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Lateralization of Click-Trains with Opposing Onset and Ongoing Interaural Delays

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Summary

Lateralization of a click-train containing 200 clicks was examined in a two-interval, forced-choice design. The first of two intervals consisted of a diotic reference train while the second interval contained the test train. The initial click of the test train carried an interaurale time difference (*ITD*) favouring one ear and the interaural delay of subsequent clicks were reversed. Subjects were instructed to identify the side to which the test-train was lateralized (right or left) relative to the reference. Data were organized in terms of the percentage of times the test-train was lateralized to the same side as the ear which favoured the *onset* click. Short interclick intervals (*ICI*<2 ms) resulted in high percentages and long *ICIs* (>4 ms) resulted in small percentages. Subjective reports indicated a single fused image for short and long *ICIs*, and the presence of two concurrent percepts for intermediate *ICIs* during the presentation of the test stimulus.

Lateralisation von Klickfolgen mit gegenläufigen Anfangs- und Folgeverzögerungen

Zusammenfassung

Es wurde die Lateralisation einer Klick-Folge aus 200 Klicks in einem Zweiintervall-Versuch untersucht. Im ersten der beiden Intervalle wurde eine diotische Bezugsfolge dargeboten, während das zweite Intervall die Testfolge enthielt. Der Anfangsklick der Testfolge beinhaltete eine interaurale Zeitdifferenz (*ITD*) zugunsten des einen Ohrs, die interauralen Verzögerungen der nachfolgenden Klicks wurden umgekehrt. Die Versuchspersonen sollten angeben, ob die Testfolge rechts oder links von der Bezugsfolge gehört wurden. Aus den Versuchsdaten wurde der Prozentsatz der Versuche ermittelt, bei denen die Testfolge auf der Seite des anfangs begünstigten Ohres gehört wurde. Kurze Werte der Verzögerung (<2 ms) ergaben hohe Prozentsätze, während lange Verzögerungen kleine Prozentsätze lieferten. Subjektive Angaben wiesen auf ein einzelnes, verschwommenes Bild für kurze und lange Verzögerungen hin und auf das Auftreten zweier konkurrierender Wahrnehmungen für mittlere Verzögerungen während der Darbietung des Testsignals.

Latéralisation d'un train de clics à retards interauraux opposés pour le premier et les suivants

Sommaire

Par une procédure à choix forcé sur deux intervalles, on a étudié la latéralisation d'un train de clics contenant deux cents impulsions. Le premier intervalle contenait un train diotique de référence, le second contenait un train test dichotique. Le premier clic du train test avait une différence interaural de temps au profit d'une oreille, puis tous les autres avaient un retard interaural opposé. Les sujets devaient indiquer le côté (droit au gauche) vers lequel le train test était latéralisé par rapport à la position apparente du train de référence. A partir des réponses nous avons déterminé le pourcentage de latéralisation du côté de l'oreille favorisée par le clic initial. Ces pourcentages étaient élevés pour des intervalles entre clics (*ICI*) brefs (<2 ms) et faibles dans le cas contraire (*ICI*>4 ms). Le stimulus test produit une image auditive unique fusionnée pour des *ICIs* courts et longs, et une double image pour les *ICIs* intermédiaires.

1. Introduction

This paper is the outcome of an observation made during experiments on onset dominance in lateralization [1]. If a a single dichotic click with an interaural difference in time (*ITD*) favouring one ear is followed by 199 clicks with an *ITD* favouring the opposite ear, a single image is perceived on the side of the head where the *ITD* favours the onset click. This onset dominance, which is observed for interclick intervals (*ICI*) shorter than 2 ms, resembles other phenomena in sound localization. These include the precedence effect also known as the law of the first wavefront [2–4]; the Clifton effect [5]; binaural adaptation [6]; and the Franssen effect [7]. Such phenomena are not only of theoretical importance to understanding the temporal processing of binaural information, but also of significant practical importance to such applied areas as architectural acoustics [2] and sound reproduction systems [8]. The following is a short report on our observations.

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2. Lateralization of broadband click-trains

2.1. Procedure

In a two-interval, forced-choice (2IFC) design, subjects were instructed to judge the lateral position of a test stimulus relative to a diotic reference stimulus. The diotic reference was a click train containing 200, 40-μs clicks. The test stimulus was a dichotic click train containing 200, 40-μs clicks. The *ICI* was the same for the test and reference trains. The first and last clicks of the test stimulus had an interaural delay favouring one ear (randomized from trial to trial), while the remaining 198 clicks had an interaural delay which was equal but opposite to that of the first and last clicks [1]. The subject's task was to indicate whether the test stimulus was perceived to be to the left or right of the reference. Subjects were also instructed that if double images were heard to respond on the basis of the more dominant image and to report this double image at the end of the run.

Each run consisted of 100 trials during which the *ITD* and the *ICI* remained constant. *ICI*s were measured from the onset of the first click of one dichotic pair to the onset of the first click of the next dichotic pair. The interaural delay was either 100, 200, 400, or 600 μs. The *ICI*s ranged from 0.42 to 10.3 ms although not all *ICI*s were paired with all *ITD*s. As a result of constraints on the apparatus the total *ICI* was the sum of a standard delay plus the *ITD*. Thus as seen from Fig. 1, the *ITD*s do not line up for a given *ICI*. In addition, the duration of the click-train depended on the *ICI* and varied from 0.084 to 2.05 sec. A minimum of two runs were completed per subject per condition.

2.2. Signals

The 40-μs clicks were generated by a pair of multi-function signal generators (Wavetek 184). The amplitude spectrum of each of these clicks had a zero crossing at 25 kHz (6 dB down at 15 kHz).

Thus the spectra of the signals were primarily shaped by the transfer function of the headphones (TDH-49). Sound pressure level measured with a 6 cc coupler and a sound level meter for a continuous train of clicks presented at a rate of 100/s was 60 dB *SPL*.

2.3. Results

Averaged data are plotted for two subjects (TS and SB) in Fig. 1. The data are organized in terms of the percentage of times the test click-train was lateralized to the same side as the ear which carried the leading edge of the dichotic onset click. For *ICI*s shorter than 2 ms, the majority of responses fall on the same side as the ear which carried the lead click of the onset (that is, above the 50% line), suggesting that the onset click dominates the percept of lateralization. For *ICI*s above 4 ms, the opposite of this occurs, suggesting a dominance of the ongoing click-train. There does not seem to be a substantial effect of *ITD*, although the 600-μs data (filled triangles) do provide slightly higher percentages.

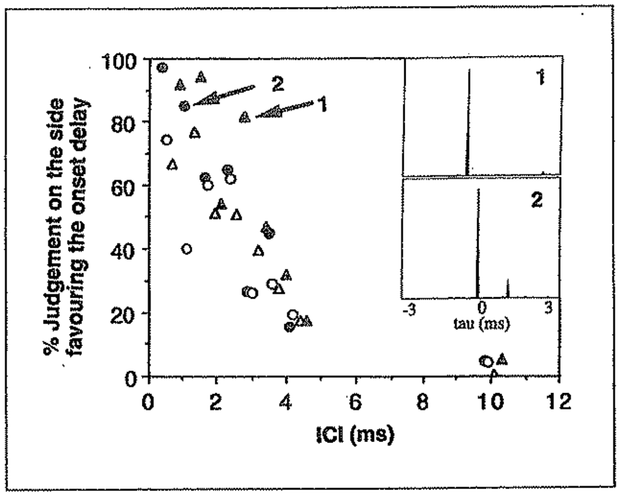

Fig. 1. Percentage of times subject judged the position of the broadband click-train to be on the side favouring the onset. The abscissa shows the interclick interval and the parameter is interaural delay. Filled circles are 100, open circles 200, open triangles 400, and filled triangles 600 μs. Data are the average for two subjects. The two inserts are cross-correlation functions for the data marked by arrows.

Subjective reports indicated that for short and long *ICI*s a single image was heard lateralized to one side, while for intermediate *ICI*s between 2 and 4 ms two concurrent images were heard during the presentation of the test stimulus. Each of these images lasted the entire duration of stimulation and they were reported to be lateralized to opposite sides of the head. Subjects were instructed to respond to the stronger of the two images. The perception of this double image is not shown in Fig. 1. However, by the subjects' own reports the data which fall near 50% are indicative of the two lateralized images with nearly equal weights.

A few additional observations may help characterize this onset dominance. Onset dominance was observed for *ICI*s shorter than 2 ms when the opposing interaural delay was contained solely in the onset click, suggesting that these results are not contingent on the offset of the signal. This latter configuration was then presented under monaural listening conditions. In this case, a single click was presented monaurally to one ear followed by 199 clicks presented monaurally to the opposite ear.

[1] Originally this experiment was designed to study the Franssen [4] effect for dichotic listening. We therefore imposed the opposing *ITD* on both the first and last clicks. As described later in the paper, eliminating the opposing offset click had no noticeable effect.

Here, the onset dominance failed and subjects reported the onset as a click to one ear and the ongoing train to the other. A similar test configuration was informally arranged using two loudspeakers separated by 60 degrees in the free-field and placed symmetrically about the median sagittal plane. Observations were made in both a reverberant room and a room modified to attenuate reflections. For comparison with Fig. 1 it should be noted that a 60 degree separation translates roughly into a ± 240 µs interaural disparity [9]. Here, an *ICI* of 2 ms was used and a single click was presented from one speaker while subsequent clicks (199) were presented from the other speaker. Results were similar to those observed using dichotic clicks; that is, an onset dominance was observed. In another observation under headphone conditions ($ICI = 2$ ms) the click-train was presented with the first and the 100th dichotic clicks carrying the opposing interaural delay. The purpose was to trigger a release from onset dominance via the sudden change in interaural delay at the centre of the 200-click train. Still the click-train was perceived entirely on the side favouring the onset *ITD* and the "deviant" click (number 100) "stood out" separately.

3. Lateralization of high-frequency filtered click-trains

3.1. Procedure and results

The procedures were the same as described in the previous section, however, the stimuli were different. The click-train consisted of either 10, 30, or 100 clicks whose temporal envelopes were Gaussian and centred at the cosine phase of a 4 kHz carrier. A single click had a Gaussian amplitude spectrum of ± 1400 Hz at $\pm 1\,\sigma$. The click-train was generated by an IBM PC and presented through DACs at a rate of 50 kHz. This click-train was then subsequently high-pass filtered at 2 kHz by a dual variable electronic filter (Kemo VBF 8) before being led to STAX SR-5 electrostatic earphones. The initial click of this train carried an interaural delay of 400 µs favouring one ear, and the remaining clicks favoured the other ear with the same magnitude of interaural delay. The results of this experiment, plotted as the mean for 3 subjects (JN, JT, SH) in Fig. 2, are similar to those observed using broadband sounds, indicating an onset dominance of the perceived lateral position of a long duration signal. We will, shortly, discuss the implications of this latter experiment.

4. Discussion

The results reported here are consistent with previous work [2–4, 6]. A strong influence of the first-arriving wavefront was observed on the localization of a sound in

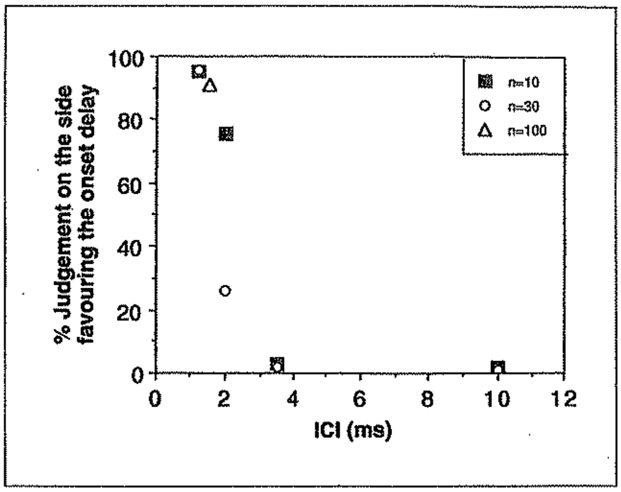

Fig. 2. Data obtained using high-frequency click-trains (high-pass filtered at 2 kHz). The parameter (n) represents the number of clicks in the train. The interaural delay was 400 µs. Data are the average for three subjects.

space. We describe here two common explanations of onset dominance and argue that neither may account for the current results.

4.1. Onset dominance and the cross-correlation function

If the *ITD* is large relative to the *ICI*, and if the second click of the first dichotic pair is grouped with the first click of the second dichotic pair, then the binaural system may evaluate the click train as consistently leading to the side of the onset. For example, if the *ICI* is 1 ms and the *ITD* is 600 µs, then by re-grouping clicks as above, the binaural system may consider an ongoing *ITD* of 400 µs leading to the same side as the onset *ITD*. This interpretation for onset dominance, which may be evaluated by the cross-correlation function, holds only for some combinations of *ICI*s and *ITD*s, and cannot explain much of our data. The broadband cross-correlation function (eq. (1)):

$$\Gamma_{x,y}(\tau) = \frac{W(\tau) \int\limits_{-T}^{+T} y(t)\, x(t-\tau)\, \mathrm{d}t}{\sqrt{\int\limits_{-T}^{+T} [y(t)]^2\, \mathrm{d}t \int\limits_{-T}^{+T} [x(t)]^2\, \mathrm{d}t}} \tag{1}$$

with an exponential centre-weighting window (eq. (2)):

$$W(\tau) = \begin{cases} 1, & |\tau| \leqq 0.15\ \text{ms}, \\ \exp(-[|\tau| - 0.15]/0.6), & \text{otherwise} \end{cases} \tag{2}$$

where τ is the argument of the function and x and y are the half-wave rectified time waveforms to be cross-correlated, was calculated for several *ICI-ITD* combinations. For the case where the *ICI* was 2.7 ms and the *ITD* was 600 µs (i.e. a point which yielded 82% judgement favouring the onset *ITD*; Fig. 1, shown by the arrow labeled 1) almost the entire signal energy (for $-3 < \tau < +3$ ms) favoured the lagging delay, suggesting that the train should have been lateralized to the side of the ongoing delay (top insert of Fig. 1). The cross-correlation function for the datum pointed to by the arrow labeled 2 is in the lower insert of Fig. 1. There are several other similar data from the current study for which the cross-correlation function is unable to predict reversals in lateralization. Reducing the integration window for the cross-correlation function (to less than 15 ms), which effectively diminishes the weight given to the ongoing signal, does not alter the above predictions. That is, the cross-correlation calculations would still favour the ongoing delay.

4.2. Effects of low-frequency energy

The auditory periphery band passes a broadband sound trough a series of overlapping narrowband filters. The response of low-frequency auditory channels to click stimuli is an oscillating function which may last for several ms [10]. Such oscillations may reduce the accuracy of the neural coding of temporal information for individual clicks, which in turn, may affect interaural timing after binaural convergence. Since low-frequency energy has been shown to dominate the percept of localization [11], it may then be argued that the observed onset dominance is related to the increased uncertainty of interaural-delay information at the output of low-frequency channels. Such explanation, however, does not account for our results with high-passed clicks. Measurement of signal energy at 500 Hz showed that the levels of these high-passed signals were lowered by 64 dB at this frequency relative to the peak level of the signal. Thus, low-frequency interference may be considered negligible.

4.3. A multi-level mechanism

The mechanisms for precedence are not well understood. There is evidence which implicate peripheral [6] as well as central [1, 5, 12] processes in limiting the binaural informativeness of some stimuli to their onset. Some reports support a loss of binaural information before binaural convergence, possibly at the level of the cochlear nucleus. Such studies support a peripheral mechanism since monaural spectral changes have been shown to reduce the relative effectiveness of the onset while binaural changes have not [6]. There is also evidence for learning [1], and other cognitive effects in onset dominance [5, 7]. These very different findings, which implicate a peripheral mechanism in some cases, and a central one in others, suggest that several processes which all affect the relative potency of the onset of an acoustic stimulus may be simultaneously at work. Although most of these effects have been collectively termed the "precedence effect", they may well reflect a variety of stages or levels of processing. Traditional models, such as those based entirely on the cross-correlation function [13], cannot fully explain the diversity of results observed in recent years.

5. Summary

A strong influence of the onset was observed on the perceived lateral position of a long-duration click train with opposing onset and ongoing interaural delays. This onset dominance was greatest for *ICI*s less than 2 ms in general agreement with previous work [2–3]. A double-image was perceived for *ICI*s between 2 to 4 ms. Similar results were observed informally under free-field conditions. However, monaural presentation of the onset click to one ear, and the ongoing clicks to the opposite ear did not result in onset dominance.

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