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Research paper

Measurement of the binaural temporal window using a lateralisation task

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ABSTRACT

Binaural temporal resolution was measured using the discrimination of brief interaural time delays (ITDs). In experiment 1, three listeners performed a 2I-2AFC, ITD-discrimination procedure. ITD changes of 8 to 1024 μs were applied to brief probe noises. These probes, with durations of 16 to 362 ms, were placed symmetrically in time within a 500-ms burst of otherwise interaurally uncorrelated noise. Psychometric functions were measured to obtain thresholds and temporal windows fitted to those thresholds. The best-fitting window was a symmetric roex shape (equivalent rectangular duration = 197 ms), an order of magnitude longer than monaural temporal windows and differed substantially from windows reported by Bernstein et al. [Bernstein, L.R., Trahiotis, C., Akeroyd, M.A., Hartung, K., 2001. Sensitivity to brief changes of interaural time and interaural intensity. J. Acoust. Soc. Am. 109, 1604–1615]. Experiment 2, replicated their main experiment, comparing their ITD-detection task with a similar discrimination procedure. Thresholds in the detection conditions were significantly better than those in the discrimination condition, particularly for short probe durations, indicating the use of an additional cue at these durations for the detection task and thus undermining the assumptions made in their window fit.

1. Introduction

Binaural temporal resolution describes the limits of our abilities to discriminate rapid changes in binaural stimuli over time. These limits can impair the tracking of moving sound sources (Perrot and Musicant, 1977), localisation of consecutive sounds (Perrot and Pacheco, 1989), and understanding of speech in noise (Culling and Colburn, 2000). One way of characterising this effect of temporal "blur" is to suppose that information about the binaural features of the stimulus are always integrated across time within a finite processing window of fixed duration. This temporal window slides across the stimulus giving as its output an average of the information within the window at each point in time. Several attempts have been made to measure the duration and shape of this binaural temporal window (Kollmeier and Gilkey 1990; Culling and Summerfield, 1998; Akeroyd and Summerfield, 1999; Bernstein et al. 2001).

These experiments have demonstrated that the window applies progressively lower weight to interaural statistics such as interaural time delay (ITD) that precede or lag the centre of the window, thus attenuating information that occurred ahead or behind a given point in time. The shape of temporal windows has been described in terms of time constants, which control the weighting of information as a function of time from the centre of the window. The time constants control the duration over which information is integrated. A shorter window reflects better temporal resolution. Although the window is not thought rectangular, a short-hand term for the duration of a temporal window is the equivalent rectangular duration (ERD), similar in concept to the equivalent rectangular bandwidth (ERB) of an auditory filter (Patterson and Moore, 1986). For windows constructed from exponential and rounded exponential ("roex") functions, the ERD is numerically equal to the (weighted) sum of the two time constants defining the exponential functions, and for a window constructed from Gaussian functions, the ERD is $\sqrt{\pi}$ times this value (see Eqs. (A8) and (A9)). There is one time constant for information before the centre, and one for after. If these two are equal the window is termed "symmetric", if not, "asymmetric" (see Appendix A).

A number of studies have measured binaural temporal windows using the binaural masking level difference (BMLD) as the dependent variable (e.g., Grantham and Wightman, 1979; Kollmeier and Gilkey, 1990; Culling and Summerfield, 1998). Signals are more easily detected in noise if there is an interaural phase difference between the interfering noise and the signal (Hirsh, 1948). Typically, the noise is in-phase across the ears (N0), while the phase of the signal is shifted by 180° or π radians (N0Sπ), or vice versa (NπS0), and the signal can be detected at a lower signal-to-noise ratio than if the noise and signal are both in-phase (N0S0), or both out-of-phase (NπSπ). The temporal window can be measured by varying the binaural configuration of the masking noise over time and recording masked thresholds for tone pips placed at different points in time. In this way, Kollmeier and Gilkey (1990) measured the temporal response of the binaural system

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using a binaural analogue of monaural forward and backward masking. The detection thresholds for 20-ms, 500-Hz Sπ tone pips were obtained at different points within a 750-ms noise masker, which switched from Nπ to N0, or from N0 to Nπ, after 375 ms. The best fits to their data were obtained by using exponential functions to weight both forward and backward masking effects, creating a "double-sided" window. The value of the ERD of these windows ranged from 33.2 to 83.2 ms. These ERDs are of the same order of magnitude as Grantham and Wightman's (1979) 'binaural minimum integration time' of 44–243 ms. These are long ERDs compared to those measured for monaural processing (e.g., Plack and Moore, 1990). Grantham and Wightman consequently described the binaural system as "sluggish". Culling and Summerfield (1998) built on this approach by using a binaural analogue of the notched-noise technique developed for the measurement of the auditory filter (Patterson and Moore, 1986). Using this method, off-time listening (the temporal analogue of off-frequency listening) could also be modelled. The best-fitting function was found to be an asymmetric Gaussian, and was largely independent of frequency and level, as was the ERD of the windows, which ranged from 55 to 188 ms.

Akeroyd and Summerfield (1999) used a binaural analogue of gap detection in order to measure the shape of a binaural temporal window. A binaural 'gap' in interaural correlation was created by presenting listeners with a segment of interaurally uncorrelated noise (Nu) between two contiguous segments of N0. The action of the temporal window is to smooth the dip in correlation created by the segment of Nu in the same way that a monaural temporal window would smooth out a dip in signal energy. Assuming that binaural gap detectability is determined by the detectability of the resulting dip, and given that the just-noticeable difference (jnd) in correlation from unity is known, the ERD of the temporal window can be calculated. Measurements of binaural-gap thresholds and jnds in interaural correlation from unity for stable binaural cues were obtained and analyzed using a computational model of binaural processing. Temporal windows with a mean ERD of 140 ms were fitted to these data, a result also consistent with binaural sluggishness.

Finally, Bernstein et al. (2001) measured binaural temporal windows using an ITD-detection procedure,[1] in which listeners detected the presence of an interaurally delayed probe segment embedded within a longer noise burst. We distinguish this technique from ITD discrimination in which probe segments with different ITDs are presented in each presentation interval. In order to measure the window, they applied an ITD to a 2, 4, 8, 16, 32 or 64-ms probe section of noise, temporally centered within a 20, 40 or 100-ms burst of otherwise-diotic noise (see Fig. 1a). Like Akeroyd and Summerfield (1999), Bernstein et al. assumed that the temporal windows were symmetric, and that the listener detected the ITD imposed on the probe by centering a temporal window at the midpoint of the probe in order for the maximum amount of delayed noise to fall within the window. They further assumed that the window integrates together the ITD of the probe with the zero ITD conveyed by any of the diotic noise fringes that also falls within the window. That is to say that the "internal or effective ITD" was the weighted mean ITD of the stimulus, where the weighting was determined by a temporal window centered on the probe segment. As a result of this "dilution produced within the window by the surrounding diotic noise," the external ITD must be increased to a magnitude that will bring the internal ITD up to threshold (cf. Bernstein et al., 2001, p. 1610). The fitted temporal windows were described by exponential-skirt functions. These windows were composed of two time constants; one of a short duration (between 0.02 and 0.12 ms) that described the central peak of the window, and a second longer time constant (between 7.48 and 64.21 ms) that described the window skirts. The shapes of these windows thus diverged radically from previous measurements, and the calculated ERDs were only around 1 ms. Nonetheless, the longer time constant of the skirt enabled an averaged window to predict the decline with modulation frequency[2] in listeners' ability to discriminate noise with sinusoidally modulated ITDs from interaurally uncorrelated noise (Grantham and Wightman, 1978).

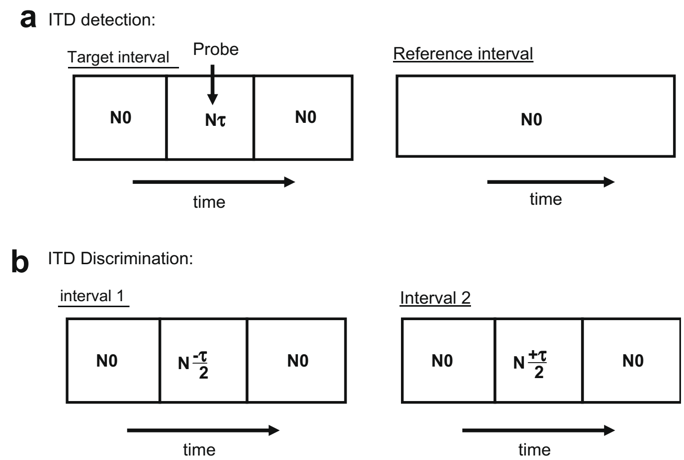

Fig. 1. (a) Schematic of the stimuli presented in the ITD-detection task used by Bernstein et al. (2001), where N0 interfering noise was presented contiguous to a delayed probe (Nτ). The same stimulus design is used in the ITD-detection tasks in experiment 2. (b) Schematic of the stimuli presented in an ITD-discrimination task in experiment 2. The delayed portion of noise presented in the first interval is always delayed in the opposite direction to that in the second interval.

Notwithstanding the success of Bernstein et al.'s binaural temporal window in predicting Grantham and Wightman's data, the wide divergence in its shape and duration from previous estimates is a source of concern. One possible problem with their approach was the dilution assumption made in their modelling. However, Kolarik and Culling (in press) have recently measured the effect of a diotic noise masker on ITD discrimination in a simultaneous masking situation. They found that it does indeed obey a dilution principle, in that threshold ITD is inversely related to the proportion (in terms of power) of delayed noise in the stimulus. Kolarik and Culling characterised this relationship through the slope of the regression line relating log ITD threshold to log proportion of delayed noise. This slope, termed the correlated-noise masking coefficient (CMC), did not differ significantly from −1 (i.e., consistent with dilution). In contrast, the corresponding coefficient for uncorrelated masking noise (the uncorrelated-noise masking coefficient, UMC) was significantly steeper than −1, its value lying somewhere in the range −1.4 to −1.9, indicating that uncorrelated masking noise is *more* disruptive than correlated (diotic) masking noise to ITD processing.

Since Bernstein et al.'s window is the only one to be based upon a task involving ITDs, another possibility is that different types of binaural information (e.g., ILDs, ITDs, interaural coherence) are subject to different temporal windows. Experiment 1 addressed this possibility by making a new temporal window measurement using such a task.

[1] Bernstein et al. also used an IID-detection procedure. Overall their fit accounted for 98% of the variance in the two data sets.

[2] The predictions were made up to 20 Hz modulation frequency. At higher modulation frequencies Grantham and Wightman found that thresholds stabilized and then improved, presumably as a result of some confounding perceptual cue becoming available.