Detection of dynamically varying interaural time differences

Kohlrausch, Armin; Le Goff, Nicolas; Breebaart, Jeroen

Published in:
Proceedings of 20th International Congress on Acoustics 2010, ICA 2010 - Incorporating Proceedings of the 2010 Annual Conference of the Australian Acoustical Society

Publication date:
2010

Document Version
Early version, also known as pre-print

Citation (APA):
Kohlrausch, A., Le Goff, N., & Breebaart, J. (2010). Detection of dynamically varying interaural time differences. In Proceedings of 20th International Congress on Acoustics 2010, ICA 2010 - Incorporating Proceedings of the 2010 Annual Conference of the Australian Acoustical Society (pp. 3292-3297). International Congress on Acoustics.

Proceedings of 20th International Congress on Acoustics, ICA 2010

23–27 August 2010, Sydney, Australia

Detection of dynamically varying ITDs

Armin Kohlrausch (1,2), Nicolas Le Goff (2,3) and Jeroen Breebaart (1)

(1) Philips Research Europe, Eindhoven, The Netherlands
(2) Human Technology Interaction, Eindhoven University of Technology, Eindhoven, The Netherlands
(3) Centre for Applied Hearing Research, Technical University of Denmark, Lyngby, Denmark

PACS: 43.66Pn, 43.64Bt, 43.66Ba

ABSTRACT

Humans are highly sensitive to Interaural Time Differences (ITDs) in stimuli presented via headphones. For broadband noise stimuli of long durations, ITD detection thresholds can be as low as 10 to 15 μs. When the stimulus duration is shortened, thresholds increase by about a factor 2 for a tenfold decrease in duration. ITD thresholds also increase, when the probe carrying an ITD is surrounded by diotic fringes. When a 5-ms probe is combined with preceding or trailing fringes, the effect of a fringe preceding the probe is stronger than that of a trailing fringe for fringe durations $<$ 35 ms. The effect of fringes surrounding the probe is equal to the addition of the effects of the individual fringes. In this contribution, we present behavioral data for the same experimental condition, called dynamically varying ITD detection, but for a wider range of probe and fringe durations. Probe durations varied between 5 and 400 ms, and fringe durations had values of 5, 20, 100 or 200 ms. In contrast to earlier findings, we observed for most duration combinations a stronger effect of the trailing fringe than of the preceding fringe. For these configurations, the effect of surrounding fringes was dominated by the trailing fringe. Only for the combination of 5-ms fringes with 5-ms probes did we see the clear dominance of the preceding fringe. These results are not easy to align with the concept of onset emphasis often used to explain binaural localization data for short stimuli. In fact the data seem to be difficult to predict with a purely signal-driven model of perception and thus form an interesting challenge for modeling human localization.

INTRODUCTION

Experiments investigating the sensitivity to interaural differences in arrival time (Interaural Time Differences, ITDs) or level (Interaural Level Differences, ILDs) are usually performed by applying the same value of the interaural parameter over the full duration of the stimulus. For such a condition it has been shown that, with increasing stimulus duration, the threshold value for detecting the presence of an ITD decreases (Hafter *et al.* 1979). ITD detection has, however, also been studied with diotic fringes surrounding the signal that carries the ITD (the probe), a condition that is sometimes referred to as dynamic ITD detection (e.g., Bernstein *et al.* 2001). In this article, we will also investigate the effect of such diotic fringes on ITD detection conditions, but in contrast to previous studies which mostly used rather short stimuli, we evaluate the influence of such fringes for longer durations.

The paradigm used in our experiments is closely linked to hypotheses, how the onset and the ongoing parts of a stimulus contribute to the percept of lateralization. Houtgast and Plomp (1968) had suggested that the weak dependence of ITD thresholds on stimulus duration (in the range 10 to 1000 ms) was due to the fact that the information carried by the onset of the stimuli contributed more to the perceived lateral position than the ongoing part. They also suggested that this phenomenon was the basis of the precedence effect. Zurek (1980) tested this hypothesis by conducting experiments on ITD (and ILD) discrimination where the onset of the stimuli did not necessarily carry any binaural information. He used a stimulus of 50-ms duration, of which only a 5-ms portion (which will be called probe in this paper) had an ITD, while the remaining preceding or trailing parts where presented diotically. The detection performance was poorest when the probe was located about 10 ms after the onset of the stimuli. Furthermore, a forward fringe (fringe preceding the probe) of 45-ms duration had a stronger effect than a backward (trailing) fringe of the same duration. The results from Zurek's study and a later one by Houtgast and Aoki (1984) were explained by proposing a post-onset-weighting function which combines both an emphasis of the onset part and a brief attenuation about 5 ms after signal onset.

Bernstein *et al.* (2001) and Akeroyd and Bernstein (2001) further investigated the role of fringes in ITD (and ILD) detection conditions. In the first paper the sensitivity to brief changes of the ITD was studied using broad-band noise stimuli. Thresholds were measured for probes in isolation, and for probes which were temporally centered in diotic noises. The experiment was conducted for several combinations of the duration of probes (2 to 64 ms) and fringes (2 to 18 ms), resulting in three different overall durations. The presence of fringes led to a decrease of performance of the listeners at all probe durations, and, for comparable probe durations, longer fringes were more detrimental. Akeroyd and Bernstein (2001) replicated the conditions first proposed by Zurek (1980) and extended the experiment with conditions where only a forward fringe or a backward fringe was present. Their measurements showed that a forward fringe had a stronger effect than a backward fringe. They could describe their data quite well by considering a combination of the temporal window proposed by Bernstein *et al.* (2001) and a post-onset-weighting function as formalized by Houtgast and Aoki (1984).

The use of diotic fringes has been motivated by the assumed dominance of onset information over the ongoing information. The underlying hypothesis was that the presence of diotic forward fringes removed the emphasis of the binaural information located near the onset of the stimulus. Given this assumption, and as it has been reported in the literature, one would assume that a forward fringe will always have a stronger effect than a backward fringe.

This influence of fringes regarding lateralization information is quite different from the role that (masker) fringes have in binaural detection experiments. It has been shown in a number of studies that detection thresholds are higher when masker and signal are presented with the same duration, compared to a situation where the masker is starting before the signal onset (forward fringe) or extended beyond the end of the signal (e.g., Trahiotis *et al.* 1972, Robinson and Trahiotis 1972, Bernstein *et al.* 2006). The increase in detection performance is larger for a forward fringe than for a backward fringe. One difference between the studies on fringes in signal detection and those on ITD detection is that in the former, effects have been studied for much longer durations of the fringes. In order to allow a better comparison between these conditions, we have chosen to study the role of fringes in ITD detection experiments for longer duration of both fringes and probes compared to studies in the literature.

METHOD AND STIMULI

The experiment was controlled by a computer program running in the software environment Matlab. The stimuli were reproduced with Beyerdynamic DT 990 headphones. The listeners were seated in a sound-attenuating listening booth.

The base condition consisted of ITD detection measurements for band-limited noise probes that had a duration between 5 and 400 ms and that were presented in isolation. In addition, thresholds were measured at all probe durations with a forward fringe of 100 or 200 ms, a backward fringe of 100 or 200 ms or with surrounding forward and backward fringes that had a duration of 100 ms each. In a second experiment, additional fringe durations of 5 and 20 ms were used. Not all experimental data are shown in this paper.

Prior to each adaptive threshold run, a 5-s buffer of bandlimited noise (100-2900 Hz) was generated. The transition between fringe (diotic) and probe (part carrying an ITD) was essentially instantaneous. Stimuli were shaped with 1-ms Hanning onset and offset ramps and were generated by randomly selecting a portion of the noise buffer before each presentation. ITDs were created by applying a phase shift in the frequency domain. In order to prevent audible clicks at the transition between probe and fringe, stimuli were low-pass filtered with an 8^{th} order Chebyshev filter with a 3-dB cut-off frequency at 3.14 kHz.

Thresholds were measured using a three-alternative forced-choice presentation of the stimuli. One of the three intervals contained the stimulus carrying the ITD to be detected. The stimuli in the other two intervals had zero ITD. Lateralization of the probe in the target interval was always towards the same side. ITDs were adaptively varied using a two-down one-up procedure in order to estimate the 70.7% correct value (Levitt 1971). ITD values were increased or decreased by using a specific factor which was set to a value of 1.584 at the beginning of a track and was reduced to a value of 1.122 after two reversals. The pause between successive intervals of the forced-choice procedure was kept constant (500 ms) regardless of the stimulus duration. A run was terminated after 12 reversals and thresholds were defined as the average ITD across the last 10 reversals. Three young males and a female who were experienced in psychoacoustic experiments and who had no evidence or history of hearing loss, served as listeners. An extensive training was conducted until the performance of all listeners had reached reasonable consistency. Four repetitions of the measurements were made for each subject.

RESULTS

Each figure in this section represents ITD thresholds as a function of the probe duration on axes that have both logarithmic scales. All statistical analyses performed on ITD thresholds were done in the log-ITD domain. For convenience, we will discuss the results by expressing threshold variations in dB with the ITD considered as a non-quadratic magnitude $(20*\log_{10}(ITD1/ITD2))$; the results will, however, be shown on figures with logarithmic axes scaled in μs. The duration axis is chosen to be logarithmic as it shows best the variation of the thresholds with accumulation of information due to increasing stimulus durations.

Figure 1 shows the results for the conditions in which ITD thresholds were measured for probes in isolation (squares) or with fringes of 100 ms either surrounding, preceding or following the probe. Thresholds for probes in isolation decrease with increasing probe duration and the decrease is stronger for short durations than for long durations. Represented in such a figure with log-log axes, the decrease of thresholds can be characterized by slopes between -0.49 for stimulus durations between 10 and 20 ms, and -0.19 for durations between 100-400 ms. The presence of 100-ms forward fringes induces a limited increase of the thresholds. Thresholds measured with forward fringes elicit a very similar temporal integration pattern as those measured for probes in isolation.

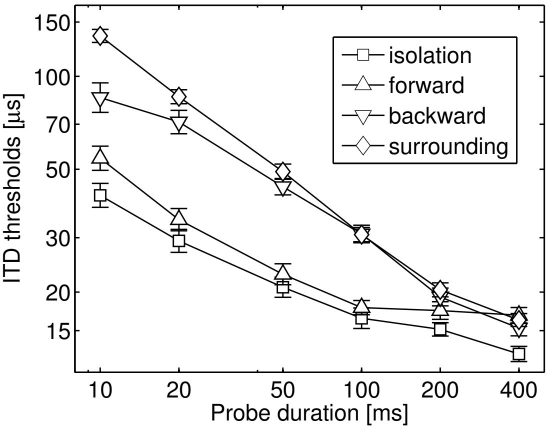

Figure 1: ITD thresholds as a function of probe duration. Thresholds are averaged across four listeners and the error bars represent the standard error of the mean across the average threshold of each listener. Thresholds measured with probes in isolation are shown by squares. Other symbols indicate thresholds where the probe was surrounded by 100-ms fringes (diamonds) or preceded by 100-ms forward fringes (upward triangles) or followed by 100-ms backward fringes (downward triangles).

The effect of the backward fringe is small for probe durations of 400 and 200 ms where it amounts to about 1.7 dB. The effect is, however, much larger for probe durations shorter than 200 ms where it amounts up to 8 dB. Thresholds obtained with a sole backward fringe and those obtained with the surrounding fringes are virtually identical for probe durations of 100, 200 and 400 ms. For probe durations of 10, 20 and 50 ms the difference in thresholds between these two conditions increases with decreasing probe durations. For probe durations equal to or larger than 200 ms, the effects of a forward and a backward fringe of the same duration (100 ms) are comparable. For probe durations shorter than 200 ms the effect of a backward fringe is clearly *stronger* than that of a forward fringe.

In a second experiment, we repeated this measurement for shorter fringe durations down to 5 ms, which come closer to those used in the literature (Akeroyd and Bernstein 2001). Three of the listeners who participated in the first experiment also participated in experiment II.

Figure 2 shows the results of experiment II for a fringe duration of 20 ms. Thresholds are again shown for conditions measured with probes in isolation (squares), with a forward fringe (upward triangles), with a backward fringe (downward triangles) and with surrounding fringes (diamonds). In addition, thresholds from Akeroyd and Bernstein (2001) for a 5-ms probe and 22.5-ms fringes are shown isolated on the left with the same convention of symbols.

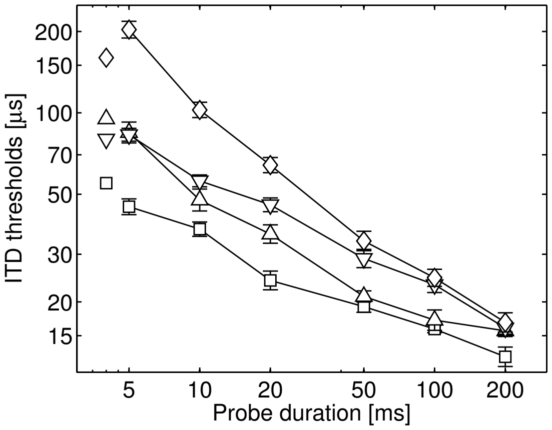

Figure 2: ITD thresholds as a function of probe duration for a fringe duration of 20 ms. Thresholds are averaged across three listeners and the error bars represent the standard error of the mean across the average thresholds of each listener. The figure shows thresholds measured with probes in isolation (squares), with a forward fringe (upward triangles), with a backward fringe (downward triangles) and with surrounding fringes (diamonds). Isolated thresholds on the left side represent thresholds from Akeroyd and Bernstein (2001) with the same convention of symbols, for a probe duration of 5 ms and for fringe durations of 22.5 ms.

The results from the experiment with 20-ms fringes in Fig. 2 reveal that the effect of fringes is qualitatively similar to that of 100-ms fringes, only with a reduced strength of about 50%. In addition, for the shortest probe duration, sole fringes lead to identical thresholds.

If we shorten the fringes down to 5 ms (data not shown), we observe the following effects. For the longer probe durations between 20 and 200 ms, sole fringes have virtually no effect and surrounding fringes have only a very small influence. For shorter probe durations, a backward fringe has also nearly no effect. A forward fringe has, however, a strong effect that is clearly dominating over that of a backward fringe. The effect of surrounding fringes for probe durations of 5 and 10 ms comes very close to that of the forward fringe.

Discussion

The experiments allow to observe the effect of fringes for a wide range of probe and fringe durations. Results obtained with 100-ms fringes in experiment II are consistent with the results of experiment I for fringe durations of 100 and 200 ms. Results of experiment II for 20-ms fringes are qualitatively similar to those observed with 100-ms fringes, only the strength of the effect is greatly reduced, particularly for long probe durations. Furthermore, as can be seen in Fig. 2, we obtained a fairly good replication of the measurement by Akeroyd and Bernstein (2001). For a 5-ms probe and 20-ms fringe durations, the effects of a forward and backward fringe are equivalent, and the effect of the surrounding fringes is resulting from a combination in equal proportions of each of the individual fringes. The results obtained for 5-ms fringes are fundamentally different from those obtained with longer fringes, in the sense that it is the only fringe duration for which a forward fringe is observed to have a clearly stronger effect than a backward fringe.

Based on observations of experiments I and II, the effects of fringes may be summarized as follows:

- *General*: Fringes result in an increase in ITD thresholds at all measured durations of probes and fringes. The effect is, in tendency, stronger for longer fringes and shorter probes. For the longest probes, the effect of fringes is small and relatively independent of the fringe duration.
- *Forward and backward fringe*: The effect of a forward fringe is in general smaller than that of a backward fringe. It is only for short (5-ms) fringe and short probe durations (5 and 10 ms) that a forward fringe has a clearly stronger effect than a backward fringe.
- *Surrounding fringes*: The effect varies between being equal to that of the effect of the dominant sole fringe, and being equal to a combination of the effect of the sole fringes. When sole fringes have no effect, the surrounding fringes have also no effect.

MODELING

In this section we will discuss our attempts to use the model by Breebaart *et al.* (2001a) to describe the data obtained in experiments I and II. This model is a binaural model (EC type) that has been developed for predicting many binaural conditions including binaural detection and, to a lesser extent, lateralization discrimination for long-duration stimuli. As is described in detail in Le Goff (2010), this model can also be used to describe ITD detection thresholds as a function of stimulus duration. In order to observe temporal integration in the model which is in line with experimental data, it is necessary to reduce the onset overshoot of the model which has repeatedly shown to be too strong and gives the model a higher sensitivity than observed experimentally for very specific conditions. This modification of the original model by Breebaart *et al.* (2001a) leads to an ITD threshold increase for short duration stimuli and gives a good description of experimental data.

Simulations were conducted with the model proposed by Breebaart *et al.* (2001a) with an extra stage consisting of a dynamic compression stage added after the series of adaptation loops. The EI cell used for the simulations had an internal delay of τ=-23 μs. This particular position is chosen because it was found to provide the best fit for data derived in static ITD detection conditions. Five 1-ERB-wide auditory channels centered between 540 Hz and 960 Hz were used to conduct the simulations. These channels were chosen because they are located in the spectral range for which human listeners and the model are the most sensitive to ITDs (see Fig. 1 in Breebaart *et al.* 2001b)). Simulations were conducted with the same method as the experiments described above and results are shown for conditions where band-limited noise probes were presented in isolation or surrounded by 100-ms forward and backward fringes.

Figure 3 shows that the modified version of the model can replicate the ITD thresholds (squares) in terms of both threshold values and variation as function of the duration of the probe. The simulated thresholds obtained for the stimuli with surrounding fringes (diamonds) are also well in line with the experimental

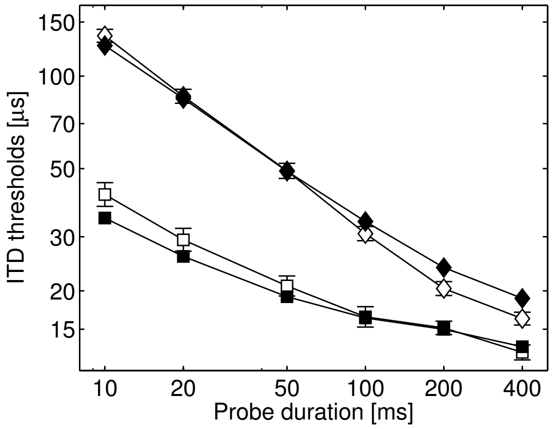

Figure 3: ITD thresholds as a function of probe duration. Experimental thresholds are shown by the open symbols and simulated thresholds by the filled symbols. Squares represent thresholds obtained when the probe was presented in isolation and diamonds represent thresholds when the probe was surrounded by 100-ms forward and backward fringes.

results. In such a figure with log-log axes, the simulated thresholds follow a straight line that has a very similar slope as the experimental data. To investigate how the presence of the forward and backward fringes lead to such an alignment of the data, simulations were also conducted for stimuli in which the probe is either preceded or followed by a fringe.

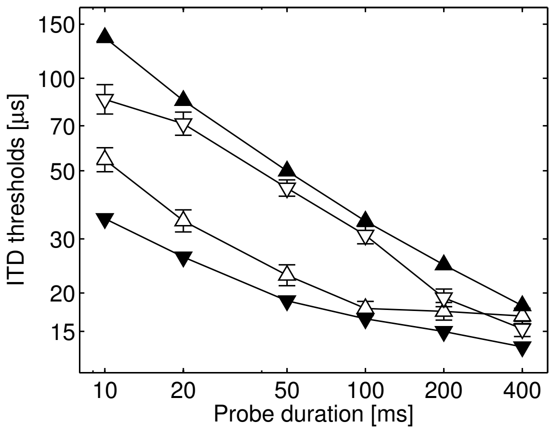

Figure 4: ITD thresholds as a function of probe duration. Experimental thresholds are shown by the open symbols and simulated thresholds by the filled symbols. Upward triangles represent thresholds obtained with a sole 100-ms forward fringe and downward triangles those obtained with a sole 100-ms backward fringe. Simulated thresholds are obtained with a modified version of the model, see text for more details.

Figure 4 shows experimental thresholds (open symbols) for the conditions in which the probe was preceded by a 100-ms fringe (upward triangles) or followed by a 100-ms fringe (downward triangles). The figure shows the simulated thresholds corresponding to these two experimental conditions with corresponding filled symbols. The behavior of the model for the conditions with only one fringe is not in line with that of human listeners. As previously remarked, the presence of a forward fringe has a minor effect on the experimental thresholds, while the presence of a backward fringe has a strong effect. The model sensitivity to the fringes is the opposite.

In the model, a diotic *backward* fringe has no effect on the detection process because it is perfectly canceled in the binaural processor. This model property is reflected in the similarity between thresholds simulated for probes in isolation and with backward fringes. A diotic *forward* fringe is also perfectly canceled in the binaural processor but its presence or absence has a major effect on the following stimulus part, the probe, due to peripheral processing. For stimuli in which the probe is preceded by a forward fringe, the onset overshoot (transient onset emphasis) is triggered by the onset of the fringe, which is identical in the left and right signals and will therefore be perfectly canceled in the binaural processor. For stimuli in which the probe is in isolation, the onset overshoot is triggered by the onset of the probe and therefore carries binaural information. As a consequence, the internal representation of the target intervals will show a strong onset overshoot. Despite the additional peripheral stage that reduces the onset overshoot, there is still more activity present at the onset of the internal representation of stimuli where probes are in isolation than at the onset of internal representation of stimuli with forward fringes, hence the difference in simulated thresholds.

The main result of these simulations is that the model proposed by Breebaart *et al.* (2001a) can not account for the fact that a backward fringe has a stronger effect than a forward fringe as seen in a majority of our experimental results. The model can, however, predict an asymmetry in the effect of fringes due to the peripheral adaptation stage, but a forward fringe will always have a stronger effect than a backward fringe.

We also analyzed our findings with other models proposed in the literature. Bernstein *et al.* (2001) proposed to account for their experimental results for probes surrounded by fringes of identical duration by an analysis relying on the assumption that the decision of the listener is based on an averaging of the ITD over the course of the stimulus through a symmetric double-exponential two-stage temporal window. Such an analysis is consistent with other studies conducted by, for instance, Kollmeier and Gilkey (1990) or Wagner (1991). In this approach the effect of each sole fringe is accounted in the same manner and there is, therefore, no mechanism that can give more weight to either the forward or the backward fringe. This approach can, consequently, not account for the differences in the effect of sole fringes observed in our own experimental data.

An asymmetry in the effect of the fringes has, however, been considered by Akeroyd and Bernstein (2001) in a similar modeling framework. These authors successfully accounted for their experimental results by using a method fairly similar to that used by Bernstein *et al.* (2001). The new approach consisted of a combination of the temporal window and a post-onset-weighting function that leads to an asymmetry in the effect of the fringes. Due to the nature of the post-onset-weighting function this asymmetry is, however, only in the form of a stronger effect of a forward fringe than a backward fringe. Such approach can, therefore, not explain the stronger effect of a backward fringe observed in our data.

In summary, this evaluation of present-day models did not reveal any solution that explains the varying influence of forward and backward fringes on ITD detection performance. We want to add that, in our view, the data seem to be difficult to predict with a purely signal-driven model of perception.

DISCUSSION

Our experimental investigations have shown that the respective effect of forward and backward fringes varies greatly with their duration as well as with the duration of the probe. For a majority of combinations of fringe and probe durations, the effect of a backward fringe is stronger than that of a forward fringe. This observation stays in clear contrast to the so-far published findings on fringe effects in lateralization deetection experiments. The most obvious reason for this difference in outcomes lies in the used stimulus duration. While literature data were measured for stimuli that did not exceed 50 ms in most cases, our measurements were also conducted with longer stimuli.

While literature data, as those obtained by Akeroyd and Bernstein (2001) can be described with the concept of onset emphasis or a post-onset-weighting function, the present study shows that this approach fails for longer stimulus durations. Our understanding of the effect of fringes for long stimulus durations is rather limited. A study on Gaussian noise discrimination by Goossens *et al.* (2009) provides a suggestion for an underlying mechanism. The authors found that adding 200-ms noise fringes to 50-ms noise tokens degraded significantly the performance of the listeners. They suggested that this phenomenon was due to the inability of the auditory system to “break” the stimuli into separate probes and fringes and that the resulting 250-ms long stimuli were treated by the auditory system as a single auditory object. Such an effect has also been reported for binaural conditions by Heller and Trahiotis (1995). A similar mechanism could be responsible for the effect of the fringes on ITD detection for long durations.

It is not unknown that the binaural system behaves differently for short and long stimulus durations. In particular, it is known that the binaural system has a relatively poor temporal resolution, a phenomenon referred to as binaural sluggishness. Binaural sluggishness has been reported for binaural detection conditions (Kollmeier and Gilkey 1990, Holube *et al.* 1998) and characterizes the fact that the binaural system can not temporally resolve events that occur too fast. One can therefore imagine that if stimulus durations are shorter than the characteristic duration of binaural sluggishness (50-100 ms), the stimuli carrying ITDs are processed in a way that can be accounted for by models based on temporal averaging and post-onset-weighting. For longer stimuli such a process would become ineffective and another process, possibly more influenced by top-down processes, would be responsible for the degradation of performance due to the presence of the fringes.

In the literature, the main motivation for using fringes has been to test the dominance of onset information. It was assumed that the presence of a forward fringe would remove any emphasis of the binaural information at the onset of the stimuli. While this assumption is not questioned on the basis of our investigations, our experimental results show that there are additional mechanisms involved in the processing of dynamically varying ITDs. Given the range of probe and fringe durations considered in our experiments, one could even argue that the mechanisms responsible for the effect of a backward fringe are stronger than those involved in the effect of forward fringes.

One interpretation of the effect of a backward fringe is that it impairs the binaural information near the offset of the stimuli which, considering our results, appears to be critical. Interestingly a study by Stecker and Hafter (2009) also suggests such a possibility. The authors conducted a free-field pointing experiment where listeners had to localize trains of clicks of various lengths. As a result of the experiment the relative weight of each click for the localization performance was determined. The experiment was conducted for trains of 4, 8, 16 or 32 clicks that were separated by 5-ms intervals. The results show that the initial and the last clicks have a stronger weight than ongoing clicks. The authors attempted to predict these results using the model proposed by Akeroyd and Bernstein (2001). The model could account fairly well for the experimental results with the noticeable exception that it underestimated the increase of weight of the last clicks and in particular for the two longest duration trains. Stecker and Hafter (2009) suggested a *post-hoc* analysis of the late arriving sound, but remarked that the responsible mechanisms are not yet understood. This conclusion fits also well to the role of backward fringes observed in our study.

REFERENCES

Akeroyd, M. A., and Bernstein, L. R. (**2001**). “The variation across time of sensitivity to interaural disparities: Behavioral measurements and quantitative analyses,” Journal of the Acoustical Society of America **110**, 2516–2526.

Bernstein, L. R., Trahiotis, C., Akeroyd, M., and Hartung, K. (**2001**). “Sensitivity to brief changes of interaural time and interaural intensity,” Journal of the Acoustical Society of America **109**, 1604 – 1615.

Bernstein, L. R., Trahiotis, C., and Freyman, R. L. (**2006**). “Binaural detection of 500-Hz tones in broadband and in narrowband masking noise: Effects of signal/masker duration and forward masking fringes,” Journal of the Acoustical Society of America **119**, 2981–2993.

Breebaart, J., van de Par, S., and Kohlrausch, A. (**2001**a). “Binaural processing model based on contralateral inhibition. I. Model structure,” Journal of the Acoustical Society of America **110**, 1074–1088.

Breebaart, J., van de Par, S., and Kohlrausch, A. (**2001**b). “Binaural processing model based on contralateral inhibition. II. Dependence on spectral parameters,” Journal of the Acoustical Society of America **110**, 1089–1104.

Goossens, T., van de Par, S., and Kohlrausch, A. (**2009**). “Gaussian noise discrimination and its relation to auditory object formation,” Journal of the Acoustical Society of America **125**, 3882–3893.

Hafter, E., Dye, R. J., and Gilkey, R. (**1979**). “Lateralization of tonal signals which have neither onsets nor offsets,” Journal of the Acoustical Society of America **65**, 471–477.

Heller, L., and Trahiotis, C. (**1995**). “The discrimination of samples of noise in monotic, diotic, and dichotic conditions,” Journal of the Acoustical Society of America **97**, 3775–3781.

Holube, I., Kinkel, M., and Kollmeier, B. (**1998**). “Binaural and monaural auditory filter bandwidths and time constants in probe detection experiments,” Journal of the Acoustical Society of America **104**, 2412–2425.

Houtgast, T., and Aoki, S. (**1984**). “Stimulus-onset dominance in the perception of binaural information,” Hearing Research **72**, 29–36.

Houtgast, T., and Plomp, R. (**1968**). “Lateralization threshold of a signal in noise,” Journal of the Acoustical Society of America **44**, 807–812.

Kollmeier, B., and Gilkey, R. H. (**1990**). “Binaural forward and backward masking: Evidence for sluggishness in binaural detection,” Journal of the Acoustical Society of America **87**, 1709–1719.

Le Goff, N. (**2010**). *Processing interaural differences in lateralization and binaural signal detection*, Ph.D. thesis, Eindhoven University of Technology.

Levitt, H. (**1971**). “Transformed up-down methods in psychoacoustics,” Journal of the Acoustical Society of America **49**, 467–477.

Robinson, D. E., and Trahiotis, C. (**1972**). “Effects of signal duration and masker duration on detectability under diotic and dichotic listening conditions,” Perception & Psychophysics **12**, 333–334.

Stecker, G. C., and Hafter, E. R. (**2009**). “A recency effect in sound localization?” Journal of the Acoustical Society of

America **125**, 3914–3924.

Trahiotis, C., Dolan, T. R., and Miller, T. (**1972**). “Effect of “backward” masker fringe on the detectability of pulsed diotic and dichotic tonal signals,” Perception & Psychophysics **12**, 335–338.

Wagner, H. (**1991**). “A temporal window for lateralization of interaural time difference by barn owls,” Journal of Comparative Physiology **169**, 281–289.

Zurek, P. M. (**1980**). “The precedence effect and its possible role in the avoidance of interaural ambiguities,” Journal of the Acoustical Society of America **67**, 952–964.