responding to the cues carried by early-arriving direct sound rather than the spurious cues carried by later-arriving reflected sound. The various phenomena associated with this observation are known collectively as the precedence effect (for reviews, see Blauert, 1997; Litovsky *et al.*, 1999). In the classic precedence paradigm, a pair of clicks simulating a direct source and single echo, hereafter referred to as the *lead* click and *lag* click, are presented from loudspeakers positioned to each side of a subject in the free field (Wallach *et al.*, 1949). The delay between the lead and lag is reduced until the subject perceives a single auditory event. This delay, typically 5–10 ms for clicks and up to 50 ms for running speech (see Litovsky *et al.*, 1999), is known as the echo threshold, the point of lead-lag *fusion*. At delays shorter than echo threshold, subjects localize the fused image in the direction of the lead (a phenomenon termed localization dominance), and are impaired in their ability to discriminate changes in the location of the lag (discrimination suppression). In some cases (e.g., trains of clicks in free-field localization tasks, Yang and Grantham, 1997), however, subjects are able to discriminate changes in the lagging sound despite strong fusion, suggesting that separate cues or different perceptual mechanisms might be utilized for different stimuli and listening tasks.

Click trains have been used to measure localization dominance and discrimination suppression over durations of

tens to hundreds of milliseconds (e.g., Saberi and Perrott, 1995; Freyman *et al.*, 1997). Such studies have demonstrated that, just as lead-lag click pairs are spatially fused at lead-lag delays shorter than around 5 ms (Litovsky *et al.*, 1999), click trains are spatially fused for inter-click intervals (ICI) in the same temporal range. Fusion has been shown to persist for up to several seconds at short ICI (e.g., 2 ms), giving rise to a single auditory event at the location cued by the first click of the train, despite tens or hundreds of "lag" clicks containing conflicting interaural information (Saberi and Perrott, 1995; Freyman *et al.*, 1997). This exaggerated salience of the onset click in relation to the ongoing clicks (termed *onset dominance*) has been quantified in several studies where the sensitivity of listeners' judgments to variation in spatial cues has been measured independently for each temporal portion of a stimulus (e.g., each click in a train), and plotted as a function of time to form a *temporal weighting function* (TWF). To date, TWFs have been measured for headphone interaural time difference (ITD) discrimination using narrow-band click trains (Saberi, 1996) and broadband noise bursts (Dizon *et al.*, 1998), free field localization using narrowband click trains (Stecker and Hafter, 2002, 2009), median-sagittal plane localization using directionally filtered noise bursts (Macpherson and Wagner, 2008), and ITD and interaural level difference (ILD) lateralization in bilateral cochlear implant (CI) users (van Hoesel, 2008). Consistent with other studies of precedence, a typical finding in TWF studies has been that, for high-rate stimuli (e.g., $\text{ICI} < 5$ ms), weights are high at onset and relatively low for the remainder of the stimulus. For lower-rate stimuli (e.g., $\text{ICI} > 5$ ms), weights are roughly equivalent for each portion of the stimulus, resulting in a "flat" TWF indicative of uniform binaural sensitivity over the stimulus duration. That is, onset dominance

^{a)}Author to whom correspondence should be addressed. Electronic mail: cstecker@u.washington.edu

has been evidenced at high rates, but not at lower rates, in agreement with maintained post-onset binaural sensitivity facilitating better discrimination performance at lower rates (e.g., [Hafter and Dye, 1983](#); [Bernstein and Trahiotis, 2002](#)).

A second feature observed in TWFs for sound localization in the free field ([Stecker and Hafter, 2002, 2009](#)) and in virtual acoustic space ([Macpherson and Wagner, 2008](#)) that is somewhat more difficult to relate to other studies of precedence is an increase in the weighting of information near the end of the stimulus. This TWF feature, termed “upweighting” by [Stecker and Hafter \(2002, 2009\)](#), was observed over a wider range of ICI (3–8 ms ICI) than was onset dominance (3 ms ICI only) in their study of free field localization ([Stecker and Hafter, 2002](#)). Although upweighting appears consistent with the effects of temporal integration in ITD detection in noise ([Zurek, 1980](#); [Akeroyd and Bernstein, 2001](#); see discussion by [Stecker and Hafter, 2009](#)), upweighting has not been observed in headphone ITD studies explicitly measuring ITD TWFs ([Saber, 1996](#); [Dizon et al., 1998](#); [van Hoesel, 2008](#)). That discrepancy led [Stecker and Hafter \(2002, 2009\)](#) to speculate that upweighting might be observed only in the presence of non-ITD cues (e.g., ILD and/or spectral cues), or alternatively, only in explicit localization (and not discrimination) tasks. [Macpherson and Wagner \(2008\)](#) reported upweighting in TWFs for localization of virtual acoustic space stimuli distributed in the median-sagittal plane. That result lends support to the notion that listeners may be sensitive to late-arriving spectral cues, but the possible contribution of post-onset ILD cues to localization of high-rate amplitude-modulated stimuli in azimuth is unclear.

Recent investigations have attempted to characterize the time course of listeners’ sensitivity to ILD (e.g., [van Hoesel, 2008](#); [Stecker and Brown, 2010](#)). [Stecker and Brown \(2010\)](#) demonstrated a profound impairment in high-rate ITD discrimination when click trains carried a diotic onset and dichotic offset (i.e., no interaural difference until after onset), but found no such impairment in ILD discrimination under corresponding conditions, suggesting equal sensitivity to ILD at onset and offset. Comparable sensitivity at onset and offset suggests either uniform sensitivity to ILD over the duration of the stimulus, or, alternatively, a combination of onset dominance and upweighting as seen in free field TWFs ([Stecker and Hafter, 2002, 2009](#)). In a study explicitly measuring TWFs in bilateral CI users, [van Hoesel \(2008\)](#) found that ILD after onset contributed more to listeners’ lateralization judgments than did ITD after onset (i.e., onset dominance was reduced for ILD), while neither cue appeared to produce upweighting. Bilateral CI users, however, generally show significantly higher overall sensitivity to ILD than ITD (e.g., [van Hoesel, 2004](#); [Grantham et al., 2008](#)); the time course of normal hearing sensitivity to ILD thus remains to be established. Different TWFs for ITD and ILD discrimination would seem to contradict the data of [Hafter and colleagues \(Hafter and Dye 1983, Hafter et al. 1983, 1990\)](#), which suggest comparably degraded post-onset sensitivity (termed “binaural adaptation”) for ITD and ILD, prompting [Hafter et al. \(1990\)](#) to propose a mechanism for adaptation common to both cues. Of course, even given such adapta-

tion, differences in ITD and ILD sensitivity could arise at subsequent stages of processing, and differences in the time courses of sensitivity to the cues might be undetectable in overall threshold measurements without careful stimulus design (for further discussion of this point, see [Stecker and Brown, 2010](#)). Moreover, substantial individual differences suggested in studies of ITD versus ILD sensitivity (e.g., [McFadden et al., 1973](#)) and in studies of onset dominance specifically ([Saber and Antonio, 2003](#); [Saber et al., 2004](#)) may complicate direct comparison of studies of ITD versus ILD sensitivity in different listeners, even when directly comparable stimuli have been employed. The present study aimed to address the foregoing issues by directly measuring TWFs for ITD and ILD discrimination in the same subjects.

II. 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.

A. Subjects

Six normal hearing subjects (0501, 0502, 0601, 0804, 0805, 0815) aged 21–36 participated in this experiment. Subjects 0601, 0804, 0805 and 0815 were naive to the purposes of the experiment and were compensated for their participation. Subjects 0501 and 0502 were the two authors. All subjects reported normal hearing and demonstrated pure-tone detection thresholds <20 dB HL over the range 250–8000 kHz.

B. Stimuli and procedure

Stimuli were trains of 16 Gabor clicks (Gaussian-windowed tone bursts). Each click consisted of a 4 kHz cosine multiplied by a Gaussian temporal envelope with $\sigma = 221 \mu\text{s}$. The resulting spectral bandwidth was also Gaussian, with $\sigma = 750 \text{ Hz}$ (half-maximal bandwidth $\sim 1.8 \text{ kHz}$). Clicks were synthesized at 48.848 kHz (Tucker-Davis Technologies RP2.1, Alachua FL) and presented using STAX model 4070 closed-back electrostatic headphones (STAX Ltd., Saitama, Japan). Click trains were presented with one of four peak-to-peak inter-click intervals (ICI) (1.25, 2.5, 5, or 10 ms ICI) at 65–74 dB SPL (65 dB SPL at 10 ms ICI–74 dB SPL at 1.25 ms ICI). A 4-button response box (TDT RBOX) recorded subject responses. Testing was completed in a double-walled sound booth (IAC, Bronx, NY). Each trial consisted of two equal-duration click trains separated by a 550-ms silent interval. The click train duration was dependent on the ICI. The first train, presented as a reference, was always diotic; the probe train followed, presented with one of three different “base” interaural values with additional interaural variation imposed on each click (see Fig. 1). Two separate conditions employed ITD and ILD cues.

The base interaural value was varied pseudo-randomly from trial to trial. In the ITD conditions, the base values were $-100, 0$, or $100 \mu\text{s}$; in the ILD conditions, the base values were $-1, 0$, or 1 dB^1 . By convention, negative ITD and ILD

FIG. 1. Schematic illustration of stimuli (not to scale). Each trial consisted of a diotic reference stimulus followed by a probe stimulus. The reference stimulus was comprised of 16 equal-amplitude Gabor clicks presented synchronously to the left and right earphones. Following a 550 ms silent interval (ISI), an ITD or ILD probe stimulus was presented, comprised of 16 Gabor click pairs with random ITD or ILD imposed on each. In the ITD probe, each click pair carried an ITD drawn from a uniform distribution of $\pm 100 \mu\text{s}$ about a base ITD of -100 , 0 , or $100 \mu\text{s}$ (0 in the above illustration); clicks were presented at equal amplitude to the two earphones in this condition. In the ILD probe, each click pair carried an ILD drawn from a uniform distribution of $\pm 2 \text{ dB}$ about a base ILD of -1 , 0 , or 1 dB (0 in the above illustration); clicks were presented synchronously to the two earphones in this condition. The inter-click interval (ICI), which corresponded to the rate of click presentation, was held constant within and between trials of a single run.

values led to or favored the left ear; positive ITD and ILD values led to or favored the right. Additional random ITD or ILD variation, drawn from a uniform distribution of $\pm 100 \mu\text{s}$ or $\pm 2 \text{ dB}$, was added independently to each click in a train. These ranges were selected to correspond roughly to the $\pm 11^\circ$ azimuthal variation employed by [Stecker and Hafter \(2002, 2009\)](#), based on the physical correspondence between azimuth, ITD, and ILD described by [Gulick et al. \(1989\)](#), and an ITD/ILD trading ratio of approximately $50 \mu\text{s}/\text{dB}$ ([Hafter and Jeffress, 1968](#)). Due to the per-click variation in ITD or ILD, trials with a base value of 0 carried nonzero interaural differences on each click, and thus a nonzero average ITD or ILD per trial.

The subject's task was to indicate via button press whether the probe stimulus was presented to the left or right of the reference stimulus. All subjects received training with immediate visual feedback until performance stabilized. Feedback was then turned off and testing began. One hundred trials comprised a single run; in each run, 60 trials had 0 base interaural difference, 20 were left-leading and 20 were right-leading. Base values were presented in random order over the course of each run; rate and cue type were randomized and counterbalanced between runs. Each subject completed four runs at each of the four ICIs in ITD and ILD conditions, giving 3200 trials in total ($400 \text{ trials} \times 8 \text{ conditions}$). Only 0 base trials were included in the TWF analysis ($1920 \text{ trials in total; } 240 \times 8 \text{ conditions}^1$).

C. Statistical methods

TWFs were computed following the logic of previous observer-weighting approaches (e.g., [Berg, 1989](#); [Saber, 1996](#); [Stecker and Hafter, 2002](#)). In the present investigation,

weights were computed using a receiver operating characteristic (ROC) analysis to quantify the accuracy with which listener responses could be predicted on the basis of interaural differences applied on each trial. For example, the "weight" of click #1 in a particular ITD condition for a particular subject was determined by classifying the subject's responses (one "left" or "right" response per trial) on the basis of the values of ITD applied to click #1 (the decision variable); an ROC curve was generated by plotting hits (probability of classification "left" given the subject responded "left") versus false alarms (probability of classification "left" given response "right") for all presented criterion values of click #1 ITD (i.e., for ITD from $-100 \mu\text{s}$ to $+100 \mu\text{s}$). The area under the ROC (termed " AUC_1 " for click #1) can thus be construed as the weight assigned to click #1, since its value corresponds directly to the accuracy with which click #1 ITD predicts the subject's response, expected to range between chance ($\text{AUC}=0.5$), indicating zero weight, and perfect ($\text{AUC}=1$). To generate the TWF, this procedure was repeated separately for each click in the train (giving $\text{AUC}_2, \text{AUC}_3, \dots, \text{AUC}_{16}$). Note that this application of ROC analysis reverses the roles of stimulus and response variables relative to their usual roles in ROC analysis. Here, the analysis quantifies the accuracy with which stimulus values predict subject responses rather than the accuracy with which subjects discriminate stimulus values (see Section IV C and Fig. 5 for further discussion of the use of ROC analysis in the present study). An additional analysis classified subject responses using the mean ITD or ILD across clicks in a train as the decision variable. The resulting AUC (termed " AUC_{mean} ") describes the performance of a classifier that explicitly averages the ITD or ILD of all clicks in the train, after multiple-looks theory (cf. [Viemeister and Wakefield, 1991](#)). Note that AUC_{mean} is *not* the average of $\text{AUC}_1 \dots \text{AUC}_{16}$. Comparing AUC_1 against AUC_{mean} (i.e., $\text{AUC}_1 - \text{AUC}_{\text{mean}}$) thus provides a measure of onset dominance, since onset dominance entails salience of onset cues over the long-term interaural value (cf. [Saber and Perrot, 1995](#)), where optimal performance in this task is facilitated by a cue-averaging strategy that minimizes decision variance ([Saber, 1996](#)). A final analysis classified responses using only the maximum leftward or rightward interaural difference of each trial as the decision variable. The resulting AUC (hereafter " AUC_{max} ") describes the performance of a classifier dominated by the most lateral click in a train, irrespective of that click's temporal position (see Section IV B). $\text{AUC}_1 \dots \text{AUC}_{16}$, AUC_{mean} and AUC_{max} were computed separately for each combination of subject, ICI and cue type (ITD or ILD) and subsequently compared in several null-hypothesis tests described in the following sections.

Statistical confidence intervals on weight estimates were generated using a permutation test (e.g., [Moore and McCabe, 2005](#)). For each combination of subject and condition, subject's responses were randomly permuted across trials, and a TWF generated following the AUC procedure described above. This procedure was repeated 1000 times; the standard deviation of estimated weights across repetitions was then used to estimate the standard error and to generate 95% statistical confidence intervals for each weight estimate. For the

Averaged Temporal Weighting Functions

FIG. 2. Temporal weighting functions (TWFs) averaged across subjects for ITD (left column) and ILD (right column) conditions for each inter-click interval (ICI) (rows). Within each panel, per-click ITD or ILD weights ($AUC_1 \dots AUC_{16}$, filled circles) are plotted against click number to form the TWF; the weight of the mean ITD or ILD (AUC_{mean} , dashed line) and the maximum ITD or ILD (AUC_{max} , cross) are plotted for comparison (see text). The shaded region plots the range of chance classification (see text).

purpose of illustration, and because standard errors did not vary systematically with click position (ranging less than 0.002 across the train), summary 95% confidence intervals were computed from the mean standard error across clicks for each combination of subject and condition, indicated by gray shading around the chance performance level ($AUC = 0.5$) in Fig. 3. Similar confidence intervals are shown for the group-mean TWFs in Fig. 2.

III. RESULTS

A. Temporal weighting functions for ITD and ILD

Figure 2 displays TWFs averaged across subjects for each of the eight conditions tested. Filled circles plot the AUC obtained using each click ITD or ILD ($AUC_1 \dots AUC_{16}$), the dashed lines plot the AUC obtained using average click train ITD or ILD (AUC_{mean}), and the crosses plot the AUC obtained using maximum ITD or ILD within each click train (AUC_{max}). The shaded region plots the range of chance classification (95% CI of $AUC = 0.5$), as described above. Overall, AUC_1 decreased with increasing ICI in both the ITD and ILD conditions. A monotonic increase in AUC_{mean} (dashed line) with increasing ICI was also observed in both the ITD and ILD conditions. Onset dominance, indicated by $AUC_1 > AUC_{mean}$, was apparent for ITD at ICI values of 1.25 and 2.5 ms, but only at 1.25 ms ICI for ILD. Although the overall shape of the TWF for ILD at 2.5 ms was similar to that for ITD, the mean ILD appeared to be the best overall predictor of subjects' responses in that condition; that is, although AUC_1 exceeded the values of $AUC_2 \dots AUC_{16}$, it did not exceed the value of AUC_{mean} .

Related to this point, the value of AUC_{mean} for ILD was greater than the value of AUC_{mean} for ITD at all ICI (averaged AUC_{mean} values at 1.25, 2.5, 5 and 10 ms ICI for ILD = 0.63, 0.67, 0.68, 0.69; for ITD = 0.58, 0.61, 0.65, 0.67; also see Fig. 4). Consistent with previous studies (Saberi, 1996; Stecker and Hafter, 2002), no onset dominance was evidenced at 5 ms or 10 ms ICI for either cue ($AUC_1 < AUC_{mean}$), and weights were nearly equal across clicks at 10 ms ICI. Finally, the value of AUC_{max} was less than the value of both AUC_1 and AUC_{mean} across conditions (see Section IV B). Taken together, the averaged TWFs suggest onset dominance for both ITD and ILD at short ICI, with a possible reduction in onset dominance for ILD relative to ITD, attributable specifically to greater cue-averaging for ILD. The data do not suggest "upweighting" for ILD, as proposed by Stecker and Hafter (2002, 2009).

Figure 3 displays TWFs for individual subjects across each of the eight conditions tested (legend as in Fig. 2). Substantial intersubject variability is evident, with the data of subjects 0501, 0502, 0601 and 0815 generally in agreement regarding the effects of ICI and cue type on onset (AUC_1) and mean (AUC_{mean}) weights, but the data of subjects 0804 and 0805 diverge from this common pattern. Most strikingly, neither 0804 nor 0805 exhibited onset dominance in the ITD condition. This result is inconsistent with past studies which have measured TWFs for ITD discrimination (Saberi, 1996; Dizon et al., 1998) and with the TWFs of other subjects in the present investigation. It is, however, consistent with the individual variability in ITD discrimination suppression observed by Saberi and Antonio (2003) in a population study of the precedence effect, which suggested that onset dominance in ITD discrimination occurs for most but not all listeners. Both subjects 0804 and 0805 reported that it was often difficult to lateralize the ITD stimulus. Our initial assumption was that these subjects simply had higher overall ITD discrimination thresholds and thus lacked sensitivity to $\pm 100 \mu s$ ITD variation about the midline. Thus, we attributed their unique TWFs to lower overall ITD sensitivity rather than to different time courses of sensitivity, and, accordingly, attempted testing both subjects with a greater number of suprathreshold ITD clicks per trial by increasing levels of ITD variation to $\pm 200 \mu s$ and subsequently $\pm 150 \mu s$. For both manipulations, the subjects reported that the probe sounded "broken up," but no easier to lateralize. The perception of "broken" spatial fusion in this context is most interesting, as it might be construed to imply that these subjects actually were sensitive to the presented ITD but, in the absence of onset dominance, perceived a diffuse image centered at the midline, reflecting the expanded range of left- and right-leading ITD. Nonetheless, since the wider range of ITD variation resulted in a percept that was qualitatively different from the spatially fused images perceived by other subjects with less ITD variation, we elected to proceed with $\pm 100 \mu s$ variation for all subjects, similarly maintaining ± 2 dB variation for all subjects in the ILD conditions. Subjects 0804 and 0805 did not report difficulty lateralizing the ILD probe, and their data agreed more closely with the averaged TWFs in that condition. Whether subjects 0804 and 0805 simply had higher ITD than ILD thresholds (McFadden

FIG. 3. Temporal weighting functions for individual subjects. Legend as in Fig. 2.

et al., 1973) or were rather more similar to listeners lacking onset dominance in ITD discrimination (Saber and Antonio, 2003) is a matter that cannot be definitively resolved in the present investigation since sensitivity was not measured, although additional intersubject variability in ILD TWFs (see Section III B.) may lend support to the latter idea.

Importantly, upweighting was not observed in any of the conditions tested. The suggestion of Stecker and Hafter (2002, 2009) that upweighting might be attributable to ILD sensitivity near stimulus offset is clearly not supported by the present data. The prediction of upweighting in this experiment would be for AUC values near the end of the train to exceed other post-onset AUC values and perhaps even AUC_1 at 5 ms ICI. In all of the conditions tested, for both ILD and ITD, AUC_1 invariably exceeded AUC_{16} . Thus, contrary to the suggestion of Stecker and Hafter (2002, 2009), the time course of ILD sensitivity does not appear to feature upweighting. Rather, TWFs measured by the present method for both ITD and ILD are consistent in terms of individual click weights with those described by Saber (1996) for ITD lateralization and by van Hoesel (2008) for ITD and ILD lateralization by bilateral CI users, with high onset weights followed by relatively low and uniform post-onset weights at short ICI. Possible differences in the TWFs for ITD versus ILD (van Hoesel, 2008)—specifically, the apparently higher

salience of post-onset ILD than ITD suggested by higher weighting of mean ILD than mean ITD—are considered below.

B. Reduced onset dominance for ILD

Although averaged TWFs (Fig. 2) for ITD and ILD appeared similar in terms of *individual* click weights, mean ILD appeared to be a more salient cue than mean ITD at all ICI, and a more salient cue than onset ILD at $ICI > 1.25$ ms, suggesting that the salience of onset ILD may be tempered by the salience of the mean ILD even at short ICI, while onset ITD remains dominant over mean ITD at short ICI. Clear intersubject variability was present in individual TWFs (Fig. 3) for both ITD and ILD conditions, however, warranting further treatment. Of the four subjects demonstrating clear onset dominance for ITD at 1.25 and 2.5 ms ICI, two (0502 and 0815) exhibited no onset dominance for ILD regardless of ICI, while one (0501) demonstrated onset dominance for ILD at 1.25 ms only. One subject (0601) demonstrated onset dominance for ILD at both rates, but also relatively greater weighting of the mean ILD at those rates than in the corresponding ITD conditions. As noted above, the data of subjects 0804 and 0805 differed from the mean data. Subject 0805 was particularly divergent from the oth-

FIG. 4. Cross-subject averages of $AUC_1 - AUC_{mean}$ against inter-click interval (ICI) for ITD (black) and ILD (gray) conditions. Error bars indicate one standard error of the mean. Data suggested a shift from onset dominance at high rates to cue-averaging at low rates, with greater cue-averaging for ILD than ITD.

ers, exhibiting the greatest degree of onset dominance among any subject at 1.25 ms ICI in the ILD condition, while exhibiting no onset dominance in ITD conditions and greater AUC_{mean} values for ITD than ILD at all rates. Bearing in mind the possible importance of individual differences discussed heretofore, the overall observation that subjects exhibited onset dominance at high rates, but to a reduced degree for ILD compared to ITD (particularly at 2.5 ms ICI), is broadly consistent with the studies of [van Hoesel \(2008\)](#) and [Stecker and Brown \(2010\)](#), as well as with the interpretation of results presented by [Saber et al., \(2004\)](#), which suggested onset dominance may be more effective in ITD than ILD discrimination.

Figure 4 plots a derived measure of onset dominance, $AUC_1 - AUC_{mean}$, across ICI for both ITD and ILD (averaged across subjects). $AUC_1 - AUC_{mean}$ for ITD exceeded that for ILD at all ICI, anticipated from the observation that AUC_{mean} was greater for ILD than ITD at all ICI (see Fig. 2), although the difference was minimal at 1.25 and 10 ms ICI. With the caveat of individual differences, the cross-subject effects of ICI and cue type on $AUC_1 - AUC_{mean}$ were submitted to a 4×2 repeated measures ANOVA. The main effect of ICI was significant [$F(3, 15) = 17.53$, $p < 0.05$], while neither the main effect of cue type [$F(1, 5) = 3.64$, $p = 0.115$] nor the ICI by cue type interaction [$F(3, 15) = 1.20$, $p = 0.344$] were significant, doubtless the result of a large subject-by-cue type error term arising from the disparity of subjects 0804 and 0805 and the others. Although performing the analysis without these “divergent” subjects did yield a significant main effect of cue [$F(1, 3) = 26.89$, $p < 0.05$]—a result consistent with reduced onset dominance in ILD relative to ITD ([van Hoesel, 2008](#); [Stecker and Brown, 2010](#))—the work of [Saber and colleagues \(Saber and Antonio, 2003; Saber et al., 2004\)](#) suggests that the large subject-by-cue type “error” term may actually represent significant natural variation in the time course of ITD versus ILD sensitivity among the

general population. These findings are discussed further with respect to the hypotheses of binaural adaptation and up-weighting in the following sections.

IV. DISCUSSION

A. Onset dominance for ITD and ILD

The present investigation suggests that normal hearing listeners are more sensitive to the ITD or ILD carried by the onset of a rapidly fluctuating signal envelope than to the ITD or ILD carried by any discrete post-onset portion of the signal, consistent with previous studies of the precedence effect and related phenomena (e.g., [Wallach et al., 1949](#); [Zurek, 1980](#); [Haft et al., 1990](#); [Saber, 1996](#)); ITD or ILD presented at the onset of a brief 16-click train was found to be more predictive of subjects’ discrimination judgments than ITD or ILD presented in any of the 15 subsequent clicks at $ICI \leq 5$ ms. The present results additionally suggest, however, that listeners’ lateralization of rapidly fluctuating signal envelopes carrying ILD is influenced by the mean signal ILD; the influence of mean click train ILD exceeded that of onset ILD at 2.5 ms ICI on average. This was not true for ITD, and mean ILD was a better predictor of subjects’ responses than mean ITD across the four tested ICI for all but one subject. This finding compares favorably to TWFs measured for ITD and ILD lateralization in bilateral CI listeners ([van Hoesel, 2008](#)), although larger differences between ITD and ILD were reported in that study, and substantial intersubject variability was noted in the present study, with one subject in particular (0805) displaying a pattern exactly the opposite of other subjects—an observation consistent with previous reports of variable onset dominance in both ITD and ILD discrimination among the general population ([Saber and Antonio, 2003](#); [Saber et al., 2004](#)).

The present investigation is the first report, to our knowledge, of ILD TWFs for normal hearing listeners. Previous TWF investigations in normal hearing listeners have indicated near-complete onset dominance for high-rate stimuli carrying ITD ([Saber, 1996](#); [Dizon et al., 1998](#)), and strong onset dominance for high-rate free field stimuli carrying both ITD and ILD ([Stecker and Haft, 2002](#)). Pairing our results with existing findings suggests that onset dominance in the free field reflects sensitivity to both ITD and ILD in the early-arriving sound, consistent with previous studies of binaural adaptation for ITD and ILD (e.g., [Haft and Dye, 1983](#); [Haft et al., 1983](#)). Reduced onset dominance for ILD relative to ITD in the majority of our subjects (specifically, higher weighting of mean ILD than mean ITD), however, suggests that sensitivity to ILD must persist at some level over the duration of the stimulus. This interpretation is inconsistent with the suggestion of equal binaural adaptation for ITD and ILD arising from a single mechanism ([Haft et al., 1990](#)), but is consistent with the “level-meter” hypothesis of [Hartmann and Constan \(2002\)](#), which posits that ILD sensitivity entails a running integration of interaural intensive differences over the duration of the stimulus.

In spite of better sensitivity to ILD than ITD over the duration of the stimulus, upweighting for ILD, as proposed by [Stecker and Haft \(2002, 2009\)](#), was clearly not present

in the measured TWFs; an interesting interpretation of the results of [Stecker and Brown \(2010\)](#) may be given in this context: Although equivalent thresholds for ILD detection at stimulus onset and offset reported in that study could arise from an elevation of sensitivity at onset and again at offset (cf. [Stecker and Hafter, 2002](#)), the same results can be explained by sensitivity to the *mean* ILD, since the mean ILD information available was identical in the onset and offset ILD conditions of that study.

A final consideration is that the several investigations discussed here, which have sampled small numbers of subjects, may appear to offer partially conflicting results because, in fact, the time course of sensitivity to binaural cues varies significantly among normal hearing individuals ([Sabeti and Antonio, 2003](#); [Sabeti et al., 2004](#)). The importance of careful attention to individual differences in studies of this type rather than exclusive emphasis on group statistics might thus be underscored; the question of why the seemingly low-level process of onset dominance (cf. [Hafter et al., 1990](#)) would vary among normal hearing listeners is a fascinating one which certainly cannot be addressed by discussing what “typical” subjects do.

B. Cue-averaging versus sensitivity to peak interaural value

In several conditions, elevated values of AUC_{mean} were observed despite low values for individual click weights. We have interpreted this result as evidence for cue-averaging in those conditions. Importantly, the relatively greater AUC_{mean} values for ILD versus ITD suggest a greater role for cue-averaging in ILD than ITD in the majority of our subjects. An alternative interpretation, however, might be that judgments reflected a minority of clicks which carried large interaural differences but which varied in temporal position from trial to trial (e.g., the *peak* interaural value on each trial). In that case, low individual-click weights would reflect the low probability (1/16) that the peak value occurred at a given click number, and the high value of AUC_{mean} would reflect the strong influence of these outlying values on the mean ITD or ILD across clicks, rather than cue-averaging by the subjects (note that such an account would still imply sensitivity to post-onset clicks, despite the lack of explicit cue-averaging). We examined this possibility by computing AUC_{max} , classifying subject responses on the basis of the maximum ITD or ILD occurring on each trial. AUC_{max} values are plotted as crosses in Figs. 2 and 3, where they appear consistently lower than both AUC_{mean} and AUC_1 . A $2 \times 4 \times 2$ repeated measures ANOVA with factors of measure (AUC_{mean} versus AUC_{max}), ICI, and cue type confirmed that AUC_{mean} was a significantly better predictor of subject response than AUC_{max} [$F(1,5)=184.81$, $p<0.05$], indicating that maximum interaural values did not account for the salience of the mean. Indeed, the value of AUC_{max} across conditions and rates was similar to the AUC values of individual post-onset clicks (i.e., $AUC_2 \dots AUC_{16}$), as would be expected under the null hypothesis since the long-term AUC_{max} samples, on average, each click position equally. In contrast, AUC_{mean} increased monotonically with increasing ICI, giv-

ing rise to a significant measure by ICI interaction [$F(1,5)=9.93$, $p<0.05$], consistent with better cue-averaging as subjects gained sensitivity to the interaural information in each click at slower rates.

C. ROC analysis for TWFs

The application of ROC analysis in the present investigation differs from its usual application and from previous approaches to observer weighting analysis such as COSS analysis ([Berg, 1989](#); [Sabeti, 1996](#)), linear regression ([Stecker and Hafter, 2002](#); [Macpherson and Wagner, 2008](#); [van Hoesel, 2008](#)), and point-biserial correlation ([Richards and Zhu, 1994](#); [Lutfi, 1995](#)). In such studies, computed weights have conventionally been normalized to some standard referent (e.g., the weight of the onset, [van Hoesel, 2008](#)) and thenceforth presented as “relative weights.” Normalized weights can then be evaluated in terms of relative salience (i.e., the perceptual weight of a stimulus component relative to other components) and, normalized for each subject, are amenable to intersubject comparisons. Raw computed weights are more cumbersome in their interpretation (e.g., in COSS analysis, [Sabeti, 1996](#)) and may differ in magnitude between subjects (e.g., [Stecker and Hafter, 2002](#)). Thus, an immediate advantage of ROC analysis is that it produces raw weights which can be interpreted directly and compared across conditions and across subjects without normalization. Specifically, computed AUC values in the present investigation correspond to the degree to which particular stimulus features predicted the listener’s response (i.e., proportion correct classification of responses). This use of ROC analysis resembles previous applications of ROC analysis to neural data, where it has been used to assess the degree to which a neural response measure (e.g., spike count) correctly predicts the stimulus eliciting that response (e.g., [Skottun et al., 2001](#)). Importantly, the interpretation of AUC weights does not change with the statistics of the feature used for classification. Here, we used three types of features: (1) ITD or ILD imposed on single clicks in the train ($AUC_1 \dots AUC_{16}$), (2) the mean ITD or ILD across clicks in a train (AUC_{mean}), and (3) the largest click ITD or ILD imposed in each train (AUC_{max}). Regarding (2) specifically, ROC analysis produces, by the same procedure applied in (1) and (3), a “cue-averaging” weight which can be directly compared to individual click weights—a parsimonious means of evaluating the salience of mean ITD or ILD.

Figure 5 displays two example ROC plots generated by the present method (subject 0502, ILD condition, 5 ms ICI, ROC for click #1 [left panel] and mean ILD [right panel]). Note that ROC curves were not interpolated; rather, in this example, the ROC was given by the accumulation of “hits” ($ILD < \text{criterion } c$ for response “Left”) and “false alarms” ($ILD < \text{criterion } c$ for response “Right”) for the 240 trials with 5 ms ICI and 0 dB base ILD as the criterion c was adjusted across all presented values of ILD. The AUC was computed directly by numerical integration, corresponding in this case to the percent correct classification of subject 0502’s responses by click #1 ILD (left) and mean ILD (right). To ascertain that the ROC method of weight estima-

Weight Estimation by ROC Analysis

FIG. 5. Two ROC plots generated by the present method (subject 0502, ILD condition, 5 ms ICI, for click #1 ILD [left panel] and mean ILD [right panel]). In this example, the ROC was given by the accumulation of hits ($\text{ILD} < \text{criterion } c$ for response “Left”) and false alarms ($\text{ILD} < \text{criterion } c$ for response “Right”) as the criterion c was adjusted across all presented values of ILD, plotted as probabilities ranging from 0 to 1. The AUC, computed by integrating the ROC with respect to false-alarm probability, gives the percent correct classification of responses by the ILD of click #1 (left) and the mean ILD of the click train (right). The same procedure was applied for each combination of subject, condition, and classifier to generate the AUC weights given throughout the paper.

tion was comparable to a more conventional method, we also computed TWFs using logistic regression. The resulting logistic TWFs did not differ qualitatively from those computed using ROC analysis, but lacked both the simplicity of interpretation and parsimony provided by the ROC method. We thus suggest that the ROC method may be a useful approach in future studies of observer weighting employing discrimination paradigms.

D. Cues in agreement versus cues in conflict

In considering the differences between TWFs measured in the free field by [Stecker and Hafter \(2002, 2009\)](#) and those measured in this and other studies where ITD or ILD were manipulated exclusively (e.g., [Sabeti, 1996](#); [van Hoesel, 2008](#)), it should be kept in mind that free field stimulation presents ITD and ILD in agreement, whereas the current and related headphone studies present a situation in which the two cues conflict (i.e., a dichotic ITD or ILD combined with a diotic ILD or ITD). Although a number of studies have investigated binaural sensitivity to various combinations of ITD and ILD in conflict and agreement (e.g., [Haft and Jeffress, 1968](#), [Haft et al., 1990](#)), little is known about the possible effects of cue conflict on the temporal integration of individual binaural cues. While it seems unlikely that the effect of cue agreement versus conflict could give rise to drastically different TWFs (i.e., the presence or absence of upweighting), the notion of combination-dependent changes in sensitivity to one cue over the other is generally consistent with the “plausibility hypothesis” of [Rakerd and Hartmann \(1985\)](#).

E. Possible effects of the task employed

One explanation for upweighting in TWFs measured by [Stecker and Hafter \(2002, 2009\)](#) concerns the nature of the task employed in the estimation of TWFs. [Stecker and Hafter \(2002, 2009\)](#) measured TWFs for free field localization by asking subjects to point to the location of click trains comprised of clicks presented randomly from speakers in an array about the subject; TWFs were then computed by multiple linear regression (per-click “slope” plotted against click number). Free field localization is different than intracranial lateralization (e.g., [Plenge, 1974](#)), and a number of studies

have suggested additional important differences between explicit localization (or lateralization) versus discrimination of binaural stimuli ([Bernstein and Trahiotis, 1994](#); [Buell et al., 1994](#); [Tollin and Henning, 1998](#)). [Stecker and Hafter \(2002, 2009\)](#) thus suggested that the difference between orienting to a sound source and simple discrimination might underlie differences in TWFs for localization ([Stecker and Hafter, 2002, 2009](#); [Macpherson and Wagner, 2008](#)) versus discrimination tasks (e.g., [Sabeti, 1996](#))—specifically, the finding of clear upweighting in the former case versus no upweighting in the latter case. That is, they speculated that upweighting might reflect the operation of memory mechanisms (e.g., temporal integration) required for programming motor responses in an explicitly spatial reference frame, but not for other types of tasks. The current results are consistent with that view in that discrimination of either cue presented over headphones failed to produce upweighting. Future work explicitly comparing TWFs across multiple tasks could provide further insight on such discrepancies in the literature.

F. The range of interaural variation

A final but critical consideration is whether the nature of interaural variation across clicks exerted any influence on the measured TWFs. For example, a restricted range of variation would be expected to result in less sensitivity to TWF features (such as onset dominance or upweighting) than would a larger range of variation. Too large a range of variation, however, could cause the auditory image to become diffuse, as indeed occurred when we increased the range of ITD variation for subjects 0804 and 0805 (see Section III A). Interaural variation in the current study utilized a uniform distribution spanning $\pm 100 \mu\text{s}$ of ITD or $\pm 2 \text{ dB}$ of ILD. Those ranges were selected to correspond roughly to the $\pm 11^\circ$ azimuthal variation employed by [Stecker and Hafter \(2002, 2009\)](#), based on acoustic measurements of ITD and ILD ([Gulick et al., 1989](#)). The ITD range was also roughly similar to that employed by [Sabeti \(1996\)](#), who employed Gaussian distributions of ITD with $\sigma = 100 \mu\text{s}$. The similarity of TWFs obtained in that study and the current report suggest that the range of ITD variation was sufficient for the stated purpose. Likewise, the onset dominance observed at 1.25 ms

ICI in the ILD condition suggests that the ILD range was similarly sufficient for detection of non-uniform TWFs. Thus, reduced onset dominance at longer ICI and the failure to observe upweighting does not reflect insensitivity of the method due to insufficient cue variation.

V. SUMMARY AND CONCLUSIONS

The current study measured the time course of ITD and ILD sensitivity in the same subjects in order to directly compare TWFs for the two cues. Such comparisons are necessary to address conflicting reports that suggest, on the one hand, similar time courses (specifically, onset dominance) for the two cues, and, on the other, limited onset dominance for ILD. The findings of the current study suggest the following conclusions.

- (1) Consistent with prior studies, discrimination of ITD in high-rate (short ICI) click trains was dominated by the ITD of the onset click. For $ICI \geq 5$ ms, ITD discrimination appeared to follow the average ITD across clicks.
- (2) Discrimination of ILD followed a pattern qualitatively similar to discrimination of ITD, but strong onset dominance was restricted to the shortest ICI tested (1.25 ms), and cue-averaging appeared more robust for ILD than for ITD.
- (3) Substantial intersubject variability in (1) and (2) was evident, suggesting onset dominance for ITD and ILD occurs to varying degrees across listeners, consistent with the reports of Saberi and Antonio (2003) and Saberi *et al.* (2004).
- (4) The similar pattern in individual click weights for ITD and ILD is consistent with studies reporting similar time-courses of sensitivity to the two cues (Zurek, 1980; Hafter and Dye, 1983; Hafter *et al.*, 1983), but the apparently more effective averaging of post-onset ILD than ITD suggests temporally different processing of the cues at some level of the auditory system.
- (5) Neither ITD nor ILD TWFs showed “upweighting” of late-arriving sound (Stecker and Hafter, 2002, 2009), contradicting the hypothesis of Stecker and Hafter (2002, 2009) that upweighting observed in free-field localization reflects a specific contribution of late-arriving ILD.
- (6) Thus, the discrepancy between free field and headphone TWFs is likely not explained by the simple difference in binaural cues available. Rather, the discrepancy might relate to differences between conflicting and congruent cues, spectral cues, differences in the task employed, or differences in the externalized vs. intracranial perception of the sounds. Future work should address these possibilities.

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¹AUC values (and thus TWFs) were computed and compared only on trials where the base ITD or ILD was 0. Trials presented with nonzero base ITD and ILD were included in the experiment to mediate the perceived task difficulty and to provide a basis for feedback during training. Although per-click variation in ITD or ILD was likely effective in biasing the *degree* of lateralization perceived, our discrimination task was inherently insensitive to gradations of lateralization; nonzero base trials, being in general strongly lateralized according to the sidedness of the base, were instead useful in sustaining vigilance between 0 base trials (on which biasing across the midline could be measured), and in ascertaining that subjects could perform the task at the outset of the experiment. Mean values for nonzero base conditions (± 1 dB ILD, ± 100 μ s ITD) were selected to produce approximately equivalent lateralization in both conditions.

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