The Time Course of Binaural Masking in the Inferior Colliculus of Guinea Pig Does Not Account for Binaural Sluggishness

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Shackleton TM, Palmer AR. The time course of binaural masking in the inferior colliculus of guinea pig does not account for binaural sluggishness. J Neurophysiol 104: 189–199, 2010. First published April 28, 2010; doi:10.1152/jn.00267.2010. Psychophysical studies show a slower response to changes in the specifically binaural input than to changes in the monaural input (binaural sluggishness). However, there is disagreement about the time course. Tracking changes in a target yields fast time constants, while detecting a constant target against a varying background yields the slowest. Changes in the binaural properties of a target are tracked up to high rates by cells in the midbrain. Indeed cells respond rapidly to a step change and then the firing rate slowly adapts. These experiments, though, are analogues of psychophysical experiments that give the faster time constants. Sluggishness should be more apparent physiologically in a binaural masking paradigm, detecting a short tone in a noise masker with a step change in masker correlation: the small change in firing rate due to the signal must be detected against the adapting firing rate change caused by the step change in the masker. However, in 40 inferior colliculus cells in the anesthetized guinea pig, in a direct analogue of the psychophysical masking paradigm, measuring thresholds for short tones across a transition in a binaural masker (e.g., from N0S0 to NπS0) provided little evidence of sluggishness within individual cells despite masking level differences in these cells comparable with previous data. Previous studies of physiological correlates of binaural masking level difference suggested that different psychophysical thresholds arise from different populations of cells. This suggests the hypothesis that sluggishness may result from a change in focus between the different populations of cells signaling threshold in different binaural configurations rather than within the intrinsic properties of the cells themselves.

Introduction

The auditory system is somewhat unusual among sensory systems because it is able to track most changes in input with a time constant of the order of milliseconds. However, the processing of the difference in sounds between the two ears, thus providing the perception of spatial location, often proves to be an exception to this generalization. The initial quantitative observation of this was a psychophysical experiment by Grantham and Wightman (1978). They modulated the low-frequency cue for lateralization, the interaural time difference (ITD), and found that the ability to detect the perceived motion declined markedly as the modulation rate increased above a few hertz. They interpreted this as indicating that the binaural system had a time constant of 100–400 ms and coined the term “sluggish” for the phenomenon. Although a factor of 2π was missing in estimating the time constant, which led to the conclusion that the time constant was nearly an order of magnitude longer than it actually was, a large number of subsequent experiments (see Table 1 for details) have come to the conclusion that the binaural system is, indeed, sluggish.

In apparent contrast to these psychophysical studies, physiological measurements (Joris et al. 2006; Siveke et al. 2008) in the midbrain have shown that neural responses can follow changes in the interaural correlation of a stimulus up to very high rates (<500 Hz). There is thus a discrepancy between the conclusions drawn from psychophysical experiments and those from physiology. However, closer examination of the psychophysical experiments suggests that this discrepancy may not be as great as is generally thought to be the case.

A number of different paradigms have been used to measure binaural sluggishness (Table 1). There is considerable variation in the estimates of time constants both between subjects within an experiment and between paradigms. At one extreme is an experiment by Akeroyd and Bernstein (2001), who changed the ITD of a short target section of noise within a longer burst of interaurally correlated noise and modeled the results with an exponential window. They found that a window equivalent rectangular duration (ERD) of around 12 ms was needed, which is not very “sluggish” and matches some estimates for the monaural system. At the opposite extreme is an experiment by Grantham and Wightman (1979), who measured the detectability of a target tone pulse in a background noise masker with a modulated interaural correlation. They found that for a tone of 250 Hz, the ERD was between 122 and 243 ms for different subjects, with a mean of 170 ms. This is, indeed, sluggish. There are three important differences between these paradigms. In the first, the ITD of the target is the aspect of the stimulus which is being varied, and it is varied in a stepwise fashion. In the second, it is the interaural correlation of the background masker that is being varied, the target only serves as a probe, and it is being varied sinusoidally. The experiments shown in Table 1 are ordered by the value of the ERD of the window used to fit the data. With two exceptions, the experiments in which the target was varied yielded the shorter ERDs, whereas the experiments where the background was varied yielded the longer ERDs.

It thus appears that the physiological experiments (Joris et al. 2006; Siveke et al. 2008) that showed little evidence of sluggishness were performed using a paradigm that exhibits the least sluggishness. We hypothesized, therefore, that we would be more likely to find evidence of sluggishness in neural activity, if it exists, by using a masking paradigm in which the background is varied. A further reason why we believed we might see apparent sluggishness under these conditions is the phenomenon observed by Ingham and McAlpine (2004). They observed that when the ITD of a tone is changed from a value...
that poorly drives a neuron (the worst delay) to an ITD at which the neuron is well driven (the best delay), the firing rate rises rapidly but then adapts slowly to a lower rate. The time constant of this adaptation is of the order of hundreds of milliseconds, similar to the time constants observed in the psychophysical experiments in which a background masker was varied. Signal detection theory (Green and Swets 1988) argues that signal detectability depends both on the magnitude of the change due to a signal and on the variability of that change. Because the detection of a target in noise requires the discrimination of a small change in the ongoing response to the noise, if the noise response is varying, then we might expect thresholds to be raised relative to stationary noise. Thus under conditions in which the masker changes from one in which the target is poorly detectable to one in which it is easily detected, we might expect the transition to be smoothed by adaptation raising the threshold after the transition even though the system responded rapidly to the initial transition.

In the experiments reported in this paper, therefore, we measured the thresholds to short tone bursts before and after a transition in the interaural phase of a noise masker. We found little evidence that the increased variability after the noise transition caused the thresholds to vary in a manner consistent with binaural sluggishness.

M E T H O D S

Recordings were made in the right IC of 12 pigmented guinea pigs weighing 554–838 g; in most of these experiments, data were also collected for other purposes. Animals were anesthetized with urethan (0.9 g/kg ip, in 20% wt/wt solution in 0.9% saline) and further analgesia provided by Hypnorm (Janssen: 0.2 ml im, comprising fentanyl citrate 0.315 mg/ml and fluanisone 10 mg/ml). To prevent bronchial secretions, atropine sulfate (0.06 mg/kg sc) was administered at the start of the experiment. Anesthesia was supplemented with further doses of Hypnorm (0.2 ml im) on indication by pedal withdrawal reflex. A tracheotomy was performed, and animals were artificially respired with pure oxygen via a tracheal cannula. Respiratory rate and end-tidal CO₂ were monitored by means of a capnometer placed in the tracheal cannula. Heart rate was monitored using a pair of electrodes inserted into the skin to either side of the animal’s thorax, and core temperature was maintained at 38°C via a heating blanket and rectal probe. The animals were placed inside a sound attenuating room in a stereotaxic frame in which hollow plastic speculae replaced the ear bars to allow sound presentation and direct visualization of the tympanic membrane. A craniotomy was performed over the position of the IC. The dura was reflected and the surface of the brain covered by a solution of 1.5% wt/wt agar in 0.9% saline. All experiments were carried out in accordance with the United Kingdom Animal (Scientific Procedures) Act of 1986 and local ethical committee oversight.

Recordings were made with glass-insulated tungsten electrodes (Bullock et al. 1988) advanced into the inferior colliculus through the intact cerebral cortex, in a vertical penetration, by a piezoelectric motor (Burleigh Inchworm IW-700/710). Extracellular action potentials were amplified (Axoprobe 1A, Axon Instruments), single units were isolated, and their time of occurrence recorded with a resolution of 1 µs using a level-crossing detector (SD1, Tucker-Davis Technologies).

Stimuli were delivered to each ear through sealed acoustic systems comprising custom-modified Radioshack 40–1377 tweeters joined via a conical section to a damped 2.5 mm diam, 34 mm long tube (M. Ravić, Eaton Peabody Laboratory, Boston, MA), which fitted into the hollow speculum. The output was calibrated a few millimeters from the tympanic membrane using a Bruel and Kjær 4134 microphone fitted with a calibrated 1 mm probe tube. All stimuli were digitally synthesized (System II, Tucker-Davis Technologies, Alachua, FL) at 100 kHz sampling rate and were output through a waveform reconstruction filter set at ¾ the sampling rate (135 dB/octave elliptic: Kemo 1608/500/01 modules supported by custom electronics). In all tests, several noise stimuli (tokens) were precalculated with a bandwidth of 50–5,000 Hz, and a spectrum level of ~50 dB relative to full scale pure-tone level. The number of tokens precalculated and duration depended on the test. Stimuli were switched on and off simultaneously in the two ears with cosine-squared gates with 2 ms rise/fall times (10–90%). The search stimulus was a binaural pure tone of 50 ms duration presented every 250 ms of variable frequency and level. An ITD equivalent to 0.1 cycles of the tone period was used for the search stimulus, since this is the modal best delay in the IC (McAlpine et al. 2001). When a unit was isolated, the best frequency (BF) and threshold at BF were obtained using a level-crossing detector (SD1, Tucker-Davis Technologies).

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to tones and noise were obtained to allow the efficient selection of signal levels for the masked rate level functions.

**Frequency response areas** were obtained with single presentations of 50-ms duration, dichotic pure tones, which were randomly chosen over a range of frequencies from 4 octaves below BF to 2 octaves above BF with a spacing of 1/8 octave and levels from 100 to 0 dB attenuation in 5 dB steps. Maximum sound level was \( \sim 100 \) dB SPL between 50 Hz and 1.5 kHz. The number of spikes elicited between 10 and 60 ms after the stimulus onset were represented as colors on an attenuation versus frequency grid.

**Rate-level functions** were obtained using both noise and BF tones. Rate-level functions to 50-ms duration noise bursts both in-phase at the two ears (N0) and inverted at one ear relative to the other (N\( \pi \)) were obtained at a rate of S/s. One of five precalculated noise tokens was randomly chosen (with replacement) per trial. Rate-level functions were also obtained to 20-ms duration tones presented diotically (S0), dichotically with a 180° interaural phase shift (S\( \pi \)), and monauraly to the left and right ears at a repetition rate of one every 150 ms. Ten repeats of levels between 0 and 100 dB attenuation in 5 dB steps were presented in random order. Every level was presented before any particular level was repeated. All spikes between 10 and 80 ms after the stimulus onset were included in the spike count.

**ITD functions** to noise or BF tones were obtained by delaying, or advancing, the fine structure of the signal to the ipsilateral ear while keeping the signal to the contralateral ear fixed. Positive ITDs correspond to the signal at the contralateral ear leading (i.e., signal to ipsilateral ear delayed). Stimuli were switched on and off simultaneously in the two ears, so that there was no onset ITD. Spikes were included in the spike count if they occurred between 10 and 80 ms after the stimulus onset. ITD functions were measured in ITD steps equivalent to 0.1 cycles of the period of the BF over ±1.5 cycles of BF using 10 repeats. A single repeat consisted of the full range of ITD steps presented in pseudorandom order. The tone signals were 20-ms duration from 0 to 50 dB above rate threshold at a repetition rate of one every 150 ms. The noise stimulus were 50-ms duration from −40 to 10 dB spectrum level above tone rate threshold at a repetition rate of 5/s. Three different noise tokens were calculated for each ITD before each run and were chosen randomly (with replacement) for each trial. Mean best delay (BD) and vector strength were calculated from the ITD functions using a modification of the method of Goldberg and Brown (1969) in which the ITD function was treated like a period histogram and the strength of locking to the ITD measured.

**Masked rate-level functions** were obtained to estimate binaural masked thresholds (cf. Jiang et al. 1997a,b; Palmer et al. 2000) and assess the degree of sluggishness at a repetition rate of one stimulus per 400 ms. The masker was kept at a constant level while the tone level was pseudorandomly varied over a range of −40–50 dB in 2 dB steps around the expected thresholds. In addition to these signal levels, one stimulus with the tone muted was also recorded per repeat. Between 20 and 50 repeats were obtained depending on the holding time of the IC unit with total recording time ≤90 min. The masker comprised a 325 ms noise burst that was inverted in phase at one ear after 150 ms (Fig. 1). The noise was originally interaurally in phase (N0), stepping to interaurally out of phase (N\( \pi \)), or was originally interaurally out of phase (N\( \pi \)) stepping to in phase (N0). The noise was usually presented at a spectrum level 10 dB below the pure-tone diotic threshold unless the noise was ineffective in driving the unit in which case the level was raised to 0 dB.

In preliminary experiments not reported here, single tone bursts of 20-ms duration were presented at various times through the noise burst, but it was found that data collection times were excessive. Instead, to improve collection efficiency two tone series were synthesized. Each had a 20 ms tone burst every 60 ms. One started 30 ms after the noise onset, the other started 60 ms after the noise onset (Fig. 1). These two series were played separately in pseudorandom order during data collection so that the tone-in-noise response was sampled every 30 ms during the stimulus, but there was a 40 ms recovery period after each tone. Previous experience in the central IC indicated that this ratio of stimulus duration to recovery was sufficient to minimize the carryover effects of one tone pulse on the response to the next. The signal was either diotic (S0) or interaurally out of phase (S\( \pi \)) throughout the stimulus.

To enhance data reliability and the ability to compare conditions, all combinations of noise phase (N0 \( \rightarrow \) N\( \pi \) \( \rightarrow \pi \) N0) and series (30 ms and 60 ms start offset) were interleaved in random order within a single run; however, all combinations of stimulus and level were presented before the next repeat was collected.

The number of spikes between 10 and 40 ms after the onset of each tone burst were counted to form rate-level functions for each combination. These were then analyzed using receiver operating characteristic (ROC) analysis (Bradley et al. 1987; Cohn et al. 1975; Green and Swets 1988; Shackleton et al. 2003) comparing the response with the tone muted to that with the tone at each level to obtain a neurometric function (see Shackleton et al. 2003 for examples) in which the proportion of correct trials in a simulated two-interval forced-choice (2IFC) experiment is plotted against signal level. These functions were then three-point smoothed (with a triangular window) and the point at which the smoothed function first crossed the 75% or 25% correct levels taken as the masked threshold. The 75% threshold was taken if the tone caused the masked firing rate to increase, (P-type) whereas the 25% threshold was taken if the tone caused the noise driven rate to decrease (N-type) (Jiang et al. 1997a,b; Palmer et al. 2000).

**R E S U L T S**

Single-unit recordings were made from 40 units in the central nucleus of the IC. The location was validated from the physiological recordings by the position within tonotopic tracks, the short latency of the responses, narrow tuning curves and reliable responses.
The tone and noise level functions for one example unit with a best frequency (BF) of 481 Hz, threshold of 43 dB SPL, and best delay (BD) of 37 µs are shown in Fig. 2. The unit is a “peak” type (McAlpine et al. 1996, 1998; Yin and Kuwada 1983), which has a strong response near zero ITD and minimal response around 180° interaural phase difference (ITD = 1 µs). There is no variation in best delay as level is varied over a range of 50 dB above pure-tone threshold. Rate-level and neurometric functions for this unit are shown in Fig. 3 for a noise spectrum level of ~10 dB. On the left are shown the rate-level functions for the four interaural phase conditions (N0S0 → NπS0, NπS0 → N0S0, N0Sπ → NπSπ, and NπSπ → N0Sπ), and in the middle are the neurometric functions for the same conditions. Separate lines show the functions corresponding to different tone burst delays after noise onset. The point at the extreme left of the rate-level functions shows the noise alone response (tone muted). Neither N0 nor Nπ strongly drive this unit except at the transition Nπ → N0 (see Fig. 3, B and D; all functions are near 0 firing rate at low signal levels except for the function at 150 ms after stimulus onset just after the transition). There is a clear separation between the functions for tone onsets before the noise transition and after the transition. With the exception of the tone burst just after the transition in the NπSπ → N0Sπ condition, all of the neurometric functions are rising through the 75% correct point and are thus defined as P-types (positive going neurometric function) (cf. Jiang et al. 1997a,b; Palmer et al. 2000). Thresholds are plotted for the S0 signals in Fig. 3I and for Sπ in J. Thresholds are reasonably constant before and after the transition, and there is a small, but reliable separation between the different interaural phase conditions. Concentrating on the N0S0 → NπS0 condition in Fig. 3I (circles), there is a transition from a higher threshold (N0S0) just before the noise transition to a lower threshold (NπS0) just after the noise transition. The difference between these two thresholds is termed the binaural masking level difference (BMLD) and is consistent both with psychophysical and physiological measurements (Jiang et al. 1997a,b; Palmer et al. 2000). The NπS0 → N0S0 condition (squares in Fig. 3I) shows complementary behavior, with a low threshold before the transition in the NπS0 condition and a high-threshold after the transition in the N0S0 condition. Irrespective of which noise transition is presented, or whether the tone is in the first or last part of the stimulus, the threshold reflects the interaural conditions. The thresholds 30 ms after the transition (i.e., at 180 ms) are virtually at the same level as all of the subsequent thresholds. The thresholds just after the transition at 150 ms (the tone bursts began coincident with the transition) are either at the same level (Fig. 3I, circle) or intermediate (Fig. 3I, square) between the steady state levels, suggesting some smearing of the effect of the transition into the measured thresholds. Taken together these data suggest that for this unit there is little evidence of sluggishness because the time constant is less than ~20 ms. Looking at the Sπ data (Fig. 3J), thresholds are only measurable when the interaural phase is NπSπ, no threshold is measurable for the N0Sπ condition with the exception of the 150 ms tone delay, where the brief burst of activity due to the Nπ → N0 transition yields a baseline firing rate that can be reduced by the addition of the Sπ tone (i.e., for this particular point only, the unit is defined as an N-type because the neurometric function is negative going). Thresholds in complementary conditions before and after the transition are similar. It is interesting to note that although neither N0 nor Nπ produce sustained driven activity, there is still an interaction between the tone and noise masker because thresholds depend on the relative interaural phases of tone and noise.

Tone and noise delay functions are shown for a second example unit in Fig. 4. This unit had a BF of 516 Hz and threshold of 23 dB SPL. The unit had a BD of 360 µs, which was fairly constant across a range of 50 dB above threshold (Fig. 4, A and D). Both the tone delay functions and the noise delay functions were slightly asymmetric around the central peak. As level was increased, there was a tonic increase in firing rate in the noise delay function (Fig. 4B), but for pure tone stimuli, the change in firing rate with level was nonmonotonic. For this unit, we also had sufficient recording time to obtain tone delay functions across frequency (Fig. 4, C and E). The characteristic delay (CD) obtained from this was 516 µs and the characteristic phase (CP) ~0.18 cycles. This unit would therefore be classified as an intermediate type (McAlpine et al. 1998). This unit responded strongly to N0, but relatively poorly to Nπ (far left of masked rate-level function, Fig. 5). Detection of both S0 and Sπ in N0 was cued by a decrease in firing rate (N-type), whereas detection in Nπ was cued by an increase in firing rate (P-type). As with the previous example, the thresholds for S0 detection (Fig. 5J) were consistent before and after the noise.

**FIG. 2.** Tone (A) and noise (B) interaural delay functions for an example unit with best frequency (BF) of 481 Hz, threshold of 43 dB SPL, and best delay (BD) of 37 µs. Firing rate is shown as a function of interaural time difference (ITD) with signal level as parameter. Levels are shown relative to the diotic BF tone absolute threshold.
transition, and the transition in thresholds occurred within 30–60 ms of the noise transition. However, unlike the previous example, the N0S0 thresholds immediately after the noise transition were elevated, this suggests that variability after the transition made detection more difficult but is inconsistent with sluggishness as modeled by a smoothing filter, which would predict intermediate thresholds. The differences between masked thresholds are again consistent with both published psychophysical and physiological data; however, the BMLD at 22 dB is larger than typically measured physiologically and at the high end of psychophysical measurements. The thresholds for S0 tones are less well defined and more variable, but there is some consistency in the N0Sπ threshold across the transition. However, after the transition, the NπSπ threshold is lower than the N0Sπ threshold, which is in the opposite direction to those obtained psychophysically but consistent with some previous physiological results (Jiang et al. 1997a,b; Palmer et al. 2000).
**Population responses**

Both of the example units described in the previous section demonstrated a change in threshold across the noise transition in some conditions but not in all. Also, the change was consistent with the sign of the psychophysically measured thresholds in some conditions but not all. This was common throughout the population of units, and a summary is shown in Fig. 6. The figure shows the number of units in the population of 40 that met certain criteria for the four noise transition and two tone phase combinations. Thresholds were averaged over the first four tone bursts and the last four bursts to quantify the size and direction of the threshold change. The left hand bar of each group shows the number of units in which a threshold was measurable in the first part of the stimulus, and the second bar shows the number that were measurable in the second part. Approximately equal numbers of thresholds were measurable in the first and second halves of the stimulus across all conditions with no particular bias either way. However, there were far fewer thresholds measurable with an S/0 stimulus. The third bar shows the number of units in which thresholds were measurable in both halves of the stimulus. The proportion of units varies between ¾ for S0 tones to ¼ for S/0 tones. However, not all of these units showed BMLDs consistent with psychophysics, that is with the homophasic threshold (N0S0 and N/0S0) being higher than the antiphase threshold (N/S0 and N/S0); the last bar shows the proportion of units that were consistent in sign with the psychophysics. It is approximately ½ for the S0 tone, and less than ½ for the S/0 tone. Thus although our sample suggests that there is a significant population that could provide thresholds consistent with psychophysics to an S0 tone either side of a noise transition and thus provide a substrate for sluggishness, there are only a minority of units that could do so for S/0. This is in contrast to the psychophysics, which suggests no such asymmetry.

Both of the example units showed a threshold change just after the noise transition which was evident within 30–60 ms (Figs. 3I and 5I). This was true throughout the population. The thresholds of all the units exhibiting a BMLD consistent in sign with the psychophysics for an S0 tone are shown in Fig. 7. The

![Fig. 4. Binaural properties of a 2nd example unit with a BF of 516 Hz, threshold of 23 dB SPL, and BD of 360 μs. The characteristic delay (CD) was 516 μs, and the characteristic phase (CP) ~0.18 cycle. Firing rate is shown as a function of ITD for BF tones (A) and noise (B) with signal level relative to the diotic BF tone absolute threshold as parameter. C: the tone delay function at 30 dB spectrum level below tone threshold at varying frequencies. D: the BD as a function of level. E: the best phase (BD*frequency) as a function of frequency.](http://jn.physiology.org/)}
thresholds are normalized, so that threshold averaged over the first four and last four time points are one or zero depending on whether the condition was homophasic or antiphasic, respectively. There is a great deal of variability within the population, especially in the $N_0S_0$ condition (Fig. 7, A, left, and B, right), although much of this is due to the small size of the BMLD in many units being close to the precision of the measurement. However, it is clear that thresholds are constant before the transition and from 60 ms after the transition (210 ms). Thresholds just after the transition (150 ms) vary over the whole range with a mean halfway between the steady-state thresholds in the $N_0S_0 \rightarrow N\pi S_0$ condition (Fig. 7A) and all the way to the later steady-state threshold in the $N\pi S_0 \rightarrow N_0S_0$ condition (Fig. 7B). In the $N_0S_0 \rightarrow N\pi S_0$ condition (Fig. 7A), the thresholds 30 ms after the transition (180 ms) are clustered around the after-transition steady-state, whereas there is greater variability in the $N\pi S_0 \rightarrow N_0S_0$ condition, but the mean is at the after-transition steady state. Thus most of the effect of the transition is over within 30 ms.

Both of the example units showed a BMLD across the noise transition that was consistent with the psychophysics using an $S_0$ tone, but the first unit did not yield an $N_0S_0 \rightarrow N\pi S_0$ threshold and the second unit only yielded $S\pi \rightarrow N\pi S_0$ thresholds in the latter part of the stimulus, which were of the wrong sign compared with the psychophysics. The thresholds for the entire population at both the start and end of the stimulus are plotted in Fig. 8. This plot ignores the noise transition and plots thresholds between different conditions but within the same unit. The first column shows the $N_0S_0$ threshold compared with the $N\pi S_0 \rightarrow N_0S_0$, $N\pi S_0 \rightarrow N\pi S_0$, and $N\pi S_0 \rightarrow N\pi S_0$. The data are plotted so that a BMLD consistent with

![Diagram](http://jn.physiology.org/)

**FIG. 5.** As Fig. 3 for the 2nd example unit shown in Fig. 4 with a BF of 516 Hz, threshold of 23 dB SPL, and BD of 360 μs. The characteristic delay (CD) was 516 μs and the characteristic phase (CP) ~0.18 cycle.
the psychophysics (homophasic threshold greater than antiphasic) will appear to the upper left of the solid diagonal line of equality. The two dashed lines show BMLDs of +5 and +10 dB. Most of the NπS0/N0S0 BMLDs are consistent with psychophysics but <5 dB, whereas most of the N0Sπ/N0S0 BMLDs are inconsistent with the psychophysical BMLDs. The second column shows the NπSπ threshold compared with the N0Sπ and NπS0 thresholds. Most of the NπS0/NπSπ thresholds are consistent with psychophysics, and most are <10 dB. However, most of the N0Sπ/NπSπ thresholds are inconsistent with psychophysics. It therefore appears that comparing within unit the N0Sπ thresholds are too high to match psychophysical BMLDs.

In the four conditions in the experiment, a particular phase combination (e.g., N0S0) appeared once at the start of one condition and once at the end of another. These are plotted as separate points in Fig. 8, and it appears that they are reasonably similar; however, a more rigorous comparison is shown in Fig. 9. In Fig. 9, the values of these thresholds are plotted against each other. The solid diagonal line shows equality, and the dotted lines on either side show a difference in threshold of 5 dB. For all four conditions, the thresholds at the start and end of stimuli are very consistent, indicating that there is no overall trend in threshold (for example all stimuli late in the stimulus giving higher thresholds that might be predicted from long term adaptation).

For a unit to be part of a neural substrate that demonstrates sluggishness at the single-unit level, then it needs to have measurable thresholds both before and after the noise transition, and the BMLD needs to be consistent in direction with psychophysics. In Fig. 6, it was shown that this was true for about half of the units tested with S0 tones. The thresholds for these units are shown in Fig. 10A along with those units with a negative BMLD. The format is similar to Fig. 8 with the homophasic threshold plotted along the vertical axis, and the antiphase threshold along the horizontal so that thresholds consistent with psychophysics are shown above the solid diagonal line of equality. The other diagonal lines show BMLDs of +5 and +10 dB. Most of the BMLDs are within 5 dB, although there are a few (like the example in Fig. 5) that have BMLDs >20 dB. There are fewer units that showed measurable thresholds both before and after the noise transition that were consistent in sign with psychophysics, namely that homophasic thresholds (N0S0 and NπSπ) should be higher than antiphasic thresholds (N0Sπ and NπS0). Last, the thresholds after the noise transition should show a monotonic trend from the pretransition threshold to the posttransition threshold with a time course of around 100 ms. In a sample of 40 units from the central nucleus of the IC, we found no units that showed these properties. Only half the units probed with an S0 tone exhibited thresholds before and after a noise transition that were consistent in sign with the psychophysics. This represents a potentially significant population; however, all of the units failed the final test.

**DISCUSSION**

The purpose of this experiment was to determine whether there was any evidence for binaural sluggishness within single units in a binaural masking paradigm. For a single unit to show binaural sluggishness, it must first provide noise masked tone thresholds on either side of a transition from one noise phase to another. Furthermore, these thresholds need to be consistent in sign with psychophysics, namely that homophasic thresholds (N0S0 and NπSπ) should be higher than antiphasic thresholds (N0Sπ and NπS0). Last, the thresholds after the noise transition should show a monotonic trend from the pretransition threshold to the posttransition threshold with a time course of around 100 ms. In a sample of 40 units from the central nucleus of the IC, we found no units that showed these properties. Only half the units probed with an S0 tone exhibited thresholds before and after a noise transition that were consistent in sign with the psychophysics. This represents a potentially significant population; however, all of the units failed the final test.

[![Figure 6](http://example.com/image6.png)](http://example.com/image6.png)

**FIG. 6.** Numbers of units out of 40 satisfying various criteria for the 4 binaural conditions (N0S0 → NπS0, NπS0 → N0S0, NπSπ → N0Sπ, and N0Sπ → NπSπ). The number of units with measurable thresholds in the 1st 4 tone pulses (30–140 ms) is shown in the 1st bar in each set; the 2nd bar shows the number of units with measurable thresholds in the last 4 tone pulses (210–320 ms). The numbers of units with measurable thresholds in both intervals are shown in the 3rd bar. Those units that yielded a positive BMLD (i.e., homophasic threshold > antiphasic threshold: consistent with psychophysics) are shown in the 4th bar.

[![Figure 7](http://example.com/image7.png)](http://example.com/image7.png)

**FIG. 7.** Normalized thresholds as a function of tone onset time for all units yielding S0 thresholds consistent with psychophysics (i.e., N0S0 > NπS0). A: data from the N0S0 → NπS0 condition. B: data from the NπS0 → N0S0 condition. Average thresholds were first obtained for each unit from the 1st 4 and the last 4 tone pulses. Data were then normalized individually for each unit by subtracting the average threshold for N0S0 for that unit from the data and dividing by that unit’s BMLD (N0S0-NπS0). The average across all units after normalization is shown by the heavy black line. The time of the transition is divided by 10.220.33.4 on October 25, 2016 http://jn.physiology.org/ Downloaded from
they were either like the example unit in Fig. 3I, which showed a monotonic trend from pre- to post-transition values, but did so within the sampling period of the tone pulses (i.e., within 30 ms), or were like the example in Fig. 5I that showed a nonmonotonic trend. Less than a quarter of the units showed an S\(\pi\) tone satisfied the first two criteria, which although small could also represent a significant population; however, although no examples are shown, all of these units also showed either a nonmonotonic trend or a fast transition.

It was argued in the introduction that the adaptation phenomenon observed by Ingham and McAlpine (2004) could form a mechanism for apparent sluggishness. They observed that when the ITD of a tone is changed from a value which poorly drives a neuron (the worst delay) to an ITD at which the neuron is well driven (the best delay) the firing rate rises rapidly but then adapts slowly to a lower rate. If this also occurred with noise stimuli, then the adaptation would effectively increase the instantaneous variance of the background noise firing and hence the variance of the tone plus noise firing rate in a tone detection task. This increase in variability would be expected to increase the tone detection threshold (Shackleton and Palmer 2006; Shackleton et al. 2003; Skottun et al. 2001) for a time corresponding to the duration of the adaptation. Such an effect might be expected to look like sluggishness with a smooth monotonic trend if the noise transition was from a condition of poor detectability (e.g., N0S0) to one of good detectability (e.g., N\(\pi\)S0). Of the 12 units shown in Fig. 7A, which shows the N0S0 \(\rightarrow\) N\(\pi\)S0 transition, 9 (75%) were monotonic. However, if the noise transition were from one of good detectability (e.g., N\(\pi\)S0) to one of poor detectability (e.g., N0S0), then we would most likely see an elevation in threshold above the normal poor threshold before a gradual decline back to the normal threshold. This is the behavior demonstrated in the N\(\pi\)S0 \(\rightarrow\) N0S0 condition of Fig. 5I, and, even in this case, the effect is over within 60 ms. Such overshooting transitions were demonstrated in 10/15 (67%) of units with a N\(\pi\)S0 \(\rightarrow\) N0S0 transition shown in Fig. 7B. It therefore appears that we have found evidence for part of the original hypothesis, namely that adaptation of the noise response following a transition does affect the postransition thresholds but that it does not do so in a manner that mimics sluggishness.

We did not make a systematic study of whether we replicated the findings of Ingham and McAlpine (2004); but qualitative examination of the noise responses did not show any marked postransition adaptation behavior over a long duration. There are three possible methodological reasons for this.

FIG. 9. Thresholds for the same phase relationship between signal and noise within a unit measured at the start and end of the stimulus.

FIG. 10. Comparison of the thresholds within a condition measured at the start and end of the stimulus. Data on the left are for S0 tones, and on the right for S\(\pi\) tones. ▲, data for the N\(\pi\) \(\rightarrow\) N0 transition; ▼, data for the N0 \(\rightarrow\) N\(\pi\) transition.
The first is that Ingham and McAlpine used tones in their experiment, whereas we used noise. It is possible that noise responses may not adapt as much responses to tones or may have different dynamics. Second, they made their transition from worst delay to best delay, whereas we made ours from N0 to N\(\pi\) or N\(\pi\) to N0. While N0 for most units was not very different from the best delay and N\(\pi\) was close to the worst delay, the difference between the firing rates in the two conditions was inevitably less in our experiment, and therefore less spike-rate adaptation would be expected. Third, Ingham and McAlpine adapted their units for \(~1\) s, whereas we only “adapted” for 150 ms; it is possible that the effect they measured requires the longer period of adaptation before it becomes apparent.

Previous attempts to measure the responses to binaurally modulated stimuli showed that the physiological responses were just as fast as to monaural changes (Joris et al. 2006; Siveke et al. 2008). Joris et al. (2006) sinusoidally modulated the interaural correlation of a noise stimulus between in-phase (N0) through uncorrelated (Nu) to anti-phase (N\(\pi\)). They found that both the rate and synchronization to the correlation envelope were maintained up to hundreds of hertz. This is in comparison to the corresponding psychophysical experiments (Grantham 1982) where the ability to detect interaural correlation modulation had significantly reduced by modulation rates of 50 Hz. Thus although we argued in the Introduction that the rank ordering of time constants showed that experiments where the target was modulated demonstrated the fastest responses psychophysically, even in this case the responses at IC are demonstrably faster than human psychophysics. It has been argued that the time constants measured for binaural sluggishness are task dependent; a good example of this is provided in the experiments of Siveke et al. (2008). They developed a novel stimulus (“Phase warping” where an identical noise is played to both ears except that the phase spectrum is translated by several frequency bins) which is perceived as rotating around the head. They found that this stimulus could be tracked up to higher rates psychophysically than the interaural correlation modulation (described above). They also measured responses to these stimuli in the dorsal nucleus of the lateral lemniscus (DNLL) both suprathreshold and using ROC analysis to determine threshold (Shackleton et al. 2003; Sotton et al. 2001). They found that although neural thresholds were higher than the human psychophysics, they were maintained up to somewhat higher frequencies. In summary, even in those conditions where psychophysics generates the fastest binaural responses, which are, in fact, not much more “sluggish” than the monaural responses, neurons at the level of the midbrain can track still faster modulations.

In this experiment, we used a step transition between N0 and N\(\pi\) or vice versa, which are comparable to the experiments of Holube et al. (1998) and Kollmeier and Gilkey (1990). These experiments showed ERDs of around 55 ms; which are in the middle of the range observed. Longer ERDs were obtained using either sinusoidal variation of the masker or a transition from Nu to N0. It is therefore possible that there would be greater evidence for neural sluggishness if these other conditions were used. It should be noted, however, that the ERD refers to the equivalent duration of a rectangular averaging window not the duration of the effect. In the experiment of Kollmeier and Gilkey (1990), for example, although the estimated ERD was 55 ms, the smoothing of thresholds was observable over 100–150 ms, thus given that we did not observe a smoothing over \(>30–60\) ms, we can be confident that the neural ERDs are much shorter than the psychophysically measured ones. Whether sinusoidal masker variation or transitions from Nu to N0 would provide measurable and longer time constants is still an open question.

Finally, although we make no quantitative comparisons, the population of neurons from which we measured have many properties in common with those reported previously (Jiang et al. 1997a,b; Lane and Delgutte 2005; Palmer et al. 2000). Thus our conclusions are likely based on comparable populations of neurons and because these studies had much larger samples, we may tentatively conclude that our sample can also be generalized to the entire population of neurons contributing to the BMLD. Compared with these studies we may have under sampled units that give reliable thresholds with S\(\pi\) tones because we used a search stimulus that biased us toward units with small best delays, but that does not negate the conclusions that may be drawn from the other conditions.

In their previous experiments, Palmer and colleagues (Jiang et al. 1997a; Palmer et al. 2000) used a constant level noise stimulus and were able to show that different populations of neurons gave the lowest threshold in different binaural conditions (N0S0, N0S\(\pi\), and N\(\pi\)S0). They concluded that the BMLD is therefore not predominantly a within-neuron effect but represents a comparison of the best responding units in different populations. In this experiment, we also included the N\(\pi\)S\(\pi\) condition but did not use a constant noise level, so are unable to confirm whether the lowest thresholds do indeed emerge in different populations. However, we do show that the response to changes in masker are temporally fast and thus do not reflect the psychophysical demonstrations of sluggishness in masking paradigms. We therefore maintain the conclusion that different populations of neurons are responsible for detection in different binaural masking conditions and further suggest that whatever sluggishness is observed is due a limitation in the rate at which focus can be changed between these populations.

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DISCLOSURES

No conflicts of interest are declared by the authors.

REFERENCES


