Dependency of the Interaural Phase Difference Sensitivities of Inferior Collicular Neurons on a Preceding Tone and Its Implications in Neural Population Coding

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Furukawa, Shigeto, Katuhiro Maki, Makio Kashino, and Hiroshi Riquimaroux. Dependency of the interaural phase difference sensitivities of inferior collicular neurons on a preceding tone and its implications in neural population coding. J Neurophysiol 93: 3313–3326, 2005. First published February 9, 2005; doi:10.1152/jn.01219.2004. This study examined the sensitivities of the neuronal responses in the inferior colliculus (IC) to the interaural phase difference (IPD) of a preceding tone, and explored its implications in the neural-population representation of the IPD. Single-unit responses were recorded from the IC of anesthetized gerbils. The stimulus was a dichotic tone sequence with a common frequency (typically the unit’s best frequency) and level (10–20 dB relative to the threshold), consisting of a conditioner (200 ms) followed by a probe (50 ms) with a silent gap (5–100 ms) between them. The IPDs of the 2 tones were varied independently. The presence of a conditioner generally suppressed the probe-driven responses; the effect size increased as the conditioner IPD approached the unit’s most responsive IPD. The units’ preferred IPDs were relatively invariant with the conditioner IPD. Two types of models were used to evaluate the effects of a conditioner on the IPD representation at the level of IC neural population. One was a version of the population-vector model. The other was the hemispheric-channel model, which assumed that the stimulus IPD is represented by the activities of 2 broadly tuned hemispheric channels. Both models predicted that, in the presence of a conditioner, the IPD representation would shift in a direction away from the conditioner IPD. This appears to emphasize the difference between the conditioner and the probe IPDs. The results indicate that in the IC, neural processes for IPD adapt to the stimulus history to enhance the representational contrast between successive sounds.

INTRODUCTION

Neurons in the inferior colliculus, the major nucleus of the ascending auditory pathway for binaural information, are sensitive to the interaural phase difference (IPD) (e.g., Irvine 1992). The IPD arises from the interaural time difference (ITD) of the sound arrival, which varies with sound source location. Responses of IC neurons to the IPD are sensitive to the stimulus context, where “context” refers to the history of stimulus, or the properties of a sound preceding a sound of interest. Previous studies often used stimuli with a continuously varying IPD, or dynamic IPD to examine the IC sensitivities to the stimulus context (Ingham and McAlpine 2004; McAlpine et al. 2000; Spitzer and Semple 1991, 1993; Yin and Kuwada 1983). A dynamic IPD stimulus would produce the sensation of a moving sound source. Those studies found that the IC neural responses to the IPD of a given instance strongly depend on the pattern of the preceding IPD modulation.

Possible mechanisms underlying the context effect have been proposed by many studies (Borisyuk et al. 2002; Cai et al. 1998a,b; McAlpine et al. 2000, 2002; Spitzer and Semple 1991, 1993). One such mechanism is spike rate adaptation (Borisyuk et al. 2002; Cai et al. 1998a,b; McAlpine et al. 2000, 2002). A stronger response driven by a stimulus with an IPD close to the unit’s preferred IPD would induce a greater degree of adaptation, and thereby reduce the responses to subsequent stimuli by a greater amount. Another possible mechanism is the interaction of binaurally sensitive excitatory and inhibitory synaptic inputs with different time courses, directly from bilateral medial superior olives (MSOs) or indirectly by the dorsal nucleus of the lateral lemniscus (DNLL) (Borisyuk et al. 2002; Cai et al. 1998a,b; Spitzer and Semple 1998). The same type of mechanism has been proposed to explain the IC responses to stimuli simulating echoes, i.e., pairs of successive clicks (Fitzpatrick et al. 1995; Litovsky and Yin 1998b; Yin 1994). However, the specific role played by the IPD-context sensitivity of the IC neurons in the processing of auditory information remains unclear.

This study sought the functional significance of the context dependency of IC neurons in terms of neural information coding. Our working hypothesis was that the context dependent changes in the IC neural population responses would result in changes in the IPD representation in the IC, which in turn would emphasize the perceptual contrast between sounds presented in sequence. The psychophysical localization after-effect (Carlile et al. 2001; Kashino and Nishida 1998b; Thurlow and Jack 1973) is an example of the context dependency of human sound localization, which could play a positive role in sound localization. In experiments on the localization aftereffect, Kashino and Nishida (1998b) for example, presented an adapter tone at a certain IPD, followed by a test tone, and the listener’s perceived IPD for the test tone tended to shift systematically with the adapter IPD. Consistent with the results of other previous studies on the localization aftereffect, Kashino and Nishida found that the shift was in a direction away from the adapter IPD, which would emphasize the perceptual difference between the IPDs of the adapter and the test tones. Also, consistent with the emphasis hypothesis,
Getzmann (2004) and Kashino (1998a) reported that sound location discrimination improved after exposure to an adapter under certain conditions.

In the present study, we used 2-tone sequences (a conditioner and a probe) as stimuli, and we varied their IPDs independently. This stimulus design was inspired by Kashino and Nishida’s psychophysical studies, albeit on a different timescale. The present paper consists of 2 parts. In the first part, we examined how the responses of single neurons to the probe were modulated by the IPD of the conditioner. We predicted, based on the spike rate adaptation, that the strength of the response to the probe would be minimal when the conditioner evoked the maximal response. We tested whether this prediction held in our stimulus configuration of the conditioner-probe sequence. In addition, we examined how the conditioner affected the other properties of the IPD sensitivity of probe-driven responses, such as the unit’s preferred IPD and the IPD tuning, which are key characteristics in terms of neural information processing.

In the second part, based on the results for single neural responses, we estimated the effects of the conditioner on the neural population level representation of IPD. Studies of the ITD sensitivities of mammalian IC neurons suggest that the stimulus ITD is represented by the activities of populations of neurons with a relatively broad ITD tuning, rather than by the activities of small numbers of neurons that are sharply tuned to a specific ITD (Fitzpatrick et al. 1997; McAlpine et al. 2001). In the present analyses, we adopted relatively simple population-based models. One was the population vector model, which is similar to the population vector model initially proposed for coding the direction of arm movement by the motor neuron population (Georgopoulos et al. 1988, 1993), and which was employed by Fitzpatrick et al. (1997) to evaluate ITD coding efficiencies in several auditory nuclei. The other model was that suggested by McAlpine et al. (2001, 2003), which assumed that the stimulus IPD or ITD is represented by the activities of 2 hemispheric channels, each of which is broadly tuned to sound that is contralateral to the IC.

METHODS

The experiments were conducted in the physiological laboratories of Doshisha and Tokai Universities. Animal experimental procedures were performed in accordance with “Guide for Care and Use of Laboratory Animals” (Institute for Laboratory Animal Research, National Research Council) and were approved by the Animal Experimental Committees of Doshisha University and of Tokai University (Isehara Campus).

Animal preparation and recording procedure

The experiments were performed on 35 adult Mongolian gerbils (Meriones unguiculatus) of both sexes, weighing between 45.8 and 85.1 g. The animals were initially sedated with an intramuscular injection (approximately 1.4 ml/kg) of a 2:1 mixture of ketamine hydrochloride (50 mg/ml) and xylazine (25 mg/ml). Additional injections were given as needed to maintain an areflexive state. A heating pad was used to maintain the animal’s body temperature. The scalp and pinnae were removed to expose the skull and the interparietal bone. A head holder was mounted around bregma of the skull.

Unit activity was recorded extracellularly with custom-made enamel-coated Elgiloy electrodes or Epoxilite-insulated tungsten electrodes (FHC, Bowdoinham, ME), with a nominal impedance of 1–2 MΩ at 1 kHz. For 5 animals, electrodes were dorsoventrally inserted into the IC through several holes (about 0.5 mm diameter) made in the posterior region of the skull. For the other 30 animals, a craniotomy of the intraparietal bone was performed, after which the cerebellum was partially removed to expose the caudal poles of the ICs, which allowed an electrode to be inserted caudorostrally into the IC. At Doshisha University, the unit responses were amplified with a pre-amplifier (DAM80, World Precision Instruments, Sarasota, FL) and digitized at a sampling rate of 44.1 kHz with a sound card (Siena, SEK’D, West Hollywood, CA). At Tokai University, the unit responses were amplified and digitized at a sampling rate of 12,207 Hz with an RA16 system (Tucker-Davis Technologies, Alachua, FL). The digitized data were stored for on- and off-line analyses. On-line, the responses were band-pass filtered (passband 0.3–3 kHz), and the activities of single units or multunit clusters were monitored. We used this information to determine the best frequencies (BFs) and threshold sound pressure levels (SPLs) of neurons. Off-line, we isolated the responses of single units with a template-matching algorithm for the formal analyses. A spike was adopted as a single-unit response when it belonged to a distinct cluster of spike waveforms with small deviations from the template waveform.

Recording lasted typically for about 12 h. Once the recording had been completed, the animal was killed with an intraperitoneal injection of a lethal dose of sodium pentobarbital. Some animals were perfused transcardially with phosphate buffer (pH 7.4), followed by 4% paraformaldehyde in the phosphate buffer. Brains were removed, postfixed with 4% paraformaldehyde, and then transferred to a 20–30% sucrose solution. Frozen sections were made in the coronal plane at 25–50 μm, and were Nissl or cytochrome-oxidase stained to examine the sites of the electrode tracks.

We infer that the majority of the units were in the central nucleus of the IC because the distribution of the BFs in the IC was generally consistent with the tonotopic organization of the central nucleus reported in previous studies (e.g., Harris et al. 1997). The stained brain slices, however, showed electrode tracks not only in the core region but also in the indefinite margins of the central nucleus of the IC (Morest and Oliver 1984; Nordeen et al. 1983). Thus the units in the present data might include units in noncentral nuclei.

Stimulus presentation

The animal was placed inside a sound-attenuating chamber and stimuli were delivered dichotically through earphones (MDRX70SL, Sony, Japan, or ER-4S, Etymotic Research, Elk Grove Village, IL) coupled to plastic tubes with an inner diameter of 3 mm, which were fitted to the openings of the external auditory meatuses. We calibrated the sound-delivery system by creating finite impulse-response filters, based on frequency responses recorded by probe-tube microphones (ER-7C, Etymotic Research), which were placed in both ears at about 3 mm from the tympanic membranes. The frequency responses of the calibrated systems were flat so the SD within the calibrated frequency range was <1 dB. Signals were produced by custom-made software on a Windows-operated personal computer. At Doshisha University, signals were generated through a sound card at a sampling rate of 44.1 kHz and with a 16-bit resolution. At Tokai University, a system fabricated by Tucker-Davis Technologies (RP2.1) was used to generate signals at a sampling rate of 48,828 Hz and with a 24-bit resolution.

Search stimuli were single-tone bursts (duration 50 to 250 ms) that varied in frequency and SPL. The tone bursts were either diotic stimuli (IPD = 0) or “binaural beat” stimuli, in which the frequencies for the 2 ears differed typically by 5 Hz. Once a single unit was detected, we determined the unit’s BF (with 1/6–1/3 octave resolution) and the threshold SPL (with 5-dB resolution), using the same
type of stimuli (i.e., diotic or binaural beat stimuli) as the search stimuli.

Subsequently, we used 2-tone sequences to examine the IPD-context effects on the unit responses. Figure 1 shows the 2-tone sequence that we used. A tone sequence consisted of a conditioner followed by a probe. The durations of the conditioner and the probe were 200 and 50 ms, respectively. We chose a 200-ms duration for the conditioner because Finlayson (1999), in his forward-masking experiment on IC units, found that the degree of suppression induced by a masker (comparable to our conditioner) increased with increasing masker duration, but was relatively constant for masker periods of more than about 200 ms. The tones were gated on and off synchronously between the ears with 5-ms raised-cosine ramps. There was a brief silent gap between the conditioner and the probe. We used a common frequency (typically the unit’s BF) and SPL (10 or 20 dB above the unit threshold) for the conditioner and the probe. A frequency lower than the BF was used when the unit showed IPD sensitivities only for a lower frequency. For most units, we tested only one duration of the silent gap between the conditioner and the probe. The gap duration was usually set at the shortest possible value (but ≥5 ms) sufficient to prevent any interaction between the post-conditioner-offset “ringing” and the onset of the probe at the level of the auditory periphery. We estimated the degree of interaction at the auditory periphery by examining the output of a gammatone filter (Slaney 1993) that was centered at the stimulus frequency. The gammatone filter coefficients were chosen so that the equivalent rectangular bandwidth of the filter corresponded to the bandwidth obtained in a behavioral study by Kittel et al. (2002). We used a longer gap duration when the unit failed to respond to the probe because of strong postconditioner suppression. Thus, the gap duration varied among units and ranged between 5 and 100 ms (median 10 ms). For some units, we tested multiple gap durations, ranging typically between 5 and 320 ms (maximum 640 ms).

We varied the IPDs for the conditioner and the probe independently. In this study, a positive IPD indicates that the phase for the ear contralateral to the side of the recorded IC was in advance of the phase for the other ear. For the conditioner, we tested several IPD values, the number of IPD values being varied among units (range 2–10 IPDs; typically 8 values). For 52 units, the intervals of the conditioner IPDs were set so that they had equal steps. For the probe, the IPD varied between −180 and +180°, with typically 8 equal angular intervals (maximum 18 intervals). We also used stimuli without a gap. The stimuli were presented in pseudorandom order such that all conditioner and probe IPD combinations were tested once before repeating all the stimuli again in a different random order. The number of repetitions for each condition varied among units (10–55 repetitions; median 40 repetitions). The interstimulus interval was 1 to 1.5 s.

**Data analysis**

**RESPONSE PROPERTIES OF SINGLE NEURONS.** We used MATLAB (The MathWorks, Natick, MA) for data analysis. In analyzing the results, we focused on the mean spike count (the number of spikes per trial) driven by the conditioner or the probe. We determined the duration of the analysis time window for both conditioner-driven and probe-driven spike counts, individually for each unit, by visually inspecting the postconditioner-onset histograms of the spike times pooled over the stimulus conditions. The window for the conditioner-driven responses spanned the interval from the conditioner onset to the time of the minimum response within the range between the conditioner offset and the onset of the probe-driven responses. The window for the probe-driven responses had a duration of 50 to 80 ms that started at the onset of the probe-driven responses. We found practically no ambiguity when distinguishing between the conditioner-driven and the probe-driven responses.

Each unit’s sensitivity to the probe IPD, termed the IPD function, was determined from the plot of the mean probe-driven spike counts versus the probe IPD. The properties of the IPD function were described in terms of the **overall response strength** (ORS), the **mean IPD**, and the **vector strength**. The ORS was the spike count for the probe averaged across the probe IPDs, and thus indicated the response strength to the probe irrespective of the probe IPD. The mean IPD and the vector strength are the direction and the resultant length, respectively, of the vector average of the spike-count–weighted probe IPD (Batra et al. 1989; Goldberg and Brown 1969), which are indices of the unit’s preferred IPD and the degree of IPD selectivity. The mean IPD without the conditioner was referred to as the unit’s **best IPD**. High vector strength values indicated that a greater proportion of spikes were elicited by stimuli with a particular IPD, indicating a sharper IPD tuning.

For 29 units, for which multiple gap durations were tested, we examined the recovery of the ORS after the conditioner offset. To examine the recovery from conditioner-induced suppression or facilitation, we averaged the ORSs across conditioner IPDs for each gap duration and each unit (Fig. 8D). As in the forward-masking experiment reported by Finlayson (1999), we fitted the recovery data of the averaged ORS with a single exponential function: $y = k_0 + k_1e^{-\tau t}$, where $k_0$ and $k_1$ are constants indicating the asymptotic response magnitude and the difference between the final and the initial response levels, respectively. Here, $t$ is the gap duration and $\tau$ is the time constant. The recovery time constant for the ORS recovery ($\tau$) was fitted using the MATLAB’s “lsqcurvefit” function. The goodness of fit was evaluated in terms of the coefficient of determination, which was the squared correlation coefficient between the actual ORS and the estimation by the fitted function. The coefficient of determination indicates the fraction of variance accounted for by the fit relative to the total variance of the ORS.

We also examined the recovery from the **conditioner IPD effect** (i.e., the conditioner IPD–sensitive component of the ORS). The conditioner IPD effect for a gap duration was quantified as the ORS difference, or the difference between the ORSs for the conditioner IPDs nearest to and farthest from the unit’s best IPD (indicated by the arrow in Fig. 8D). A negative value for the ORS difference indicates that the ORS was reduced by a greater amount by a conditioner with an IPD closer to the best IPD. A greater absolute value of the ORS difference indicates a greater effect of the conditioner IPD. The ORS difference was expressed as the fraction of the ORS when the conditioner was absent. We fitted the same single exponential function as above to the recovery data of the ORS difference. The time constant of the fitted function was the recovery time constant for the ORS difference.

**FIG. 1.** Schematic illustration of the stimulus. Stimulus consisted of a sequence of 2 tone bursts, the conditioner and the probe, with the same frequency and sound-pressure level (SPL). Conditioner and the probe had durations of 200 and 50 ms, respectively. There was a silent gap between the tones. Usually, only one gap duration was tested for each unit, the duration being varied among units (see METHODS). Interaural phase differences (IPDs) of the 2 tones were varied independently. A positive IPD indicates that the phase in the contralateral ear to the recorded inferior colliculus (IC) was in advance of that in the other ear, and vice versa.

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MODELS OF IPD REPRESENTATION BY NEURAL POPULATIONS. We evaluated how the conditioner-induced change in the probe-driven responses for individual units would be reflected in the representation of the probe IPD by the IC unit population. The IPD representation was evaluated using 2 types of neural population based models. One was a version of the population vector model proposed for coding the direction of arm movement by motor neuron population (Georgopoulos et al. 1988, 1993). In the model, the representation of the probe IPD ($IPD_{pop}$) by a neural population was essentially the centroid (i.e., response-weighted center of mass) of the response strength distribution along the best IPD axis. This concept is illustrated in Fig. 10A. When computing $IPD_{pop}$, the IPD functions (with and without the conditioner) for each unit were normalized by dividing them by the maximum probe-driven spike count of the unit without the conditioner. Let $f_i(\theta, \phi)$ denote the normalized IPD function for the $i$th unit in the presence of a conditioner with an IPD of $\theta$, where $\phi$ is a probe IPD. Each unit was represented by $\mathbf{p}_i$, which is a vector-form representation of the $i$th unit’s best IPD (i.e., $|\mathbf{p}_i| = 1; \angle \mathbf{p}_i = \text{best IPD}$). We then computed the “population vector” $\mathbf{v}(\theta, \phi)$, which is the response-weighted vector average of the best IPDs across units in the presence of a conditioner with an IPD of $\theta$: $\mathbf{v}(\theta, \phi) = \sum_i [f_i(\theta, \phi) \mathbf{p}_i]$. Finally, the $IPD_{pop}$ for a given probe IPD was defined as the direction of the population vector: $IPD_{pop}(\theta, \phi) := \angle \mathbf{v}(\theta, \phi)$.

The other model we examined was that suggested by McAlpine et al. (2001, 2003), in which the stimulus IPD or ITD is represented by the activities of 2 hemispheric channels, each of which is broadly tuned to sound that is contralateral to the IC. We realized this model simply by averaging the IPD functions (normalized as in the population vector analysis) across units. We regarded the averaged responses as representing the outputs from the “channel” in one hemisphere of the ICs. Before averaging, each IPD function was interpolated in 1° steps, using MATLAB’s “interpfit” function. Then, we simulated the outputs from the channel in the other hemisphere by inverting the sign of the IPDs for the channel. The difference between the outputs of the 2 hemispheric channels was the IPD representation provided by the hemispheric channel model.

RESULTS

In this study, response characteristics were examined, unless otherwise stated, in terms of the average count of spikes driven by a probe with a duration of 50 ms. We restricted our analyses to 74 units that showed significant tuning to the probe IPDs when the conditioner was absent (Rayleigh test, $P < 0.01$). Figure 2 summarizes the distribution of units’ BFs, stimulus frequencies, and units’ best IPDs for our data set. The units’ BF (figure abscissa; open circles and crosses) ranged between 100 and 3,800 Hz (median 800 Hz). For 12 units with a BF >952 Hz that exhibited IPD sensitivities only for frequencies lower than the BFs, we used stimuli with lower frequencies (filled circles connected to crosses). Thus the stimulus frequency (open and filled circles) ranged between 100 and 1,600 Hz (median 800 Hz). The units’ best IPDs (figure ordinate) had a circular average of 66°, and 55 of the 74 units exhibited positive best IPDs (i.e., contralateral tuning).

In the following sections, we first describe the responses of individual units, mainly with respect to the effects of the conditioner IPD on the probe-driven responses. Then, based on the results for these individual units, we predict the possible consequences of the conditioner IPD effects on the IPD representation by neural populations.

![Effects of conditioner on IPD sensitivities of single neurons](http://jn.physiology.org/)

**Figure 3** shows an example of unit responses in our data set (unit 030417a), demonstrating a typical pattern of responses. Figure 3A shows the IPD functions of the unit (thick gray line: conditioner absent; lines with symbols: conditioner present). It can be seen that the strength of the response to the probe was generally reduced by the presence of a conditioner, whose size of the reduction was sensitive to the conditioner IPD. The overall profile of the IPD function, however, was relatively invariant with conditioner IPD.

The overall response strength (ORS) for the probe (i.e., the average probe-driven spike count across the probe IPDs and trials) was suppressed by the presence of the conditioner and was sensitive to the IPD of the conditioner (Fig. 3B). The ORS was modulated (a modulation depth of 56%) systematically by the variation in the conditioner IPD, being smallest when the conditioner IPD was near the unit’s best IPD (72°; vertical dashed line). This tendency can be more clearly seen when the ORS is plotted as a function of the angular separation of the conditioner IPD from the best IPD (Fig. 3E). Thus ORS increased approximately linearly with increasing angular separation ($r = 0.902$). The slope of the linear fit for the normalized ORS (percentage with respect to the maximum across the conditioner IPDs) was 0.334. This indicates that, for example, a 90° increase in the separation of the conditioner IPD from the best IPD would increase the ORS by nearly 30 percentage points (0.334 × 90°). When the ORS was plotted as a function of the conditioner-driven response, there was a strong negative correlation ($r = −0.973$; Fig. 3F). This tendency is as expected from the spike-rate adaptation.

When the generally broad tuning of the IPD functions was taken into account, there was relatively little deviation in the mean IPD in the presence of a conditioner from the best IPD (maximum 11°) and little variation in the mean IPD when the conditioner IPD was varied (maximum 9°) (Fig. 3C).

The vector strength, as an index of the IPD selectivity, varied with the conditioner IPD (Fig. 3D). It was maximum (indicating a narrow IPD tuning) when the conditioner IPD was close to the unit’s best IPD.
Below, we examine the influence of the conditioner IPD effects on the statistics described above for the sample populations of the units in our data set. Then, we examine the extent to which the duration of the gap between the conditioner and the probe influenced the conditioner effects.

### Overall Response Strength
As found for unit 030417a (Fig. 3A), the conditioner suppressed the responses of the majority of the units, and the ORS was generally modulated by varying the conditioner IPD. This can be seen by the fact that many points fell below the diagonal line of Fig. 4A, which is the plot of the ORS with the conditioner versus that without it. In the figure, the range of ORSs across all the conditioner IPDs tested for a unit is indicated by the range of a line connecting a pair of dots. Sixty-three of the 74 units exhibited a >10% decrease or increase in the ORS for at least one conditioner IPD. For 50 units, the ORS decreased by >10% for all the conditioner IPDs. A small population of units exhibited the facilitative effect of the conditioner (8 units; >10% increase for all conditioner IPDs; open symbols in Fig. 4A). We noted a close association between the facilitative effect and the units’ temporal response pattern (i.e., a “buildup” type response); that is, for the units that exhibited facilitation, there was generally a weak response level after the conditioner onset, but the response increased toward the end of the conditioner. Even once the conditioner has stopped and during the silent gap, the excitability appeared to build up. Thus the conditioner had a facilitative effect.

As seen for the example shown in Fig. 3, B and E, the ORS was sensitive to the conditioner IPD for the majority of units (49 of 74 units showed >25% modulation), and the dependency on conditioner IPD was generally well accounted for by the angular separation of the conditioner IPD from the best IPD. We computed the correlation coefficient for the ORS and the absolute angular separation of the conditioner IPD from the unit’s best IPD. ORS is represented as a percentage with respect to the maximum value across the conditioner IPDs. Solid line indicates the least-square fit of a linear function. F: ORS as a function of the conditioner-driven spike count. ORS and the conditioner-driven spike count were normalized and are represented as percentages with respect to the maximum values across all the conditioner IPDs. Asterisk indicates the absence of a conditioner.

**Fig. 3.** An example of unit responses (unit 030417a; BF: 800 Hz; stimulus frequency: 800 Hz; threshold: 35 dB; stimulus SPL: 55 dB; gap: 10 ms). A: IPD functions in the absence of a conditioner (thick gray line) and in the presence of conditioners at various IPDs, as indicated by symbols corresponding to those above the figure. Vertical dashed line at 72° represents the unit’s best IPD. B–D: overall response strength (ORS), the mean IPD, and the vector strength, respectively, as a function of the conditioner IPD. Open symbols correspond to those in A, and the dots indicate additional conditioner IPDs that we tested in the experiment. Vertical lines represent the unit’s best IPD. Horizontal lines indicate the values in the absence of the conditioner. E: ORS as a function of the absolute angular separation of conditioner IPD from the unit’s best IPD. ORS is represented as a percentage with respect to the maximum value across the conditioner IPDs.
units) associated with the conditioner-induced facilitation, or with the buildup-type response. As with unit 030417a (Fig. 3F), we fitted a straight line to the plot of the normalized ORS versus the normalized conditioner-driven spike count for each unit. The mean and the SD of the slope were -0.54 and 0.51, respectively. This indicates that on average, an increase of 1.0 percentage point in the conditioner-driven response would result in a decrease of 0.54 percentage point in the probe-driven response.

We found a few cases in which the conditioner elicited virtually no spikes but appreciable conditioner-induced suppression was present. These cases are inconsistent with the explanation of the conditioner IPD effect in terms of the conditioner-driven response. Three of the 74 units exhibited virtually no conditioner-driven response (<0.1 spikes per trial) for at least one conditioner IPD. Of those units, only one showed suppression of >90% at that IPD, and the other 2 units showed relatively weak suppression (26 and 18%).

MEAN IPD. The conditioner had relatively little effect on the mean IPD. This can be seen in Fig. 5, in which the mean IPD range for various conditioner IPDs is plotted versus the mean IPD when there is no conditioner (i.e., the best IPD). The mean IPD for many units clustered around the diagonal line. A small population of units exhibited a statistically significant effect ($P < 0.01$, Watson’s nonparametric test for common mean direction; Fisher 1993) of the presence of a conditioner (16 of the 74 units) and/or of the conditioner IPD (8 of 74). Unlike for the ORS, across those 8 units that exhibited a significant effect of the conditioner IPD, we failed to find a consistent relationship between the variation of mean IPD and the angular separation of the conditioner IPD from the unit’s best IPD.

VECTOR STRENGTH. The vector strength generally increased (i.e., tuning narrowed) in the presence of a conditioner (Fig. 6A). The figure, which is a plot of the range of vector strength in the presence of a conditioner against the vector strength without the conditioner, shows that many data points fell above the diagonal line. For 54 of the 74 units, the mean vector strength (across conditioner IPDs) was greater when the conditioner was present than when it was absent.

Unlike for the ORS, however, we failed to find a consistent pattern of conditioner IPD dependency across the units as regards vector strength. Figure 6B is a histogram of the correlation coefficient for the vector strength and the absolute angular separation of the conditioner IPD from the unit’s best IPD (cf. Fig. 4B). Here, a positive coefficient indicates that the vector strength increased (i.e., the IPD tuning sharpened) with increasing separation of the conditioner IPD from the unit’s best IPD. The figure indicates that generally the coefficients distributed broadly between -1 and 1, albeit with a weak bias toward negative values (Fig. 6B, gray bars). When the examination was restricted to the units exhibiting relatively large conditioner IPD dependency (i.e., >25% modulation induced by conditioner IPD; 35 units; black bars in Fig. 6B), nearly equal numbers of units exhibited negative and positive correlation coefficients (19 and 16 units, respectively).

To overview the effects of conditioner IPD on the response properties described above, the units in our data set are sorted by 10.220.33.3 on September 24, 2016 http://jn.physiology.org/ Downloaded from
in terms of best IPD and are plotted in Fig. 7. Each panel of Fig. 7 shows the responses of 42 units for which we experimentally tested conditioner IPDs of $-180$, $-90$, $0$, and $+90^\circ$. The 3 columns from left to right indicate the characteristics of the IPD function, that is, the ORS, the mean IPD, and the vector strength, respectively. In each panel, the abscissa indicates the unit’s best IPD and the ordinate indicates the deviation of the measure of interest from the mean value. For the ORS and the vector strength, we scaled the values for each unit relative to the maximum value across all the conditioner IPDs, before calculating the deviations.

There is a trend that the ORS was relatively small for units with best IPDs near a conditioner IPD (dashed vertical lines). The trend could be easily seen when a cosine function was fitted to the ORS-versus-best-IPD functions (thick lines). The coefficient of determination for the fit ($R^2$) ranged between 0.165 and 0.449, indicating that the 16.5 to 44.9% variability among the units could be accounted for by a cosine function. The minima of the fitted curves corresponded approximately to the conditioner IPD. This indicates that the ORS was reduced rather selectively for units with best IPDs near the conditioner IPD.

We failed to find such systematic trends for the mean IPD and the vector strength: $R^2$ range for the cosine fit was as small as 0.005–0.068 for the mean IPD and 0.004–0.028 for the vector strength, which indicates that the effects of the conditioner IPD on the mean IPD and the vector strength were negligible or, if they existed, were inconsistent among units.
Effects of gap duration

In the previous sections, the duration of the silent gap between the conditioner and the probe was fixed for each unit (see METHODS). In this section, we describe supplementary experiments that we conducted to examine to what extent the conditioner effect would be sensitive to the gap duration, and recovery functions from the conditioner effect. We tested 4 to 7 gap durations (maximum 640 ms) for 29 units.

The results for unit 030218c, which is representative of the units in our data set, are shown in Fig. 8, the top panels of which (Fig. 8, A–C) show IPD functions, each panel representing one conditioner IPD, and each function within a panel representing an IPD function for one gap duration. The basic properties of the IPD functions, that is, ORS, mean IPD, and vector strength, are represented in the bottom panels (Fig. 8, D–F), as a function of gap duration.

Within any given gap duration, the effect of the conditioner was generally consistent with our typical results described in the previous sections (Fig. 8, D–F). The conditioner IPD near the unit’s best IPD had the greatest suppressive effect on the ORS. The mean IPD was relatively insensitive to the conditioner IPD. For this unit, the vector strength tended to be largest for the conditioner IPD near the unit’s best IPD. For all the statistics, the effect of the presence of a conditioner was maximal for the shortest gap duration, and the recovery was monotonic as the gap duration increased.

We focused on the ORS to evaluate the recovery from the conditioner effect. We quantified the recovery of the ORS from the general suppression (i.e., the component of the ORS change that was insensitive to conditioner IPD) by fitting an exponential function to the average ORS across conditioner IPDs (indicated by dots in Fig. 8D) as a function of gap duration (see METHODS). The fitted exponential curve is shown by the gray line in Fig. 8D. The recovery time constant was 111.8 ms.

Similarly, we applied the exponential function to the recovery function for the 29 units for which there were more than 3 gap durations. In general, the exponential function accounted well for the ORS recovery function; the median of the coefficient of determination was 0.91. Figure 9A is a histogram of the recovery time constants, representing 25 of the 29 units for
Context Sensitivity of IPD Representation

which the coefficient of determination was >0.75. The median
time constant was 111.8 ms.

We also examined the recovery from the conditioner IPD
effect (i.e., the component of the ORS change that was sen-
sitive to conditioner IPD). The effect of the conditioner IPD for
a given gap duration was quantified as the ORS difference,
which was the difference between the ORSs for the conditioner
IPDs nearest to and farthest from the unit’s best IPD (illus-
trated by the arrow in Fig. 8D, which is an example for a 5-ms
gap). See Methods for details. For the unit shown in Fig. 8, the
size of the ORS difference decreased monotonically with
increasing gap duration. The fitted exponential function had a
recovery time constant of 114.8 ms.

An examination of the ORS differences for the population
of the 29 units led us to conclude that, in general, varying the gap
duration would influence the magnitude but not the direction
of the conditioner IPD effects. For each unit, we compared the
signs of the ORS differences across gap durations. Altered
signs should indicate that the direction of the conditioner IPD
effect (i.e., whether a conditioner IPD nearest the best or the
worst IPD induced the greatest suppression of the ORS) varied
depending on the gap duration. We restricted the examination
to the ORS differences with appreciable sizes, that is, those for
which the absolute value (expressed as a fraction of the ORS
when the conditioner was absent) was >0.1. The criterion
value of 0.1 corresponded to the median of the absolute values
of the ORS differences across all units and gap durations. As a
result, only 3 units exhibited altered signs of the ORS differ-
ence, indicating the dependency of the direction of the condi-
tioner IPD effect on the gap duration.

The exponential function was fitted to the plot of the ORS
difference versus gap duration. Figure 9B shows the distribu-
tion of the time constants for the population of units, repre-
senting 14 of the 29 units for which the coefficient of deter-
mination was >0.75 (the coefficient of determination for all 29
units had a median of 0.74). The median time constant was
68.6 ms.

Conditioner effects on neural population codes

In this section, we explore the functional significance of the
conditioner effects in the IPD representation at the level of
neural population in the IC. We adopted 2 types of models: the
population-vector model and the hemispheric-channel model
(see Methods).

The population-vector model assumes that there is an array
of IC units, somewhat broadly tuned to various IPDs, and that
each unit is represented by its best IPD (Fig. 10A, top).
Presenting a probe would evoke responses from the popula-
tions of IC units, and the IPD of the probe would determine the
pattern of the response distribution along the axis of the unit’s
best IPD (Fig. 10A, bottom). We assumed that the population
representation of the probe IPD (IPDpop) is derived as the
centroid (i.e., response-weighted center of mass) of the popu-
lation response distribution along the best IPD axis. Changes in
the individual IPD functions arising from the presence of a
conditioner should somehow alter the population response
distribution, and thus the IPDpop. Earlier analyses of the indi-
vidual units indicated a tendency for the ORS to be reduced by
the greatest amount for units with their best IPDs close to the
conditioner IPD, whereas the mean IPD was generally invari-

ant with conditioner IPD (Fig. 7). An expected consequence of
this trend is shown in Fig. 10B. The figure reveals that when a
conditioner was present with an IPD of zero, for instance, the
response strengths of the units with their best IPDs near zero
would be rather selectively reduced (Fig. 10B, top). We expect
that this change would shift the centroid of the population

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

**FIG. 10.** Illustration of the population-vector model for IPD representation,
and an example of population responses. A: an array of units tuned to various
IPDs, curves representing the units’ IPD functions of individual units (above)
and the response strength distribution along the best IPD axis for a given probe
IPD (below). Panel represents cases without a conditioner. B: as above, but
with a conditioner. C: normalized responses of the unit array to a probe with
an IPD of +90°, plotted against the unit’s best IPD. Each open circle or
asterisk represents the response of one unit in the absence of, and in the
presence of, a 0-IPD conditioner, respectively. Two asterisks accompanied by
upward-pointing arrows indicate the data points outside the ordinate rage, for
which the normalized response values are indicated by the numbers below the
symbols. Thick gray lines are drawn to guide the eye to the overall trends, by
computing running averages using a Hanning window spanning 90° (broken
line: conditioner absent; solid line: conditioner present). Vertical dashed
(conditioner absent) and solid (conditioner present) lines indicate the centroids
of the response distribution (i.e., IPD representations). See Results for details.
response for a given probe IPD in a direction away from the conditioner IPD (Fig. 10B, bottom).

We tested this expectation using a database consisting of 42 units for which we experimentally tested conditioner IPDs of −180, −90, 0, and +90°. We formed a unit array that consisted of the 42 units, plus the same 42 units for which the signs of the conditioner and the probe IPDs were inverted. We combined the units with unaltered and inverted IPD signs, to simulate the population responses in bilateral ICs. In this analysis, we neglected differences among units with respect to unit properties such as best frequency and threshold SPL and with respect to stimulus properties such as frequency, SPL, and gap duration. We computed the IPD representation by neural population, $IPD_{pop}$, for each conditioner state. See METHODS for details.

To illustrate our population-vector analysis, we provide examples of unit-array responses for a probe at +90° IPD in Fig. 10C. In the absence of a conditioner (open circles), units with best IPDs of about +90° were generally most active (compare this with Fig. 10A, bottom). The centroid of the response distribution (i.e., $IPD_{pop}$) was +64° (vertical dashed line). The 26° offset of $IPD_{pop}$ from the probe IPD (+90°) was attributed to the overrepresentation of best IPDs of −90 to +90°. When a 0-IPD conditioner was present (asterisks), the responses decreased particularly for best IPDs of 0 ± 90° (compare this with Fig. 10B, bottom). Thus the profile of the response distribution was altered. We can easily see the change in the distribution profile when we compare the running averages of the responses in the absence (broken gray line) and in the presence (solid gray line) of the conditioner. The $IPD_{pop}$ when the conditioner was present was +84° (vertical solid line). That is, the $IPD_{pop}$ for the +90° probe shifted by 20° (i.e., 84−64°) toward positive IPDs, in the presence of the 0-IPD conditioner.

The results of the analysis indicated that the $IPD_{pop}$ in the presence of a conditioner tended to shift from that without a conditioner (Fig. 11, lines connecting dots). In the figure, the shift of the $IPD_{pop}$ is plotted as a function of the probe IPD, for each conditioner IPD. Except for a conditioner IPD of −180° (Fig. 11A), the maximum shift was as great as about 45°. For each panel, the sign of the shift tended to change at a probe IPD near the conditioner IPD. The $IPD_{pop}$ for a probe at a positive IPD relative to the conditioner IPD was generally biased toward a positive IPD, and vice versa. This result is consistent with our expectation as illustrated in Fig. 10B.

The analysis with the hemispheric channel model was conducted as follows. We averaged the (normalized) IPD functions of 30 units for which the best IPDs were positive and where we experimentally tested conditioner IPDs of −180, −90, 0, and +90°. We regarded an averaged IPD function as being proportional to the outputs from the single hemispheric “channel.” Each IPD function was interpolated in 1° steps, before averaging. Figure 1A2 shows the averaged IPD functions in the absence (thick gray line) and the presence (thin lines with symbols) of a conditioner. As expected from the results reported in previous sections, the response strength (i.e., the channel output) was reduced when a conditioner was present, and the degree of reduction generally increased as the conditioner IPD changed from negative to positive. Next, by inverting the sign of the IPDs for the channel, we simulated the outputs from the contralateral channel. Then, we regarded the
stimuli were particularly comparable to that used in a forward-
Comparison with previous studies

direction away from the conditioner IPD. The probe IPD would be biased by the presence of a conditioner in

The results provided by the 2 models consistently indicated

was the hemispheric-channel model (McAlpine et al. 2001).

vector model (Georgopoulos et al. 1988, 1993) and the other

population, based on the results obtained for individual units

inconsistent among units. We evaluated the effects of condi-
tioner IPD, whereas the effects of the conditioner IPD on the

response strength varied systematically with the condi-

ditioner reduced the response strength to the probe and in-

creased the IPD selectivity (i.e., increased the vector strength).
The results for the dynamic IPD stimuli, however, were

substantially different from ours, in that the spike probability

often substantially exceeded that predicted from the responses
to a static IPD (McAlpine et al. 2000; Spitzer and Semple
1991, 1993), in contrast to our study. We consider, however, that these 2 observations are not

contradictory. As discussed in the next section, our results are
generally consistent with the prediction by the spike-rate ad-

aptation mechanism. The spike-rate adaptation mechanism is

known to be able to account for, at least partially, the variation

of the IPD function for the dynamic IPD stimuli (McAlpine et

al. 2000). Thus we expect that even for 2-sequence stimuli such

as ours, the IPD function should exhibit some apparent mod-

ulation because of the variation of conditioner IPD for certain

combinations of conditioner and probe IPDs. Note that in the

studies on the dynamic IPD, an IPD function was drawn for a

fixed IPD change from the preceding stimulus (i.e., for a given

point on an IPD function, the preceding IPD was separated

from the IPD at that point by a fixed amount and direction). By

contrast, in our study an IPD function was drawn for each fixed

conditioner IPD.

The present study agreed with previous studies on dynamic

IPD stimuli (McAlpine et al. 2000; Spitzer and Semple 1991,

1993), in that the IC neurons’ sensitivities depended on the IPD context or the IPD history. It might appear inconsistent that in

earlier studies, the shape of the IPD function was substantially

modulated by a dynamic IPD, depending on the direction and

range of the IPD modulation, whereas for the present stimuli,
the mean IPD was relatively invariant with the conditioner

IPD. We consider, however, that these 2 observations are not

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to a static IPD (McAlpine et al. 2000; Spitzer and Semple
1991, 1993), in contrast, in the present study the conditioner

had a predominantly suppressive effect. We speculate that this
difference arose from the difference in the timescale of the

stimulus and in the analysis time window. The dynamic IPD

stimuli typically had a relatively long (>8 s) duration, and the

spike-count calculation was based on the sustained portions of

the response. In the present study, on the other hand, the mean

spike counts were computed for short (50-ms) probe tones, in

which transient responses at the probe onset were the major
determinant of the mean spike count. It may be that the onset

responses were more susceptible to the conditioner-induced

suppression than the sustained portions of the responses and

thus we rarely observed facilitative effects.

Extensive studies have been conducted on the IC parallels of
the precedence effect (PE), that is, the perceptual dominance
of the first-arriving sound (or the direct sound from a source) over

echoes in sound localization (Fitzpatrick et al. 1995, 1999;

Litovsky et al. 1998a,b, 2002; Yin 1994). Stimuli for PE

FIG. 12. Results for the IPD representation based on the hemispheric
channel model. A: averaged IPD functions of 30 units, regarded as the outputs
of the IPD channel on a hemisphere. Thick gray line indicates the model
outputs without the conditioner. Symbols indicate conditioner IPDs as shown
on top of the panel. B: difference between the outputs (i.e., the averaged
responses shown in A) of the 2 hemispheric channels. Other conventions are as
in A. C: same as B, but redrawn to show the method used to compute the
IPD-representation shift. Only the results without the conditioner and with the
−90° conditioner are shown. Note the abscissa range, compared with B. See
RESULTS for details.

DISCUSSION

The present study examined the responses of single units in the

gerbil IC to sequences of 2 steady tones, the IPDs of which

were varied independently. In general, the presence of a condi-
tioner reduced the response strength to the probe and in-
creased the IPD selectivity (i.e., increased the vector strength).
The response strength varied systematically with the condi-
tioner IPD, whereas the effects of the conditioner IPD on the

neurons’ preferred IPDs and IPD selectivities were slight or

inconsistent among units. We evaluated the effects of condi-
tioner IPD on the IPD representation at the level of neural

population, based on the results obtained for individual units

using 2 types of models. One was a version of the population-

vector model (Georgopoulos et al. 1988, 1993) and the other

was the hemispheric-channel model (McAlpine et al. 2001).

The results provided by the 2 models consistently indicated

that the IPD representation by neural population for a given

probe IPD would be biased by the presence of a conditioner in

a direction away from the conditioner IPD.

Comparison with previous studies

We found that the time course and the type of the present
stimuli were particularly comparable to that used in a forward-

masking study by Finlayson (1999), in which he examined the

responses of IC neurons to a 200-ms-long masker (correspond-
ing to our conditioner) followed by a 30-ms probe, presented

monaurally and diotically. Our results for the effects of a condi-
tioner on the ORS were generally in agreement with
Finlayson’s findings for monaural stimulation. For the majority
of units (>67%), the conditioner (or the masker) had a sup-

pressive effect. The minority of units that exhibited a facilita-
tive effect were associated with a temporal response pattern of

the long-latency or the build-up type. Our recovery time

constants were slightly longer (a median of 111.8 ms) than

Finlayson’s (a median of 72.8 ms). However, we consider the
difference between the studies to be small, considering the

differences in the analysis procedure, sample numbers, and

precision of analysis.

The present study agreed with previous studies on dynamic

IPD stimuli (McAlpine et al. 2000; Spitzer and Semple 1991,

1993), in that the IC neurons’ sensitivities depended on the IPD
context or the IPD history. It might appear inconsistent that in

earlier studies, the shape of the IPD function was substantially

modulated by a dynamic IPD, depending on the direction and

range of the IPD modulation, whereas for the present stimuli,
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contradictory. As discussed in the next section, our results are
generally consistent with the prediction by the spike-rate ad-

aptation mechanism. The spike-rate adaptation mechanism is

known to be able to account for, at least partially, the variation

of the IPD function for the dynamic IPD stimuli (McAlpine et

al. 2000). Thus we expect that even for 2-sequence stimuli such

as ours, the IPD function should exhibit some apparent mod-

ulation because of the variation of conditioner IPD for certain

combinations of conditioner and probe IPDs. Note that in the

studies on the dynamic IPD, an IPD function was drawn for a

fixed IPD change from the preceding stimulus (i.e., for a given

point on an IPD function, the preceding IPD was separated

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contrast, in our study an IPD function was drawn for each fixed

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Extensive studies have been conducted on the IC parallels of
the precedence effect (PE), that is, the perceptual dominance
of the first-arriving sound (or the direct sound from a source) over

echoes in sound localization (Fitzpatrick et al. 1995, 1999;

Litovsky et al. 1998a,b, 2002; Yin 1994). Stimuli for PE
experiments are similar to ours in that they consist of a leading and lagged sounds (typically clicks), varied in terms of spatial location or ITD. Despite differences in stimulus type and temporal structure, the major finding of the present study is comparable to the results of PE studies. Litovsky and colleagues (1998b, 2002) found that IC units of anesthetized cats generally exhibited lead-induced suppression of the lag-driven response, and for the majority (about 80%) of units, the suppression was maximal when the lag location was in the unit’s response area (Litovsky et al. 1998b, 2002). It should be pointed out, however, that the predominant of the units exhibiting the greatest lag suppression by the best stimulus lead was not true for unanesthetized animals, that is, rabbits (Fitzpatrick et al. 1995).

Mechanisms underlying the conditioner effects

The presence of a conditioner generally suppressed the responses to the probe. We infer that this general suppression was largely the result of the accumulated short-term adaptation that took place in non-binaural-specific pathways below the level of the IC (Finlayson 1999).

The conditioner IPD–sensitive component of the response suppression could be well accounted for by the spike-rate adaptation (Borisyuk et al. 2002; Cai et al. 1998a,b; Ingham and McAlpine 2004; McAlpine et al. 2000, 2002). This is because, for the majority of units, the response strength to the probe was highly negatively correlated with the conditioner-driven spike count (Fig. 4C). It should also be noted that the mean IPD for the probe was relatively invariant with the conditioner IPD, indicating that there was little interaction between the conditioner and the probe IPDs in determining the probe-driven response strength. This was as expected from the spike-rate adaptation explanation because it assumes that the effect of the conditioner IPD is mediated by the conditioner-driven responses, and thus the probe-driven response would have no memory of the conditioner IPD, per se.

Arguments against the explanation in terms of the spike-rate adaptation, however, are possible, because of the following 2 observations: One is that there were a few units for which the conditioner elicited virtually no spikes but there was appreciable conditioner-induced suppression; the other is that the recovery time constant for the conditioner IPD effect (a median of 68.6 ms; Fig. 9B) was considerably shorter than the time constants estimated for the spike-rate adaptation (more than a few hundreds of milliseconds; Ingham and McAlpine 2004). One should be cautious, however, when comparing time constants for the 2 studies. Ingham and McAlpine (2004) derived time constants in experiments in which the binaural adaptation components were carefully segregated from those of the monaural adaptation, whereas the present experiment was not specifically designed to segregate the 2 types of components.

It is possible that mechanisms other than the spike-rate adaptation played certain roles in shaping the conditioner IPD effects. For example, the observed effect could be accounted for by the interaction between binaural sensitive excitatory and inhibitory synaptic inputs with different time courses, directly from bilateral MSOs or indirectly by DNLL (Borisyuk et al. 2002; Cai et al. 1998a,b; Fitzpatrick et al. 1995; Litovsky and Yin 1998b; Spitzer and Semple 1998; Yin 1994).

Validity of neural population analyses

Some might be concerned that in conducting the population analyses, we pooled the IPD functions obtained for units with different BFs. We considered this pooling acceptable because a previous report indicated that the central tendency of the best IPD, rather than the best ITD, was relatively invariant with BF (McAlpine et al. 2001). Thus the pooled population among different BFs reflected, to some degree, a population of IPD functions of units with a given BF, although the best IPDs for the units in the present study were distributed relatively broadly. It should also be noted that the 2 different models examined in the present analyses reached essentially the same conclusion as to the direction of the representation shift. Thus we consider that the predicted direction of the conditionerdependent shift of the IPD representation by neural populations should be relatively insensitive to the details of differences among units or model structures.

Implications of population sensitivity to IPD context

The present analyses estimated that the IPD of a preceding sound systematically biases the IPD representation by IC-neural populations, even though the effects of the context on individual units were merely seen in changes of response gain, without consistent changes of preferred IPD.

This bias of the population representation might be viewed as a distortion of the auditory space representation, which thus loses the coding accuracy for location-related information. There is another view, however. The context-dependent change of the neural representation enhances the representational contrasts between successive sounds, improving the efficiency of the information processing of environmental sounds. This view is along the same lines as the general notion that neural adaptation plays positive roles in efficient stimulus coding (e.g., Barlow 1990; Brenner et al. 2000; Wainwright 1999).

Consistent with this view is the fact that the representation shift induced by the conditioner was in a direction away from the conditioner IPD, which would emphasize the difference between representations of the conditioner and the probe IPDs.

The direction of the IPD-representation shift was the same as that of the perceptual shift found in the psychophysical localization aftereffects (Carlile et al. 2001; Kashino et al. 1998a,b, 1999; Thurlow and Jack 1973). There are also studies reporting that spatial discrimination on the horizontal plane improved after the presentation of an adapter sound, specifically when the target sound was close to the adapter in terms of spectral content and spatial location (Getzmann 2004; Kashino 1998a).

These results of adaptation experiments are consistent with the above view that enhancement is provided by a preceding sound. However, it should be noted that the stimuli for the adaptation experiments generally had a timescale that was about an order of magnitude longer (i.e., an adapter tone ≥1 s long followed by a ≥100-ms test tone). It is therefore possible that the neural mechanisms of the localization aftereffect are not directly relevant to the physiological findings in the present study.

Unfortunately, we are unaware of compelling psychophysical evidence for stimuli with a timescale comparable to ours that indicates a shift of perceived IPD. Perhaps the most comparable psychophysical experiment so far is the experi-
A theory about the functional role and synaptic mechanism of Barlow HB.

References

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R E F E R E N C E S


